Angeles Link – Phase 1
Quarterly Report (Q3 2024)

For the period of July 1, 2024 through September 30, 2024

Appendix 1B - Draft Reports:
GHG Study
NOx Study

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ANGELES LINK PHASE 1

GREENHOUSE GAS (GHG) EMISSIONS EVALUATION

DRAFT – JULY 2024

SoCalGas commissioned this GHG Emissions Evaluation from Stantec Consulting Services Inc. The analysis was conducted, and this report was prepared, collaboratively.

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Acronyms and Abbreviations

AB	Assembly Bill
AL	Angeles Link
APCD	Air Pollution Control District
AQMD	Air Quality Management District of California
CARB	California Air Resources Board
CEC	California Energy Commission
CFR	Code of Federal Regulations
CHP	Cogeneration or Combined Heat and Power
CO2e	Carbon dioxide equivalent
CPUC	California Public Utilities Commission
EF	Emission Factor
EO	Executive Order
FARMER	Funding Agricultural Replacement Measures for Emission Reductions
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate change
MMBtu	Million British Thermal Units
NREL	National Renewable Energy Lab

PNNL	Pacific Northwest National Laboratory
SB	Senate Bill
SMR	Steam Methane Reforming
UC	University of California
UCI	University of California Irvine
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency
ZECAP	Zero Emissions for California Ports
ZEV	Zero Emission Vehicle

1 EXECUTIVE SUMMARY

Southern California Gas Company (SoCalGas) is proposing to develop a clean renewable hydrogen[1] pipeline system to facilitate transportation of clean renewable hydrogen from multiple regional third-party production sources and storage sites to various delivery points and end users in Central and Southern California, including in the Los Angeles Basin. The CPUC's Phase 1 Decision, approving the Memorandum Account for SoCalGas's proposed Angeles Link, allows SoCalGas to track costs for conducting the feasibility studies. In the Decision, the CPUC defines clean renewable hydrogen as hydrogen that does not exceed 4 kilograms of carbon dioxide equivalent (CO2e) on a lifecycle basis per kilogram of hydrogen produced and does not use fossil fuel[2] in the hydrogen production process.

This greenhouse gas (GHG) study (GHG Study or Study) is one of the studies established to answer questions raised by the CPUC and other parties to the proceeding. The Decision directs (OP 6 (n)) SoCalGas to provide the findings demonstrating compliance with environmental laws and public policies. To demonstrate how clean renewable hydrogen could support environmental laws and public policies, this Study conducts an initial evaluation of projected GHG emissions from hydrogen infrastructure including those attributable to third-party production and third-party storage; and of anticipated GHG emission reductions from end-users; and overall GHG benefits associated with Angeles Link. This feasibility study is based on information currently available, and the analysis and corresponding conclusions are expected to evolve over time.

This GHG Study evaluates direct GHG emissions[3] associated with hydrogen combustion associated with new infrastructure (i.e., third-party production, third-party storage, and transmission of hydrogen),[4] as well as GHG emissions reductions associated with displaced fossil fuels by end users in the mobility, power generation, and hard-to-electrify industrial sectors.[5] Indirect GHGs from electricity are zero since it was assumed that only renewable electricity would be used. Should the need arise for the use of non-renewable grid electricity to produce hydrogen, the associated GHG emissions associated with production would include non-zero indirect GHGs.

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[1] In the California Public Utilities Commission (CPUC)'s Angeles Link Phase 1 Decision (D.)22-12-055 (Phase 1 Decision), clean renewable hydrogen refers to hydrogen that does not exceed 4 kilograms of carbon dioxide equivalent (CO2e) produced on a lifecycle basis per kilogram of hydrogen produced and does not use fossil fuels in the hydrogen production process.

[2] Fossil fuel is defined as a mixture of hydrocarbons including coal, petroleum, or natural gas, occurring in and extracted from underground deposits.

[3] In this Study, direct GHG emissions refer to GHG emissions from combustion, and indirect GHG emissions refer to GHG associated with non-renewable grid electricity or the estimated effect of potential hydrogen leakage on greenhouse gases in the atmosphere.

[4] The terms "new infrastructure" and "hydrogen infrastructure" refer to general hydrogen infrastructure comprised of third-party production, third-party storage, and transmission. The term "Angeles Link infrastructure" refers to transmission via pipelines including compression which supports both storage and transmission of hydrogen.

[5] Mobility, power generation, and hard-to-electrify industrial sectors as defined in the parallel Demand Study.

The GHG emissions associated with water conveyance for production of hydrogen were not included in the scope of this Study.[6] Transportation of other materials such as biomass to the production site or biomass feed preparation are beyond the scope of this feasibility study.

Projected quantities of displacement of diesel and gasoline by hydrogen fuel cells in the mobility sector; and anticipated replacement of natural gas with hydrogen in the power generation and hard-to-electrify industrial sectors were based on estimated demand values provided by the parallel Demand Study.

The potential climate considerations of hydrogen leakage, the potential for which was evaluated in the parallel Leakage Study Report, for both general hydrogen infrastructure and Angeles Link infrastructure, are also discussed. Specifically, a preliminary high-level estimate of the impacts to predicted overall (end user reductions minus infrastructure emissions) GHG reductions (using GWP 100) was conducted. Additionally, a summary of the range of estimated global warming potentials (GWP) of hydrogen found in the literature is provided for both the 20 and 100 year time horizons, that would be considered for hydrogen as an indirect GHG.[7]

The Demand Study, which was relied upon when estimating initial projected GHG emissions, projected economy wide demand by 2045 in SoCalGas's service territory using three scenarios: low demand, moderate demand, and high demand. These are referred to as conservative, moderate, and ambitious demand, respectively, in the Demand Study (Demand Study Scenarios). In comparison to the Demand Study values noted above, the projected throughput of Angeles Link, which is expected to support a portion of that demand, is estimated to range from approximately 0.5 to 1.5 million metric tonnes per year (MMT/yr.). The three throughput scenarios for the Angeles Link buildout (0.5 MMT/yr, 1.0 MMT/yr., and 1.5 MMT/yr.) align with the low, moderate, and high Demand Scenarios (1.9 MMT/yr., 3.2 MMT/yr., and 5.9 MMT/yr.)

To estimate potential GHG emissions associated with the Project, including those from third-party production and storage and end users, GHG estimates were calculated using initial estimates from the Demand Study. Then the ratio of anticipated hydrogen throughput values for Angeles Link to the projected values in the Demand Study were calculated for each of the conservative (26.85%), moderate (31.12%), and ambitious (25.36%) scenarios. The ratios were applied to the GHG estimated emissions using the Demand Study Scenarios to estimate potential GHG emission reductions associated with Angeles Link Throughput Scenarios. This analysis is shown in Table ES-1 below.

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[6] The GHG emissions associated with water conveyance for production of hydrogen were also outside the scope of the parallel Angeles Link Phase 1 Water Resources Evaluation due to the variety of potential water supply sources and unknown final selection of sources third-party producers may pursue to produce clean renewable hydrogen. In response to stakeholder feedback on potential GHG emissions associated with water supply development, the Water Resources Evaluation added a supplemental desktop analysis of potential GHG emissions associated with water supply treatment and conveyance and that analysis is now included as part of that separate study.
[7] The estimated effect of potential hydrogen leakage as an indirect GHG is discussed in Section 9 of this document.

Table ES-1 Direct GHG Reduction Estimates for Demand Study Scenarios Applied to Projected Angeles Link Throughput Scenarios				
Scenario	**Total Projected Hydrogen Demand (MMT/yr)**	**Overall GHG Reductions for Demand in 2045 (MMT/yr)**	**Angeles Link Projected Hydrogen Throughput (MMT/yr)**	**Overall GHG Reductions for Angeles Link Throughput in 2045 (MMT/yr)**
Low	1.9	16.7	0.5	4.5
Moderate	3.2	24.9	1	7.8
High	5.9	35.7	1.5	9.0

Key Findings: Demand Scenarios

The key findings for GHG emission reductions based on the Demand Study Scenarios are as follows and are discussed further herein.

- Projected up to nearly 17 and 36 million metric tons of CO2e per year removed from SoCalGas geographic service territory by end users by 2045 in low and high demand scenarios of the Demand Study, respectively. ("Low Demand Scenario" and "High Demand Scenario"). The reductions are equivalent to the annual GHG emissions of approximately 45 and 96 natural gas-fired power plants, respectively per EPA Calculator.
  - Mobility sector comprises 72.5% and 50.3% of overall GHG reductions based on the Low and High Demand Scenarios, respectively. The GHG reductions estimated for the Low and High Demand Scenarios in 2045 are equivalent to removing approximately 2.7 million and 4.3 million gasoline passenger vehicles off the roads per year, respectively.
  - Power generation and hard to electrify industrial sectors comprise 41.7% and 8.1% of the overall GHG reductions, respectively, based on the High Demand Scenario.
  - Power generation and hard to electrify industrial sectors comprise 23.6% and 3.9% of overall GHG reductions, respectively, based on the Low Demand Scenario.
  - Infrastructure GHG emissions are projected to be negligible when compared to overall emission reductions, at 0.29% and 0.25% of end-user reductions for Low and High Demand Scenarios, respectively.

Key Findings: Angeles Link Throughput Scenarios

The key findings for GHG emission reductions for Angeles Link Throughput Scenarios, which accounts for emissions from not just transmission of hydrogen, but also from third-party production and storage as well as end users, are as follows and are discussed further herein.

- Projected about 4.5 and 9 MMT of CO2e per year removed from SoCalGas's geographic territory by end users by 2045 in Angeles Link Low and High Throughput Scenarios, respectively.
- Mobility sector comprises 72.5% and 50.3% of overall GHG reductions based on the Angeles Link Low and High Throughput value scenarios, respectively. The GHG reductions estimated for the Low and High Throughput Scenarios in 2045 are equivalent to 725,000 and more than 1 million gasoline passenger vehicles driven for one year, respectively.[8]
- Power generation and hard to electrify industrial sectors comprise 41.7% and 8.1% of overall GHG emission reductions, respectively, based on the High Throughput Scenario.
- Power generation and hard to electrify industrial sectors comprise 23.6% and 3.9% of overall GHG emission reductions, respectively, based on the Low Throughput Scenario.
- Infrastructure GHG emissions are projected to be negligible when compared to overall emission reductions at 0.29% and 0.25% of end-user reductions for Low and High Throughput Scenarios, respectively.

Additional details related to both the Demand Scenarios and Angeles Link Throughput Scenarios are provided below.

2030 High Demand Scenario: In 2030, the High Demand Scenario predicts a reduction of about 6 MMT/yr of CO2e due to hydrogen replacing fossil fuels. This reduction includes the emissions from producing, storing, and transmitting hydrogen. This amount of reduction is comparable to the energy use of about 740,000 homes for one year, according to the EPA's greenhouse gas (GHG) calculator.[9] In terms of specific contributions, Angeles Link is expected to meet about 25% of the projected hydrogen demand identified in the Demand Study. This means that the specific GHG reductions attributed to Angeles Link under the High Throughput Scenario are estimated at about 1.45 million MT CO2e per year, which is equivalent to the energy use of approximately 189,000 homes for one year.

2045 High Demand Scenario: By 2045, the scenario estimates an overall reduction in CO2e emissions of about 36 MMT/yr, again due to the displacement of fossil fuels by hydrogen. These reductions are equivalent to the annual electricity usage of over 4.6 million homes, as per the

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[8] US EPA, 2023c, Greenhouse Gas Equivalencies Calculator, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results

[9] US EPA, 2023c, Greenhouse Gas Equivalencies Calculator, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results

EPA's calculator. Angeles Link is expected to supply the same percentage (about 25%) of the total hydrogen demand in SoCalGas service territory, as projected in the High Demand Scenario. As a result, the GHG emissions reductions specifically associated with Angeles Link in the High Throughput Scenario for 2045 are estimated at about 9.0 million MT CO2e per year. This would correspond to the energy use of roughly 1.1 million homes for one year.

Mobility Sector: In the Mobility sector, the estimated CO2e reductions under the High Demand Scenario are approximately 4.4 million MT in 2030 and about 18 million MT by 2045. The reductions by 2045 are equivalent to the emissions from around 4.3 million gasoline-powered passenger vehicles driven for a year. The sector accounts for between 50% to 83% of total GHG emissions reductions, varying by scenario and year. The largest contributors are heavy-duty vehicles (55.5% in 2030 and 62.8% in 2045), followed by buses (33.6% in 2030 and 22.0% in 2045), and medium-duty vehicles (7.3% in 2030 and 9.7% in 2045). Reductions from on-road vehicles significantly outweigh those from off-road vehicles, mainly due to the higher displacement of fossil fuels. In the High Throughput Scenario, the reductions for 2030 are about 1.1 million MT CO2e per year, increasing to about 4.6 million MT CO2e by 2045. The 2045 reductions would be equivalent to the emissions from 1 million gasoline-powered vehicles driven for a year.

Power Generation Sector: In the Power Generation sector, it's projected that by 2030, there could be a reduction of 0.16 million MT of CO2e under the High Demand Scenario, and by 2045, this could increase to about 15 million MT CO2e. Over 78% of these reductions are expected from the peaker and baseload plant sub-sectors in all years under this scenario with the remaining reductions attributable to the cogeneration sub-sector. By 2045, these reductions are equivalent to the yearly electricity consumption of approximately 1.9 million homes, according to the EPA's calculator. Under the High Throughput Scenario, the reductions are estimated at about 41,000 MT CO2e per year for 2030 and about 3.8 million MT CO2e per year by 2045. The reductions for 2045 under this scenario are comparable to the energy use of around 480,000 homes for one year.

Hard to Electrify Industrial Sectors: In the industrial sectors that are difficult to electrify, the estimated CO2e reductions under the High Demand Scenario are around 1.1 million MT in 2030 and could rise to about 2.9 million MT by 2045. The 2045 reductions would be equal to the annual electricity usage of about 365,000 homes. In this scenario, refineries are the largest contributors, accounting for 65.5% of reductions in 2030, followed by the Food and Beverage sector (13.4%), Stone, Glass, and Cement (12.1%), and Metals (5.3%). These percentages remain consistent from 2030 to 2045. In the High Throughput Scenario, the reductions are estimated at about 290,000 MT CO2e per year for 2030 and about 730,000 MT CO2e per year by 2045. The 2045 reductions equate to the energy use of around 96,000 homes for one year.

Hydrogen Infrastructure Emissions: Emissions associated with new hydrogen infrastructure are evaluated. The results of the conservative estimate prepared represent a small fraction of the emissions reductions achieved by end-users adopting hydrogen in the study region.

Specifically, in the High Demand Scenario:

- By 2030, emissions from the new hydrogen infrastructure are estimated at about 16,600 MT of CO2e per year. This accounts for 0.29% of total CO2e reductions expected from end-users based on hydrogen usage projections.
- By 2045, these emissions increase to about 87,900 MT per year of CO2e, which constitutes 0.25% of the total CO2e reductions from end-users. This accounts for 0.25% of total CO2e reductions expected from end-users based on hydrogen usage projections.

For Angeles Link, under the High Throughput Scenario:

- In 2030, the estimated emissions attributed to the new infrastructure are estimated to be around 4,200 MT of CO2e per year. This accounts for 0.29% of total CO2e reductions expected from end-users based on hydrogen usage projections.
- By 2045, this figure is projected to rise to 22,300 MT of CO2e per year. This accounts for 0.25% of total CO2e reductions expected from end-users based on hydrogen usage projections.

Stakeholder Input

The input and feedback from stakeholders including the Planning Advisory Group (PAG) and Community Based Organization Stakeholder Group (CBOSG) has been helpful to the development of this draft GHG Study Report. For example, in response to stakeholder comments, the Study includes an estimate of the impact to estimated GHG reductions of a preliminary high-level volumetric estimate of the potential for leakage from hydrogen infrastructure from the Draft Leakage Study Report, as well as presenting a summary of the estimated Global Warming Potential (GWP) 100 and GWP 20 for hydrogen available in the literature. In addition, the study includes a review of relevant literature provided by stakeholders, as applicable. The feedback that has been received to-date related to this Study and how those comments are addressed is summarized in more detail in Section 11.

GHG EMISSIONS DRAFT STUDY

About the Research

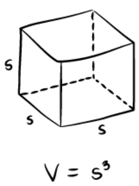
Understanding the Draft Study

Study Purpose

- Estimate GHG combustion emissions associated with Angeles Link infrastructure including third party production and third party storage.
- Assess projected GHG combustion emission reductions from displacing fossil fuels with hydrogen in various end user sectors.

Scope

- Focus on direct combustion GHG emissions from hydrogen infrastructure and reductions from fossil fuel displacement.
- Includes examination of indirect climate impacts for potential hydrogen leakage associated with infrastructure based on a summary of leakage rates provided in the Leakage Study.



Key Assumptions

- Use of renewable electricity for hydrogen production to ensure zero GHG emissions from the energy supply side.
- Anticipation of technological efficiencies and market adoption rates to project climate benefits.

Limitations

- Does not account for water conveyance and biomass transportation impacts and other potential contributors to full lifecycle GHG assessments.
- Acknowledges the draft nature of the study, indicating ongoing refinement of data and conclusions.

Informed by Research

- Literature and Studies: Equity Principles for Hydrogen, AC Transit, 2022. Bertagni et al., 2022, CARB 2022; Ocko, I. and S. Hamburg, 2023; Paulot, F., et al., 2021; Sand, M., et al., 2023, Sun, Tianyi, et al., 2024
- Notable references include detailed discussions on the impact of hydrogen leakage on overall GHG reductions and climate impacts.

Understanding the Impact of Angeles Link

Identifying End-Users Served by Angeles Link

Mobility Sector

- Heavy-Duty Trucks, Medium-Duty Vehicles, Buses, Agriculture, Construction & Mining Equipment, Cargo Handling Equipment, Ground Support Equipment, Commercial Harbor Craft.

Power Generation Sector

- Turbines and Co-generation.

Hard-to-Electrify Industries

- Chemical Manufacturing, Metal Refining and Treatment, Stone/Glass/Cement, Food & Beverage, Paper & Pulp, Aerospace, Refineries.

Overview of Direct GHG Reduction Estimates for Demand Study Scenarios Applied to Projected Angeles Link Throughput Scenarios

- **Demand Scenarios:** Specifies the level of market adoption (Low, Moderate, High) for hydrogen by end users.
- **Total Projected Hydrogen Demand:** This is how much hydrogen is expected to be used in each scenario.
- **Overall GHG Reductions based on Demand Scenarios in 2045:** This shows the estimated GHG reductions associated with Demand Scenarios.
- **Angeles Link Projected Hydrogen:** It reflects the specific contribution of Angeles Link within the larger market context.
- **Overall GHG Reductions based on Throughput Scenarios in 2045:** This represents the total anticipated GHG reduction in 2045, reflecting Angeles Link contribution.

DEMAND SCENARIO	TOTAL PROJECTED HYDROGEN DEMAND (MMT/YR)	OVERALL GHG REDUCTIONS BASED ON DEMAND SCENARIOS IN 2045	ANGELES LINK PROJECTED HYDROGEN (MMT/YR)	OVERALL GHG REDUCTIONS FOR ANGELES LINK THROUGHPUT IN 2045
LOW	1.9 MMT/yr Least amount of hydrogen expected to be used.	16.7 MMT/yr Amount of GHG reduced if less hydrogen is used.	0.5 MMT/yr Amount of hydrogen Angeles Link would transport in this scenario.	4.5 MMT/yr GHG reduction directly from Angeles Link's operations.
MODERATE	3.2 MMT/yr A moderate amount of hydrogen expected to be used.	24.9 MMT/yr Amount of GHG reduced with moderate hydrogen use.	1.0 MMT/yr Hydrogen amount transported by Angeles Link in this scenario.	7.8 MMT/yr GHG reduction from Angeles Link, reflecting its impact.
HIGH	5.9 MMT/yr The highest amount of hydrogen expected to be used.	35.7 MMT/yr Maximum GHG reduction with high hydrogen use.	1.5 MMT/yr Most hydrogen transported by Angeles Link under this scenario.	9.0 MMT/yr Largest GHG reduction by Angeles Link, showing significant impact.

Visualizing the Impact: GHG Reductions Through Angeles Link

Understanding the Impact of Angeles Link on GHG Reduction over time

The visualization underscores a dramatic scale-up in the impact of GHG reductions enabled by Angeles Link, with energy savings equivalent to homes increasing nearly sixfold from 2030 to 2045, highlighting significant long-term environmental benefits.

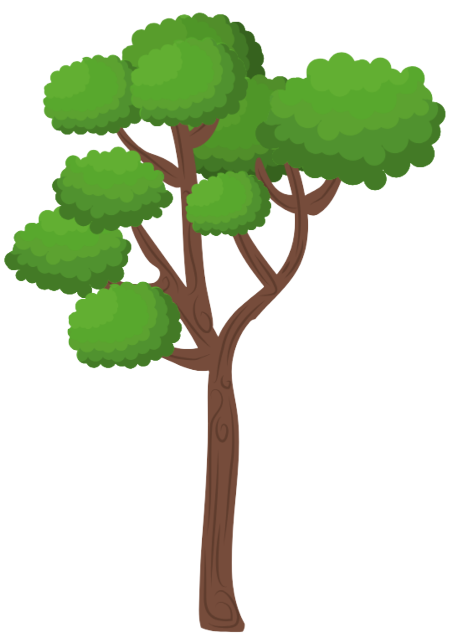
In 2030, Angeles Link would have reduced emissions by 1.4, the equivalent of 180,000 homes

1.4MMT
the equivalent of 180,000 homes

9MMT
the equivalent of 1.1 million homes

Each icon represents the energy usage of 20,000 homes.

GHG Reduction by 2045 for Angeles Link Throughput



4.5 MMT of CO2 Equivalent:

83M

tree seedlings grown for 10 years.

7.8 MMT of CO2 Equivalent:

144M

tree seedlings grown for 10 years.

9 MMT of CO2 Equivalent:

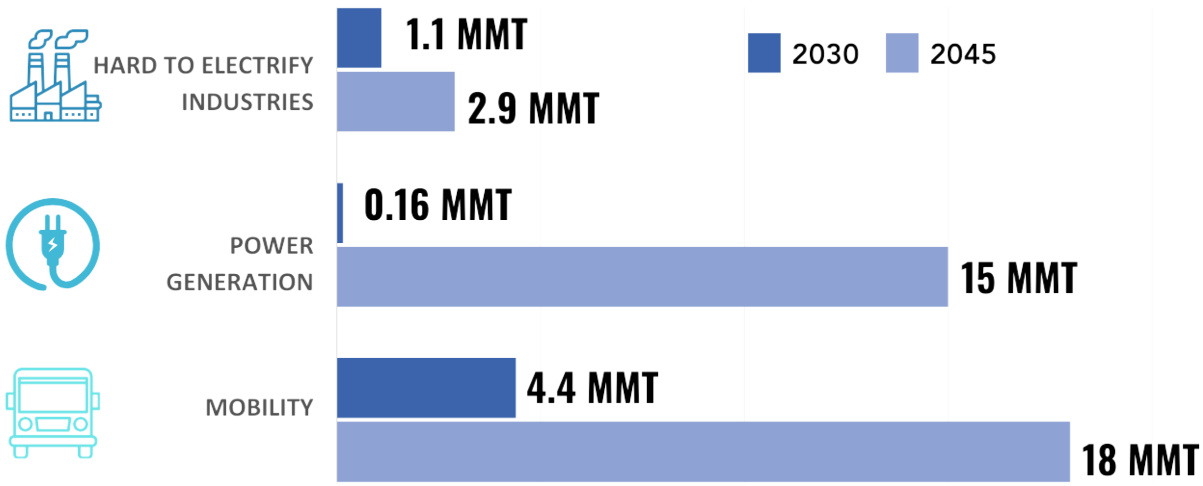
166M

tree seedlings grown for 10 years.

- **Low Throughput:** Angeles Link transports **0.5 MMT/year** of clean hydrogen, helping reduce GHGs by **4.5 MMT/year.**
- **Moderate Throughput**: Angeles Link transports **1.0 MMT/year** of clean hydrogen, reducing GHGs by **7.8 MMT/ year.**
- **High Throughput**: Angeles Link transports **1.5 MMT/year** of clean hydrogen, reducing GHGs by **9.0 MMT/ year.**

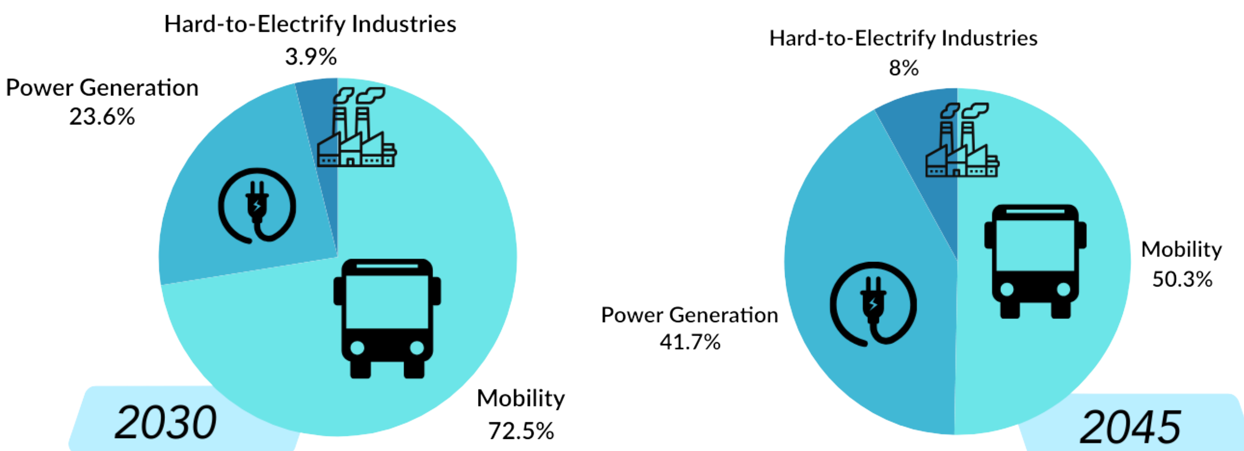
GHG Reductions by End-User Sectors: A Detailed Analysis

CO2e Reductions based on High Demand Scenario: 2030 vs. 2045 (MMT/year)



The Mobility sector's CO2e reduction quadruples by 2045, indicating its significant role in overall emission cuts.

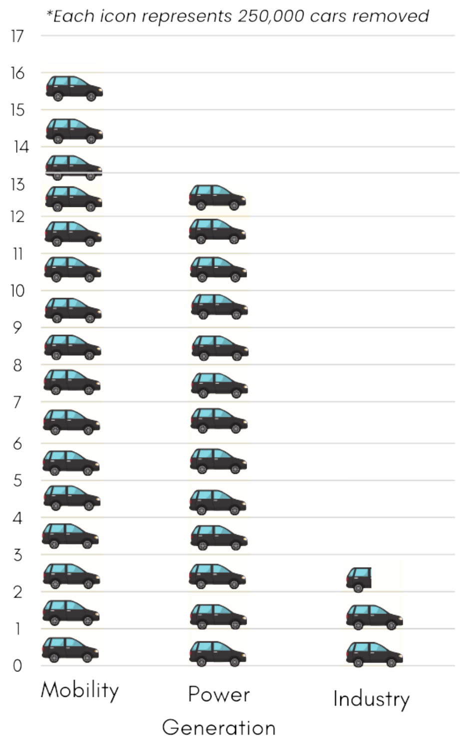
CO2e Reductions for High Angeles Link Throughput Scenario: 2030 vs. 2045



By 2045, the share of GHG reductions from mobility decreases, while power generation's contribution more than doubles, reflecting a strategic diversification in clean hydrogen usage across sectors.

Insights on Sector-Specific Impact based on Demand Scenarios

GHG Emission Reductions Across Sectors on Car Emissions Equivalent, by 2045



The Mobility Sector's reduction impact is roughly six times that of the Industrial Sectors and slightly higher than that of Power Generation, underscoring the critical role of transportation advancements in achieving broader emission reduction targets

18MMT/year

The Mobility Sector GHG reduction is equivalent to removing about **4.2 million cars.**

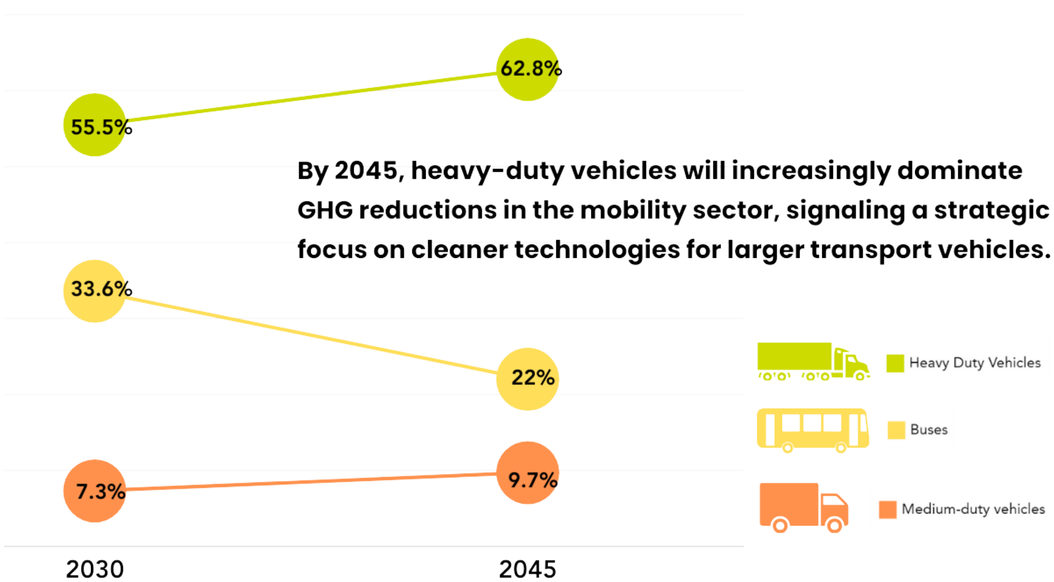
15MMT/year

The Power Generation Sector GHG reduction is equivalent to removing about **3.33 million cars.**

2.9MMT/year

Industrial Sectors GHG reduction are equivalent to removing about **644,000 cars.**

Trends in Mobility Subsector Contributions to GHG Reductions: 2030 vs. 2045

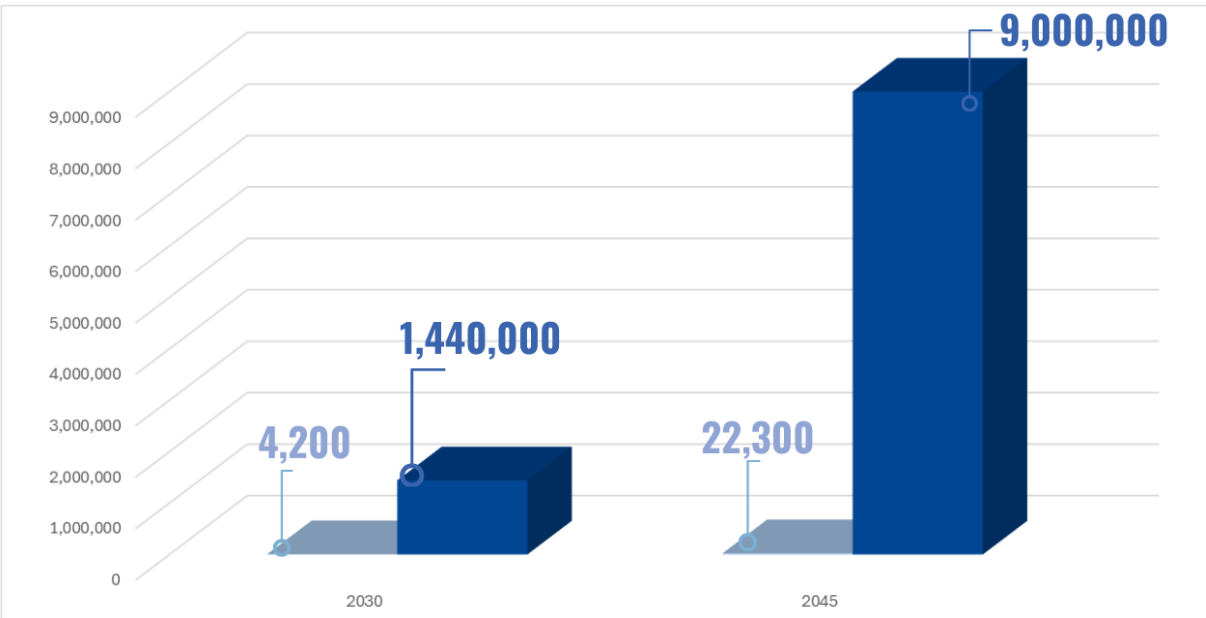


By 2045, heavy-duty vehicles will increasingly dominate GHG reductions in the mobility sector, signaling a strategic focus on cleaner technologies for larger transport vehicles.

Evaluating the Environmental Impact of the Angeles Link

New Hydrogen Infrastructure Emissions vs. End-Users Reductions: Angeles Link's Impact from 2030 to 2045

Estimated GHG Combustion Infrastructure Emissions vs. Expected GHG Combustion Reductions from End Users Served by Angeles Link (2030 & 2045)



Projected GHG Combustion Infrastructure Emissions (MT CO2e/yr)

Expected GHG Combustion End User Reductions (MT CO2e/yr)

Note: *The terms "new infrastructure" and "hydrogen infrastructure" refer to general hydrogen infrastructure comprised of third-party production, third-party storage, and transmission.*

Understanding the Impact of Hydrogen Leakage on Overall GHG reductions

3%

Preliminary High-level Estimate of the Impact of Potential Leakage on Overall GHG reductions estimates is less than 3% for General Hydrogen Infrastructure.

1%

Preliminary High-level Estimate of the Impact of Potential Leakage on Overall GHG reductions estimates is less than 1% for Projected Angeles Link Infrastructure.

2 STUDY APPROACH

The goals of this Study are to estimate GHG combustion emissions associated with the anticipated production, storage, and transmission of hydrogen and estimate GHG combustion emission reductions from end users of hydrogen in the mobility, power generation, and hard to electrify industrial sectors. The parallel Demand Study provided initial details and scenarios that were used to complete these GHG emission estimates. Additional evaluation of GHG emissions for the estimated ranges of Angeles Link throughput of 0.5 to 1.5 MMT per year of hydrogen was also conducted.

The geographic region of this study includes highly populated areas and encompasses a wide range of industrial end-users with the potential to convert to hydrogen as a source of fuel. Among these potential end-users are the San Pedro Ports Complex comprised of the Port of Los Angeles and the Port of Long Beach, the most highly trafficked ports in the United States[10] and Los Angeles International Airport, one of the top five busiest airports in the world.[11] The study covers the time period from construction of Angeles Link through a period of ongoing operations (2030 to 2045).

Where applicable, the Study relies on specific technical information from regulatory agencies, transportation agencies, and equipment manufacturers. Research conducted by entities such as academic institutions was evaluated to determine the best available methods for quantifying emissions of GHG from the combustion of hydrogen. When specific information was not available, estimates were made based on availability of related data, or assumptions were developed.

For this Study, GHG emissions from combustion of fossil fuels (diesel, gasoline, and natural gas) are comprised of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O); and GHG emissions from combustion of hydrogen include no carbon emissions and only trace amounts of N_2O.[12] Hydrogen considerations as an indirect GHG have be discussed in a number of research studies and although a single value or range has not been formally adopted by reporting agencies like the California Air Resources Board (CARB), the Environmental Protection Agency (EPA), or the IPCC, it's an important study consideration. The impact of hydrogen to climate change as discussed in the scientific literature including estimates of effective GWPs for hydrogen are presented in this study report.

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[10] https://www.portoflosangeles.org/business/statistics

[11] https://ktla.com/news/local-news/lax-soars-to-5th-busiest-airport-in-world/

[12] Some studies indicate that there is a possibility for N_2O to form directly from the interaction of N_2 and O_2 (primary components of air) during combustion of any fuel.

Technical Research

The Study collected, reviewed, and analyzed technical research studies and information related to GHG emissions associated with the combustion of hydrogen. This analysis included, but was not limited to:

- Available literature and studies from research-based academic institutions such as the University of California Irvine (UCI) Combustion Laboratory and the Georgia Institute of Technology and private organizations such as the Electric Power Research Institute (EPRI); and technical data or research identified by stakeholders (CBOSG and PAG members) including Environmental Defense Fund (EDF).
- Existing, proposed, and potential future regulatory requirements from federal agencies including the United States Environmental Protection Agency (US EPA), the United States Department of Energy (US DOE), state agencies such as the California Air Resources Board (CARB) and the California Energy Commission (CEC), and local agencies including the nine local air districts located within the geographic scope of this study such as South Coast AQMD and San Joaquin Valley Air Pollution Control District (APCD);
- Technical literature and data releases from government agencies and laboratories including the US DOE and the National Renewable Energy Lab (NREL); and
- Potential GHG minimization opportunities from technological advancements.

3 TECHNICAL APPROACH

The following assessment process (Figure 1) was used for the technical approach of this Study. The approach was based on review of technical research studies, research of anticipated technological advancements, stakeholder input and review of the expected evolution of regulatory frameworks.

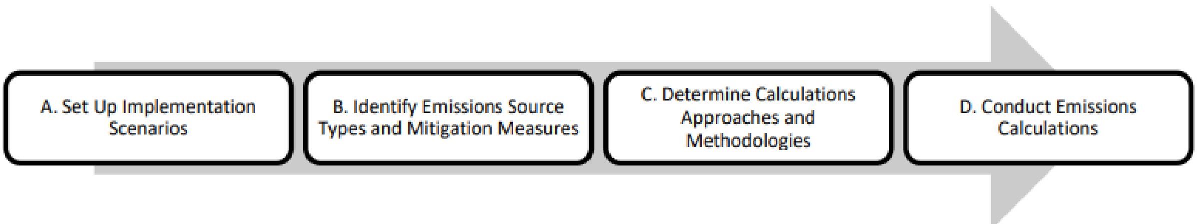

Figure 1. GHG Emissions Assessment Process for GHG Emissions Associated with Angeles Link

3.1 SET UP IMPLEMENTATION SCENARIOS

To evaluate potential GHG emissions and emissions changes associated with Angeles Link, including third party production and storage, as well as end users, the timeframe from 2030 to 2045 was used. Consistent with the findings of the Demand Study, end use sectors are anticipated to achieve the ability to accommodate 100% hydrogen fuel use at different times due to availability of technology and feasibility of transitioning existing equipment and building new infrastructure. The use of clean renewable hydrogen as fuel for each end-use sector was evaluated beginning with 2030 based on data from the Demand Study. GHG emissions were calculated using the approaches described in the next steps for both the three hydrogen Demand Study scenarios – low (1.9 MMT/yr), moderate (3.2 MMT/yr), and high (5.9 MMT/yr), as well as the three hydrogen Angeles Link throughput scenarios – low (0.5 MMT/yr), moderate (1.0 MMT/yr), and high (1.5 MMT/yr).

3.2 IDENTIFY EMISSIONS SOURCE TYPES

The Study evaluated GHG combustion emissions by developing emission calculation approaches and methodologies for the following:

- Infrastructure (Third Party Production, Third Party Storage, and Transmission) and
- End Users (Mobility, Power Generation, and Hard to Electrify Industrial)

Evaluation of GHG emission minimization opportunities was focused on equipment efficiency to minimize fuel use and thereby minimize GHG, as well as equipment design that minimizes formation of N_2O.

The study acknowledges that certain technical literature identified the potential for hydrogen leakage in the production, storage, and transmission of hydrogen. This potential, as well as opportunities to minimize and mitigate the potential for leakage, are discussed in the parallel draft Leakage Study Report.

3.2.1 Hydrogen Production (Third Party)

Three potential clean renewable hydrogen production methods were evaluated as shown below. Each are projected to produce clean renewable hydrogen consistent with the clean renewable hydrogen definition in the CPUC's Phase 1 Decision. Further details regarding production methodologies are available in the parallel Phase 1 Production Study. Appendix B includes a summary of the anticipated carbon intensities of production options as discussed in the literature.

1) Electrolyzers[13] powered by renewable electricity split water molecules into oxygen (O_2) and hydrogen (H_2). This process does not use combustion so there is no potential for GHG emissions from electrolyzers. It was assumed that only renewable electricity would be used and the indirect GHG emissions would be zero.
2) Biomass gasification[14] is a process that involves heat, steam, and oxygen to convert biomass to hydrogen without combustion. Since this process does not use combustion, there is no potential for GHG emissions from biomass gasification. It was assumed that only renewable electricity would be used and the indirect GHG emissions would be zero.
3) Renewable natural gas (RNG) fueled steam methane reformers (SMR). Steam methane reforming is a process in which biogas (RNG) reacts with steam in the presence of a catalyst to produce hydrogen and carbon dioxide. It was assumed that hydrogen would be used as the fuel for any combustion units, such as the heater. This method has direct GHG emissions and those potential emissions were evaluated. It was assumed that only renewable electricity would be used and the indirect GHG emissions would be zero.

The GHG estimates in this Draft GHG Study Report related to anticipated third-party production options are based on combustion of 100% clean renewable hydrogen and use of renewable electricity. GHG emissions associated with water conveyance and transport of feedstock such as biomass was out of scope for this Study. Estimated carbon intensity values for cradle-to-gate summarized from the literature are provided in Appendix B. Please refer to the Water Study and Production Study for additional information regarding the third-party production methodologies.

3.2.2 Hydrogen Storage (Third Party) and Transmission

For the purpose of this Study, hydrogen storage may occur above ground or below ground, and will be delivered to end users via pipelines. Storage and transmission of hydrogen will require the use of compressors. Reciprocating or centrifugal compressors would be fueled by clean renewable hydrogen and would not produce CO_2. However, trace amounts of N_2O could form

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[13] Hydrogen Production: Electrolysis | Department of Energy
[14] Hydrogen Production: Biomass Gasification | Department of Energy

from the nitrogen present in the combustion air at specific temperatures. It was assumed that only renewable electricity would be used and the indirect GHG emissions would be zero. Electric driven compressors would be powered by renewable electricity and both direct and indirect GHG emissions would be zero.

3.2.3 Hydrogen Industrial End Users

Potential GHG emissions reductions from end users in three key sectors were evaluated: Mobility, Power Generation, and Hard to Electrify Industrial sectors. Information obtained from the parallel Demand Study informed the analysis of end uses in each of these three sectors, as well as their respective subsectors and are noted below:

- **Mobility:** sub-sectors include heavy-duty trucks, medium-duty vehicles, buses, agriculture, construction & mining, cargo handling equipment, ground support equipment, and commercial harbor craft.
- **Power Generation:** turbines are the primary source for potential GHG emissions in power generation.
- **Hard to electrify industrial:** subsectors include energy intensive industries such as refining, food and beverage manufacturing, primary and fabricated metals, stone, glass, and cement, paper, chemical manufacturing, and aerospace and defense.

Equipment types with the potential for GHG emissions across the power generation and industrial sectors include hot water boilers, steam generating units, process heaters, furnaces/kilns, internal combustion engines, turbines, and miscellaneous combustion equipment.

3.2.4 Opportunities to Minimize GHG Emissions

Opportunities to minimize GHG emissions are related to production methodologies and equipment used to combust hydrogen such as reciprocating or centrifugal compressors. Advanced production technologies, including electrolysis, biomass gasification and renewable natural gas-fueled steam methane reformers, provide opportunities to minimize GHG compared to traditional hydrogen production methods. Optimization of hydrogen storage and transmission includes implementing high-efficiency compressors powered by renewable electricity or hydrogen and ensuring robust infrastructure design to minimize hydrogen leakage. Various opportunities exist to minimize N_2O emissions, particularly during the design phase of combustion equipment.

3.3 FORMATION OF GHG

Greenhouse gases are a natural part of the Earth's atmosphere that keeps the earth's global mean temperature comfortable for and inhabitable by humans. Without greenhouse gases, the Earth would be significantly colder. While some atmospheric greenhouse gases are critical for the existence of life as we know it, an excess of greenhouse gases in the atmosphere has the potential to increase the greenhouse effect to a point where the increase in global mean temperature may disrupt global ocean currents, global wind patterns, expected climatic variations, and ultimately, the way life functions on Earth. It is important to understand which gases act as greenhouse gases in the atmosphere and what anthropogenic causes contribute to their release.

Human activities are responsible for increases in greenhouse gases in the atmosphere over the last 150 years. Combustion of fossil fuels occurs when the fuel is burned with oxygen, which can lead to the formation of CO_2 and water vapor (H_2O). CO_2 is one of the most prevalent anthropogenic greenhouse gases. Roughly half of Earth's greenhouse effect is attributable to water vapor in the atmosphere.[15] Increasing global mean temperatures increase the heat flux off the ocean and other bodies of water, which increases evaporation. As temperatures increase, the air in the atmosphere can hold more water due to decreased condensation and precipitation. Water vapor is a direct greenhouse gas, which absorbs the radiation from the Earth and reflects it back. Water vapor exacerbates the warming from other greenhouse gases. The primary difference between water vapor and the other GHGs is that it is condensable. The water cycle works to keep molecules of water in the atmosphere for only a small length of time, roughly nine days on average.[16] This is in comparison to carbon dioxide which can stay in the atmosphere for hundreds of years.

The concept of "global warming potential" (GWP) measures a greenhouse gas's (GHG's) ability to trap heat in the atmosphere compared to carbon dioxide (CO_2). Defined by the US Environmental Protection Agency (EPA)[17], GWP quantifies the heat a greenhouse gas can absorb over a specified period, using the impact of one ton of CO_2 as the reference. This metric is developed and regularly updated by experts at organizations like the Intergovernmental Panel on Climate Change (IPCC) based on comprehensive reviews of scientific studies. The updates incorporate the latest data, and the GWP values are assessed over different time spans—20, 100, or 500 years[18]. The IPCC's Fifth Assessment Report (AR5)[19] recognized the 100-year GWP as a standard metric from the United Nations Framework Convention on Climate Change (UNFCCC), which was initially applied in the 1997 Kyoto Protocol. AR5 also noted that GWPs for gases that stay in the atmosphere for

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[15] Buis, A., 2022, Steamy Relationships: How Atmospheric Water Vapor Amplifies Earth's Greenhouse Effect, NASA Climate webpage article, February 8, https://climate.nasa.gov/explore/ask-nasa-climate/3143/steamy-relationships-how-atmospheric-water-vapor-amplifies-earths-greenhouse-effect/

[16] Buis, A. 2022, Steamy Relationships, Ibid

[17] Understanding Global Warming Potentials | US EPA

[18] IPCC, AR5 Synthesis Report: Climate Change 2014, https://www.ipcc.ch/report/ar5/syr/

[19] IPCC, AR5 Synthesis Report: Climate Change 2014, https://www.ipcc.ch/report/ar5/syr/

shorter periods have greater uncertainties compared to those that remain for several decades or centuries. The Sixth Assessment Report (AR6) was selected as the source for GWP values for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as these were the most recently published GWPs.[20] The AR6 GWP values are used in this study since they are the most recent values. Reporting of GHG to CARB and EPA uses the AR4 GWP 100 value that is lower for methane (25 rather than 29.8). The Study anticipates that GWP for hydrogen will be evaluated for reporting purposes in the future and undergo an evolution in values similar to methane.

3.4 GHG EMISSION FACTORS

The Study evaluated direct GHG emissions from combustion of fossil fuels, hydrogen, and natural gas/hydrogen fuel blends.

3.4.1 Combustion of Displaced Fossil Fuels

Direct GHG emissions comprised of CO_2, CH_4, and N_2O were evaluated for combustion of displaced fossil fuels: natural gas, diesel, and gasoline. EPA Title 40 Code of Federal Regulations (CFR) Part 98 "Mandatory Greenhouse Gas Reporting," was selected as the source for fuel based GHG emissions factors for CO_2, CH_4, and N_2O. The GHG emissions factors for CO_2, CH_4, and N_2O associated with diesel, gasoline, and natural gas per EPA 40 CFR Part 98, as well as the GWP 20 and GWP 100 values from IPCC AR6 Table 7.15 of "Climate Change 2021 The Physical Science Basis" Working Group 1 Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,[21] are shown in Table 1 below.[22]

Table 1
Summary of Fossil Fuel GHG Combustion Emission Factors

Pollutant	CO_2 E.F. (kg/MMBtu)	CH_4 E.F. (kg/MMBtu)	N_2O E.F. (kg/MMBtu)
Diesel	73.96	3.0 x 10-3	6.0 x 10-4
Gasoline	70.22	3.0 x 10-3	6.0 x 10-4
Natural Gas	53.06	1.0 x 10-3	1.0 x 10-4
GWP 100	1	29.8	273
GWP 20	1	82.5	273

[20] IPCC, 2021, Climate Change 2021 The physical Science Basis, Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, https://report.ipcc.ch/ar6/wg1/IPCC_AR6_WGI_FullReport.pdf

[21] IPCC, 2021, Climate Change 2021 The physical Science Basis, Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, https://report.ipcc.ch/ar6/wg1/IPCC_AR6_WGI_FullReport.pdf

[22] The AR6 GWP values are used in this study since they are the most recent values. Reporting of GHG to CARB and EPA uses the AR4 GWP 100 value that is lower for methane (25 rather than 27.9).

3.4.2 Combustion of Hydrogen

This Study also explored whether greenhouse gases are produced when hydrogen is combusted. Pure hydrogen fuel does not contain carbon and is therefore considered an option for decarbonizing certain emissions sources and sectors where other low-carbon options might not be technically or economically feasible.[23] Nevertheless, minute amounts of CO_2 might still be detected when measuring emissions, but this CO_2 originates from the combustion air itself, which contains about 0.04% CO_2 by volume.[24] This CO_2 is not produced by the combustion process; instead, it remains unchanged and can exit through the exhaust stack. When combusting hydrogen small amounts of N_2O could potentially form from the interaction of N_2 and O_2 during combustion due to nitrogen and oxygen present in the combustion air. The possibility of forming N_2O is considered minimal and is most likely to occur at low combustion temperatures.[25] When hydrogen is combusted in combination with natural gas, the emissions include CO_2, methane (CH_4) which is unburned fuel from the natural gas component, and N_2O.

CO_2 emissions decrease as the percent of hydrogen in the fuel (on a volume basis) is increased, but they do not decrease linearly. As outlined in a paper published by the US EPA titled, "*Hydrogen in Combustion Turbine Electric Generating Units Technical Support Document*," the difference in volume energy densities between natural gas and hydrogen causes a smaller CO_2 emissions reduction than the percentage of hydrogen in the fuel mixture by volume. However, the study also assessed the extent of N_2O emissions that can be expected from the combustion of hydrogen.

N_2O is a greenhouse gas that can be formed during combustion that has a 100-year GWP of 273 according to the US EPA. N_2O accounts for a very small percentage of GHG combustion emissions from natural gas, gasoline, and diesel fuels, and very small percentage of the resultant CO_2e emissions. N_2O emissions can potentially form from nitrogen in a fuel or nitrogen in combustion air. Given the potential for N_2O formation from combustion air, the potential for N_2O emissions to occur as a result of hydrogen combustion was evaluated as part of this study. Based on research, an extremely conservative emission factor for N_2O of 2 ppmvd was used for this study. Details regarding development of the N_2O emission factor used in this Study report are provided in Appendix A.

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[23] International Energy Agency (IEA), 2019, The Future of Hydrogen - Seizing today's opportunities, report prepared for the G20 by the IEA, June, https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

[24] Wait, the Atmosphere Is Only 0.04% Carbon Dioxide. How Does It Affect Earth's Climate? (scitechdaily.com)

[25] Colorado, A., V. McDonell and S. Samuelsen, 2017, Direct Emissions of Nitrous Oxide from Combustion of Gaseous Fuels, International Journal of Hydrogen Energy 42(1): 711-719, https://doi.org/10.1016/j.ijhydene.2016.09.202

3.5 CALCULATION METHODOLOGY

3.5.1 Infrastructure

GHG combustion emissions associated with hydrogen infrastructure, including third party production and storage were estimated. For hydrogen production, GHG combustion emissions associated with production (i.e., steam-methane reforming) and compression for storage and transmission fueled by hydrogen were estimated. Preliminary assumptions were made to develop GHG combustion emissions estimates. The formula used to calculate these emissions is:

*Fuel Throughput x Emissions Factor * GWP = GHG Emissions (equation 1)*

The first equation (equation 1) multiplies the quantity of clean renewable hydrogen by the N_2O emission factor assumed in this Study for hydrogen. The emissions for N_2O are then multiplied by the GWP as shown in Table 1 to determine GHG emissions in units of CO2e.

This approach applies emission factors for direct GHG components from the combustion process, scaled according to the specific equipment and operations involved in hydrogen infrastructure.

3.5.2 End Users

For end users, based on the emission source type identified, GHG emissions were estimated for combustion of the displaced fossil fuel (diesel, gasoline, natural gas) and for hydrogen combustion, as applicable. Estimating the potential for leakage associated with end users of Angeles Link was not feasible given the limited amount of information available. For example, specific end user equipment and facility data was not available. Calculations to estimate emissions were prepared using the following two equations:

*Fuel Throughput x Emissions Factor * GWP = GHG Emissions (equation 1)*

GHG Emission Reductions = Fossil Fuel GHG Emissions – Hydrogen GHG Emissions (equation 2)

The first equation (equation 1) multiplies the quantity of fuel by the GHG emission factor specific to the fuel for each GHG pollutant. These pollutants are CO_2, CH_4, and N_2O for combustion of fossil fuels and N_2O for combustion of hydrogen. Each GHG has a specific fuel dependent emission factor and a unique GWP as shown in Table 1. The emissions for each of CO_2, CH_4, and N_2O are multiplied by their respective GWP and then summed to obtain the total GHG emissions in units of CO2e.

The second equation (equation 2) calculates the GHG emission reductions in CO2e by subtracting the GHG emissions for hydrogen (either for N_2O from combustion of hydrogen or zero for hydrogen fuel cells) from the GHG emissions for combustion of displaced fossil fuels. The GHG emissions for combustion of hydrogen and for combustion of fossil fuels are both derived from equation 1.

GHG emissions were calculated at the unit level and scaled based on activity data quantified using information from the Demand Study. Calculations were prepared for the low, mid, and high scenarios in the Demand Study for each year from 2030 to 2045. The Study evaluated the potential for GHG emissions based on the type of equipment and specific source categories from the Demand Study. This approach ensures that both the potential for GHG emissions and opportunities for reductions are comprehensively evaluated.

The GHG emissions factors for CO_2, CH_4, and N_2O associated with diesel, gasoline, and natural gas per EPA 40 CFR Part 98, as well as the GWP 20 and GWP 100 values from IPCC AR6, are shown in Table 1. For combustion of clean renewable hydrogen with GHG emissions comprised entirely of N_2O, since the GWP 20 and GWP 100 for N_2O are both 273, the expected impacts in both short term and long term should be similar. Once each calculation estimates for GHG combustion emissions were prepared for new infrastructure and end use sectors, these results were summed to develop an overall estimate using equation 3:

Overall GHG Reductions = End User GHG Reductions - Infrastructure GHG Increases (equation 3)

This structured approach ensures a rigorous and detailed analysis, accommodating the specificities of the GHG emissions associated with different stages of the hydrogen value chain.

3.5.2.1 Mobility Sector

Most on-road and off-road vehicles in the Mobility sector currently use various liquid and gaseous carbon-based fuels driving internal combustion engines. The CARB Emission Factor (EMFAC) model[26] was used to provide activity data and/or emissions factors for on-road and off-road mobile sources. The EMFAC model provides activity data such as vehicle miles traveled, vehicle category population counts, fuel consumption by vehicle category, and emissions data for most mobile vehicle types evaluated in this Study. The model contains sufficient data to estimate CO_2, CH_4, and N_2O emissions for on-road mobile sources, and CO_2 emissions for off-road mobile sources. Since the EMFAC model does not include CH_4 and N_2O emissions data for off-road mobile vehicles, additional research was completed to establish the most representative CH_4 and N_2O emissions factors for off-road mobile sources. The US EPA Emission Factors for Greenhouse Gas Inventories document most recently modified on September 12, 2023, was selected. This Study consolidates these emissions factors from the Annex tables in the US EPA (2022) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020.[27]

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[26] https://ww2.arb.ca.gov/our-work/programs/msei/on-road-emfac

[27] US EPA, 2023b, Inventory of U.S. Greenhouse Gas Emissions and Sinks Ibid

3.5.2.2 Power Generation Sector

The calculation approach for Power Generation to determine the change in emissions after hydrogen adoption consisted of taking the difference in GHG combustion emissions associated with fossil fuels and GHG combustion emissions associated with hydrogen. Stationary source fossil fuel consumption was represented as natural gas for consistency with the Demand Study. The fuel types considered for stationary calculations were pure hydrogen, pure natural gas, and hydrogen-natural gas blends of various percentages.

For the power generation sector, hydrogen usage is expected to begin with hydrogen/natural gas blends and begin to use 100% hydrogen fuel as the technology becomes available. Blended fuels will continue to be used while the in-use units age out. The transition from blended fuels to 100% pure hydrogen fuels was evaluated by the Demand Study in the Power Generation model and was based on technological and economic feasibility and regulatory requirements. These blending assumptions from the Demand Study were utilized within this study.

Mitsubishi, Siemens, and GE are the three largest global turbine manufacturers and have each outlined plans for establishing pure hydrogen firing turbine technology for power generation. Siemens and GE have published goals to develop heavy-duty DLE and DLN turbines with the ability to fire pure hydrogen by 2030, and Mitsubishi set a goal to develop DLN turbines with the ability to combust 100% hydrogen fuel by 2025.[28]

While not specifically included in the blending assumptions, hydrogen fuel cell technology has also been proven useful in the Power Generation sector in such applications as primary power, back-up power, peak-shaving, grid stabilization, and tri-generation (power, heat, and hydrogen).[29]

3.5.2.3 Hard to Electrify Industrial Sectors

The calculation approach for Hard to Electrify Sectors to determine the change in emissions after hydrogen adoption consisted of taking the difference in GHG combustion emissions associated with fossil fuels and GHG combustion emissions associated with hydrogen. Stationary source fossil fuel consumption was represented as natural gas for consistency with the Demand Study. The fuel types considered for stationary calculations were pure hydrogen, pure natural gas, and hydrogen-natural gas blends of various percentages.

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[28] US EPA, 2023b, Hydrogen in Combustion Turbine Electric Generating Units, Technical Support Document, Docket ID No.EPA-HQ-OAR-2023-0072, May 23, https://www.epa.gov/system/files/documents/2023-05/TSD%20-%20Hydrogen%20in%20Combustion%20Turbine%20EGUs.pdf

[29] Air Products, 2024, Hydrogen Fueling for Power Generation, online article, n.d., https://www.airproducts.com/applications/power-generation

The Hard to Electrify Industrial sectors evaluated include energy intensive industries that currently uses mostly gaseous and liquid carbon-based fuels in internal and external combustion equipment. Although Angeles Link will deliver 100% hydrogen, usage in these sectors is anticipated to begin with hydrogen/natural gas blends in 2030 by the end users, behind the meter, and eventually transition to use 100% hydrogen fuel by 2050. Once pure hydrogen fuel combustion technology becomes available, it was assumed that blended fuel equipment would be retired or phased out until 100% of hydrogen demand would be utilized by equipment combusting pure hydrogen fuel in 2050. Equipment-level blended hydrogen combustion as a percentage of overall hydrogen consumption is depicted in Table 2B below.

Babcock and Wilcox offers a commercially available steam boiler that can operate on 100% hydrogen fuel, called BrightGen. This unit has the ability to switch between hydrogen and natural gas combustion as needed.[30] In 2020, AMF Bakery Systems released the Multibake VITA Tunnel Oven by AMF Den Boer which is fueled by pure hydrogen. Hydrogen fueled ovens have the potential to help decarbonize the Food & Beverage Hard-to-Electrify Industrial sub-sector.[31]

The US DOE is continuing to invest significant funding into the research and development of pure hydrogen capable combustion technologies to help decarbonize the Hard-to-Electrify Industrial sector. In January 2024, DOE announced $10.5M of funding into PACCAR Inc., Cummins Inc., and Powertrain for the development of heavy-duty hydrogen engine technology.[32]

Heavy-duty hydrogen turbine, engine, oven, and boiler technology has the strong potential to help decarbonize the Hard-to-Electrify Industrial sector. While not all of these technologies are commercially available yet, manufacturers have stated goals to produce this equipment within the next decade.

This Study does not dictate if end users will blend hydrogen with natural gas and makes assumptions regarding adoption rates based on currently available information regarding equipment and the anticipated evolution of adoption over time. Since only 100% clean renewable hydrogen will be delivered, to estimate GHG reductions at end users, assumptions regarding hydrogen adoption rates were made as shown in Tables 2A and 2B.

The values in Table 2A are based on an assumption of steady incremental increases with a goal of complete transition by 2050. The values in Table 2B were estimated based on manufacturer specification sheets and direct measurement studies. A dataset consisting of 22 data points,

[30] Babcock & Wilcox, 2023, BrightGen™ Hydrogen Combustion Technology: Utilizing non-carbon-based fuels for steam production, Industry Brochure, https://www.babcock.com/assets/PDF-Downloads/PS-599-BrightGen-Hydrogen-Combustion-Brochure.pdf

[31] AMF Bakery Systems, 2020, AMF Bakery Systems Introduces the World's First Emission-Free Hydrogen Tunnel Oven, press release, July 7, https://amfbakery.com/amf-bakery-systems-introduces-the-worlds-first-emission-free-hydrogen-tunnel-oven/

[32] DOE, 2024, Depart of Energy Announces $10.5 Million to Advance Hydrogen Combustion Engine Innovation, press release, January 31., https://www.energy.gov/eere/fuelcells/articles/department-energy-announces-105-million-advance-hydrogen-combustion-engine

across 14 manufacturers, from manufacturers' data and scientific literature were used to estimate equipment-level hydrogen-natural gas blending percentages by taking a direct average. The estimated emissions are based on these assumptions.

Table 2A
Equipment-level Hydrogen-Natural Gas Blending Percentages

Source	Percent of Total H2 Demand as Pure Hydrogen					
	2025	2030	2035	2040	2045	2050
Engine	0	20	40	60	80	100
Turbine	0	20	40	60	80	100
External Combustion	0	20	40	60	80	100
Oven	0	20	40	60	80	100

Table 2B
Equipment Level Hydrogen Natural Gas Blending Ratios for Industrial End-users

Source	H2 to Natural Gas Ratio
Engine	25%
Turbine	57%
External Combustion	22%
Oven	22%

3.5.3 Conduct Emissions Calculations

The Study prepared emission calculations using the emission factors and activity data compiled for each of the topic areas.

- The tool was designed to conduct calculations at the unit level (per unit equipment count, unit distance, unit throughput, or other unit parameters, as applicable).
- The emissions calculation tool was scaled from unit level information to estimate impacts across the geographic region.
- Emission calculations utilized information from evaluated research, the Demand Study, the Leakage Study, and other Phase 1 feasibility studies.

Emissions minimization opportunities can be implemented to reduce GHG (i.e., N_2O) emissions including equipment design opportunities, pre-mixing of air and fuel, management of air to fuel ratio to control combustion temperature, and emerging aftertreatment technologies. N_2O control equipment options also include existing technologies such as SCR and SNCR. Detailed information is available in the excel spreadsheets found in Appendix C.

4 BACKGROUND INFORMATION

4.1 PROPERTIES OF HYDROGEN

To effectively quantify greenhouse gas emissions from hydrogen combustion, one must fully grasp its unique combustive properties and the implications for GHG formation. Hydrogen has unique combustive properties that have the potential to eliminate the formation of GHG when combusted. Hydrogen offers a high energy content per mass and stands as a promising zero-carbon fuel, crucial in a carbon-reduced economy. Its broad flammability range allows operation across diverse air-to-fuel ratios from 34:1 to 180:1.[33] However, hydrogen's low ignition energy and high autoignition temperature may heighten the risk of flashback.[34] [35] Furthermore, hydrogen's high diffusivity helps in achieving even air-to-fuel mixtures, somewhat mitigating leakage-related safety concerns. Nevertheless, its low density means that a significantly greater volume is required to produce the same energy output as conventional fuels like natural gas.

4.2 REGULATORY INFORMATION

In the evolving landscape of energy regulation, both federal and state initiatives play a crucial role in shaping the future of Angeles Link and further deployment of hydrogen as a sustainable fuel. These policies, aimed at aligning energy production with environmental goals, are instrumental in reducing greenhouse gas emissions. The following discussion offers an in-depth examination of these legislative and regulatory measures.

Federal Legislation and Initiatives

- **Energy Policy Act of 2005[36]:** This Act supported diverse energy initiatives with provisions that specifically encouraged the development and use of hydrogen technology. It aimed to reduce dependency on fossil fuels and stimulate the commercialization of new energy technologies.
- **Energy Independence and Security Act of 2007[37]:** This legislation expanded the support for renewable fuels, including hydrogen, and required the periodic reevaluation of fuel economy

[33] College of the Desert, 2001, Module 3: Hydrogen Use in Internal Combustion Engines, Hydrogen Fuel Cell Engines and Related Technologies Rev 0., December, https://www.energy.gov/sites/default/files/2014/03/f11/fcm03r0.pdf

[34] lim, B.K., H. Darmeveil, G.H.J. van Dijk, D. Last, G.T. Pieters, M.H. Rotink, J.J. Overdiep, 2006, Should we add hydrogen to the natural gas grid to reduce CO2 emissions? (Consequences for gas utilization equipment), publication of the 23rd World Gas Conference, Amsterdam, http://members.igu.org/html/wgc2006/pdf/paper/add11558.pdf

[35] Slim, B.K., H. Darmeveil, G.H.J. van Dijk, D. Last, G.T. Pieters, M.H. Rotink, J.J. Overdiep, 2006, Should we add hydrogen to the natural gas grid to reduce CO2 emissions? (Consequences for gas utilization equipment), publication of the 23rd World Gas Conference, Amsterdam, http://members.igu.org/html/wgc2006/pdf/paper/add11558.pdf

[36] US Congress, 2005, Energy Policy Act of 2005, Public Law 109-58, August 8, https://www.congress.gov/109/plaws/publ58/PLAW-109publ58.pdf

[37] US Congress, 2007 Energy Independence and Security Act of 2007, Public Law 110-140, December 19, https://www.congress.gov/110/plaws/publ140/PLAW-110publ140.pdf

standards, which are crucial for reducing the consumption of petroleum-based fuels and encouraging the use of cleaner alternatives.

- **Infrastructure Investment and Jobs Act of 2021[38]:** This Act included funding for the development of clean hydrogen hubs, which are intended to accelerate the deployment of hydrogen as a mainstream energy source and demonstrate its viability across different sectors.
- **Inflation Reduction Act (IRA) of 2022[39]**: The IRA passed in August 2022 provides a ten-year Production Tax Credit for clean hydrogen produced after December 31, 2022. The IRA defines tax credit tiers for "qualified clean hydrogen" with a well-to-gate GHG emission rate of less than 4.0 kilograms CO_2e per kilogram hydrogen.

Regulatory Developments

- **The U.S. Department of Energy:** Established the Clean Hydrogen Production Standard, targeting lifecycle greenhouse gas (GHG) emissions of ≤ 4.0 kg CO_2 equivalent per kilogram of hydrogen produced. This standard aims to ensure that hydrogen production is aligned with environmental goals.[40]
- **The Department of Treasury**: Drafted requirements for how to calculate carbon intensity, and to determine eligibility for the new tax credits under Section 45V, which will impact financial incentives for cleaner hydrogen production.[41]
- **The U.S. Environmental Protection Agency:** Is updating regulations under the Clean Air Act[42] to promote the adoption of low-GHG hydrogen, ensuring that the integration of hydrogen technologies does not adversely affect air quality.

California State Legislation and Policies:

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[38] State of California, 2022a, SB1020 Clean Energy, Jobs, and Affordability Act of 2022, September 19, https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220SB1020

[39] US Congress, 2022, Inflation Reduction Act, Public Law 117-169, August 16, https://www.congress.gov/117/plaws/publ169/PLAW-117publ169.pdf

[40] Canary Media, "Biden admin's long-awaited hydrogen rules are here — and on the right track" Biden admin's long-awaited hydrogen rules are here —... | Canary Media

[41] US DOE, 2023a, U.S. Department of Energy Clean Hydrogen Production Standard (CHPS) Guidance, June, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/clean-hydrogen-production-standard-guidance.pdf

[42] US DOE, 2023a, U.S. Department of Energy Clean Hydrogen Production Standard (CHPS) Guidance, June, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/clean-hydrogen-production-standard-guidance.pdf

- **Global Warming Solutions Act of 2006 (AB 32)**[43]: Set ambitious targets for GHG reductions, mandating that California's GHG emissions return to 1990 levels by 2020. This act positions the state as a leader in climate action, directly influencing the adoption of cleaner technologies including hydrogen.
- **Senate Bill 32 (SB 32)**[44]: Extends the goals of AB 32 by targeting a 40% reduction in GHG emissions from 1990 levels by 2030, further pushing the need for innovative energy solutions like hydrogen.
- T**he Clean Energy and Pollution Reduction Act of 2015 (SB 350)**[45]: This Act significantly advances California's energy policy by setting ambitious targets for renewable energy adoption and energy efficiency, aiming to increase the procurement of renewable energy sources to 50% by 2030 and doubling energy efficiency savings in electricity and natural gas end uses.
- **The 100 Percent Clean Energy Act of 2018 (SB 100)[46]:** This legislation establishes a policy that 100 percent of the state's electricity should come from clean energy sources by 2045 and increased the renewable portfolio standard, indicating that 60% of electricity must be generated from eligible renewable resources by 2030, which directly impacts the hydrogen sector as part of the broader clean energy strategy.
- **Assembly Bill 197 (AB 197)**[47]: Focuses on direct emission reductions and requires public transparency in emission data, which supports informed decision-making and accountability in emission management.
- **California Climate Crisis Act of 2022 (AB 1279)**[48]: Sets a long-term goal for achieving carbon neutrality by 2045, underscoring the state's commitment to drastic reductions in GHG emissions through policies including the support for renewable energy sources like hydrogen.
- **2021 Senate Bill 643:** Requires the CEC, CARB, and CPUC to assess the hydrogen infrastructure and fuel production required for the transition to zero emission vehicles.[49] Some manufacturers are developing prototype equipment and are hoping that their

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[43] CARB, 2018, AB32 Global Warming Solutions Act of 2006 Fact Sheet, September 28, https://ww2.arb.ca.gov/resources/fact-sheets/ab-32-global-warming-solutions-act-2006

[44] State of California Legislative Information, 2016, SB32 California Global Warming Solutions Act of 2006: emissions limit, filed September 8, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB32

[45] State of California Legislative Information, 2015, SB350 Clean Energy and Pollution Reduction Act of 2015, filed October 7, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB350

[46] California Energy Commission, 2023, SB100 Joint Agency Report, agency website, https://www.energy.ca.gov/sb100

[47] State of California Legislative Information, 2016, AB197 State Air Resources Board: greenhouse gases: regulations, filed September 8, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160AB197

[48] State of California Legislative Information, 2022, AB1279 The California Climate Crisis Act, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220AB1279

[49] State of California Legislative Information, 2021, SB643 Fuel cell electric vehicle fueling infrastructure and fuel production: statewide assessment, October 7, https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220SB643

equipment can ultimately qualify as a "Zero Emission Vehicle" under CARB's Advanced Vehicle regulations. However, at this time, the only vehicle types that qualify as ZEVs are electric vehicles and hydrogen fuel cell vehicles.

- **Zero Emissions for California Ports (ZECAP):** A program funded by CARB with GTI Energy to develop and demonstrate zero-emission hydrogen fueled yard trucks at the Port of Los Angeles (POLA). Capacity Trucks built two hydrogen-fueled yard trucks, powered by Ballard fuel cell engines, that were then tested at the TraPac Terminal at the POLA for one year. They found that these hydrogen-fueled yard trucks operated successfully and with 2.5 to 3 times the efficiency of conventional diesel powertrains. [50] [51]

- **Clean Air Action Plan (CAAP)** for the Port of Los Angeles and the Port of Long Beach sets targets for 100% ZEVs for cargo handling equipment by 2030.[52]
- **Commercial Harbor Crafts:** For new or replacement short-run ferries or excursion vessels, after January 1, 2023, the Commercial Harbor Craft Regulation requires that they meet Zero Emissions Advanced Technology (ZEAT).[53]
- **Cargo Handling Equipment:** The San Pedro Bay Ports Complex issued an initial Clean Air Action Plan (CAAP) in 2017 outlining their goal of achieving 100% ZEVs for cargo handling equipment by 2030, earlier than California's goal of zero emissions from mobile sources by 2035 established in EO N-79-20.[54] CARB has proposed to begin the transition to ZEVs for cargo handling equipment in 2026.[55] The CAAP requires that a feasibility assessment for zero-emission and near zero-emission cargo-handling equipment be completed every three years. In 2020, Hyster-Yale Group entered into a partnership with Capacity Trucks to develop

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[50] CARB, 2023, LCTI: Zero Emissions for California Ports (ZECAP), CARB website, https://ww2.arb.ca.gov/lcti-zero-emissions-california-ports-zecap

[51] Sowa, B., 2023, Zero and Near Zero Emission Freight Facilities Project: Zero Emissions for California Ports (ZECAP), GTI Energy, October, https://www.gti.energy/wp-content/uploads/2023/10/ZECAP-Final-Report-GTI-Energy-Rev2.pdf

[52] San Pedro Bay Ports Clean Air Action Plan, 2023, 2017 Clean Air Action Plan, https://cleanairactionplan.org/

[53] State of California, 2022b, Final Regulation Order Commercial Harbor Craft Regulation, Final Regulation Order: amending Code of Regulations, title 13, section 2299.5 and title 17, section 93118.5, Filed December 30, https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2021/chc2021/chcfro.pdf

[54] San Pedro Bay Ports Clean Air Action Plan, 2023, 2017 Clean Air Action Plan, https://cleanairactionplan.org/

[55] CARB, 2022, 2022 State Strategy for the State Implementation Plan, Adopted September 22, https://ww2.arb.ca.gov/sites/default/files/2022-08/2022_State_SIP_Strategy.pdf

hydrogen yard trucks.[56] Conductix Wampfler is in the concept design stage for a hydrogen fuel cell-powered RTG crane.[57]

- A proposal has been published to implement a **Zero Emission Forklift** rule in California as part of CARB's Mobile Source Strategy, State Implementation Plan, and Sustainable Freight Action Plan.[58]
- **Funding Agricultural Replacement Measures for Emission Reductions (FARMER):** This program has been implemented using funds from the cap-and-trade program to invest in research and development into zero emissions agricultural vehicles.[59]
- **Advanced Clean Cars II Regulation[60]**: This regulation requires an increasing number of zero-emission vehicles, including battery electric, hydrogen fuel cell electric and plug-in hybrid electric vehicles, to meet air quality and climate change emissions standards and requires all new passenger vehicles sold in California to be zero emissions by 2035.
- **AB 8:** This legislation required 20 percent of CEC's Clean Transportation Program funding be dedicated to hydrogen refueling stations until there are 100 open retail stations. It also required the CEC and CARB to jointly review and report on progress toward establishing a hydrogen fueling network that provides the coverage and capacity to fuel vehicles requiring hydrogen fuel.[61]
- **Executive Order B-48-18[62]**: This EO ordered state entities to work with the private sector and all appropriate levels of government to spur construction and installation of 200 hydrogen fueling stations and 250,000 ZEV chargers, including 10,000 DC fast chargers, by 2025.

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[56] Hyster, 2020, Hyster-Yale Group and Capacity Trucks Enter Partnership to Jointly Develop Electric, Hydrogen, and Automation-Ready Terminal Tractors, Press Release, December 14, https://www.hyster.com/en-us/north-america/why-hyster/press-releases/2020/hyster-yale-group-and-capacity-trucks-enter-partnership-to-jointly-develop-electric-hydrogen-and-automation-ready-terminal-tractors/

[57] Tetra Tech/Gladstein, Neandross & Associates, 2022, 2021 Update Feasibility Assessment for Cargo-Handling Equipment, report for San Pedro Bay Ports Clean Air Action Plan, https://cleanairactionplan.org/strategies/cargo-handling-equipment/

[58] CARB, Zero-Emission Forklifts, 2024b, https://ww2.arb.ca.gov/our-work/programs/zero-emission-forklifts/about

[59] CARB, 2023, FARMER Program, CARB webpage, https://ww2.arb.ca.gov/our-work/programs/farmer-program

[60] CARB, 2022, Advanced Clean Cars II, https://ww2.arb.ca.gov/our-work/programs/advanced-clean-cars-program/advanced-clean-cars-ii

[61] CEC & CARB, December 2023, Joint Agency Staff Report on Assembly Bill 8: 2023 Annual Assessment of the Hydrogen Refueling Network in California, https://www.energy.ca.gov/sites/default/files/2023-12/CEC-600-2023-069.pdf

[62] Governor Brown's Executive Order to spur investments in ZEV infrastructure, https://archive.gov.ca.gov/archive/gov39/2018/01/26/governor-brown-takes-action-to-increase-zero-emission-vehicles-fund-new-climate-investments/index.html#:~:text=IT%20IS%20FURTHER%20ORDERED%20that,current%20fast%20chargers%2C%20by%202025

- **AB 1493[63], SB X1-2[64], and SB 535**[65]: These legislative measures address climate change by setting standards for vehicle GHG emissions, ensuring benefits from climate investments reach disadvantaged communities, and supporting the transition to a sustainable energy economy.
- **CARB 2022 Scoping Plan[66]:** This comprehensive strategy details actions for increasing the adoption of zero-emission vehicles, expanding renewable energy use, enhancing the cap-and-trade program to incentivize emission reductions, and developing carbon capture and storage technologies. It emphasizes fairness in the distribution of environmental benefits and burdens, particularly in pollution-impacted communities.
- **Advanced Clean Trucks and Advanced Clean Fleet regulation[67] [68]:** These regulations aim to accelerate the transition of medium- and heavy-duty vehicles to zero-emission vehicles, including hydrogen-fueled options, in both public and private transport sectors.
- **Clean Miles Standard[69] and Innovative Clean Transit rule[70]**: These initiatives specifically promote zero-emission standards in public and commercial transportation, enhancing the role of hydrogen and other clean energy sources in reducing emissions from the transport sector.
- **Sector-Specific Regulations**: Include regulations like the Zero Emission Airport Shuttle Rule[71] and a proposal has been published to implement a Zero Emission Forklift rule in California.[72]

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[63] State of California Legislative Information, 2022, AB1493 Vehicular emissions: greenhouse gases, July 22, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=200120020AB1493

[64] California Energy Commission, Senate Bill X1-2 Implementation, https://www.energy.ca.gov/proceeding/senate-bill-x1-2-implementation#:~:text=These%20regulations%20took%20effect%20February,took%20effect%20May%2020%2C%202024.

[65] State of California Legislative Information, 2012, California Global Warming Solutions Act of 2006: Greenhouse Gas Reduction Fund, September 30, http://www.leginfo.ca.gov/pub/11-12/bill/sen/sb_0501-0550/sb_535_bill_20120930_chaptered.html

[66] CARB, 2022, 2022 Scoping Plan: A pathway to carbon neutrality. 2022 Scoping Plan Documents | California Air Resources Board

[67] CARB, 2021, Advanced Clean Trucks Regulation, filed March 15, https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks

[68] CARB, Innovative Clean Transit Regulation, https://ww2.arb.ca.gov/our-work/programs/innovative-clean-transit/about

[69] CARB, 2023, Clean Miles Standard, https://ww2.arb.ca.gov/our-work/programs/clean-miles-standard

[70] CARB, Innovative Clean Transit Regulation, https://ww2.arb.ca.gov/our-work/programs/innovative-clean-transit/about

[71] CARB, 2019, Zero-Emission Airport Shuttle Regulation Factsheet, October, https://ww2.arb.ca.gov/sites/default/files/2019-10/asb_reg_factsheet.pdf

[72] US DOE, 2018, Fact of the Month November 2018: There Are Now More Than 20,000 Hydrogen Fuel Cell Forklifts in Use Across the United States, https://www.energy.gov/eere/fuelcells/fact-month-november-2018-there-are-now-more-20000-hydrogen-fuel-cell-forklifts-use

- **Additional Legislative Efforts Focusing on Hydrogen**: Bills such as SB 1075[73], which mandates a thorough evaluation of hydrogen's role in California's energy landscape, and SB 414[74], which requires an assessment of hydrogen applications, are crucial for framing the state's hydrogen strategy. SB 746, which proposes to include hydrogen as an alternate energy source in energy conservation contracts, is also significant[75].

These actions have established California as a leader in promoting renewable fuels and zero-emission technologies, significantly influencing policies across various sectors including transportation and energy.

Feedback from stakeholders such as the Los Angeles Department of Water and Power (LADWP) and the South Coast Air Quality Management District (South Coast AQMD) has emphasized the technological and regulatory challenges in adopting hydrogen. These concerns highlight the need for ongoing adjustments to regulatory approaches to accommodate technological advancements and ensure effective emission reductions.

4.3 TECHNOLOGY DEVELOPMENTS

Manufacturers are advancing technology to enable combustion engines to function entirely on hydrogen, targeting applications in power generation, industrial heating, and transportation. Currently, smaller turbines such as Siemens' SGT-A35, with a capacity of 30-40 MW, and the SGT-400, rated at 10-15 MW, already operate on 100% hydrogen.[76] However, larger turbine models still require technological enhancements to sustain full hydrogen operation and maintain low air pollution levels. The leading manufacturers in this sector are Siemens, General Electric (GE), Solar, and Mitsubishi.

Both Siemens and GE are working towards developing large, advanced turbines that can achieve 100% hydrogen combustion by 2030. In 2022, the US DOE provided financial assistance to manufacturers to develop hydrogen turbine combustion technology through the Industry Advanced Turbine Awards. The manufacturers who received these awards included GE for their

[73] State of California Legislative Information, 2022, SB1075 Hydrogen: green hydrogen: emissions of greenhouse gases, September 16, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220SB1075
[74] State of California Legislative Information, 2023, SB 414 Climate Change: applications using hydrogen: assessment, May 18, https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202320240SB414
[75] State of California, 2023, SB746 Energy conservation contracts: alternate energy equipment: green hydrogen: Tri-Valley-San Joaquin Valley Regional Rail Authority, October 7, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202320240SB746
[76] US EPA, 2023a, *Hydrogen in Combustion Turbine Electric Generating Units* Ibid

H_2 F-Class retrofits, Solar Turbines for their GT Comb System for hydrogen and natural gas blends, and GE Research for their GT-Scale RDC Demo at 7FA cycle condition.[77]

Mitsubishi aims to reach this capability by 2025 and has already made significant progress; in 2018, their proprietary burner technology in Mitsubishi Hitachi Power Systems achieved a 10% reduction in CO_2 emissions with a 30% hydrogen blend.[78,79]

GE categorizes its turbines into four groups based on their hydrogen handling capacity: Aeroderivative, B/E-Class, F-Class, and HA-Class. Per GE Vernova, gas turbines are inherently fuel flexible and can be configured to use clean renewable hydrogen as new units or units upgraded after service using natural gas. Aeroderivative, B/E-Class and F-Class can currently handle up to 100% hydrogen and the HA-Class can currently handle 50% and is expected to be able to handle 100% hydrogen in the future.[80]

Siemens has also demonstrated the adaptability of their turbines to hydrogen: the Aeroderivative SGT-A35 turbines can operate on 100% hydrogen using special burners.[81] More recently, in 2023, Siemens announced that their SGT-400 unit, with a 10-15 MW capacity, successfully ran on 100% hydrogen.[82] Siemens' HL-class turbines are engineered to manage up to 50% hydrogen combustion.[83] Finally, Siemens has announced the "Zero Emission Hydrogen Turbine Center" which is a demonstration plant in Sweden to showcase a flexible and sustainable energy system connecting gas turbines with hydrogen, renewable electricity, and energy storage.[84]

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[77] US DOE, 2023b, Addressing NO_x Emissions from Gas Turbines Fueled with Hydrogen, H2IQ Hour Webinar, September, www.energy.gov/eere/fuelcells/h2iq-hour-addressing-NO_x-emissions-gas-turbines-fueled-hydrogen

[78] US EPA, 2023a, Hydrogen in Combustion Turbine Electric Generating Units Ibid

[79] Mitsubishi Power, 2018, MHPS Successfully Tests Large-scale High-efficiency Gas Turbine Fueled by 30% Hydrogen Mix -- Will Contribute to Reducing CO2 Emissions during Power Generation, industry news release, January 19, https://power.mhi.com/news/20180119.html

[80] General Electric Vernova, Hydrogen-Fueled Gas Turbines | GE Vernova

[81] Siemens Energy, 2023a, SGT-A35 gas turbine, industry webpage, https://www.siemens-energy.com/global/en/home/products-services/product/sgt-a30-a35-rb.html#tabs-59fe95a20e-item-7c5b13e0e1-tab

[82] Hydrogeninsight, 2023, Siemens Energy burns 100% hydrogen in industrial gas turbine in energy-storage pilot, online energy transition publication, October 16, https://www.hydrogeninsight.com/power/correction-siemens-energy-burns-100-hydrogen-in-industrial-gas-turbine-in-energy-storage-pilot/2-1-1535850

[83] Siemens Energy, 2023b, SGT5-9000HL gas turbine, industry webpage, https://www.siemens-energy.com/global/en/offerings/power-generation/gas-turbines/sgt5-9000hl.html

[84] Siemens Energy, 2024, Zero Emission Hydrogen Turbine Center, https://www.siemens-energy.com/global/en/home/products-services/solutions-usecase/hydrogen/zehtc.html

5 ASSUMPTIONS AND RESULTS BASED ON DEMAND STUDY

This section summarizes draft GHG emissions calculations based on the Demand Study, aiming to project annual GHG emissions reductions for each year from 2030 to 2045. These results are grouped by infrastructure and by end-user sectors. Detailed emission calculations are provided in the Appendix to this draft report. The analysis considers the following categories for projected GHG emissions:

- Infrastructure: This includes the production, storage, and transmission of hydrogen to end-users.
- End-Users: Covers mobility, power generation, and hard-to-electrify industrial sectors that are projected to utilize hydrogen.

Methodology: The methodology aggregates draft emissions reductions totals for each end-user subsector to derive totals for each sector. These sectoral totals are then summed with the anticipated GHG emissions from the new infrastructure to estimate overall annual GHG emissions reductions for the target years.

5.1 INFRASTRUCTURE

The draft results for potential GHG emission increases from new hydrogen infrastructure based on the Low and High Demand Scenarios data for 2045 are up to 0.16% and 0.24% the magnitude of end-user reductions for Low and High Demand Scenarios, respectively.

5.1.1 Hydrogen Production (Third Party)

Three equipment options were evaluated for hydrogen production to meet the definition of clean renewable hydrogen.

1. Electrolyzers powered by renewable electricity: zero GHG emissions.
2. Biomass gasification: zero GHG emissions.
3. RNG SMR (Renewable Natural Gas Steam Methane Reforming): Could include some GHG emissions in the form of trace amounts of N_2O.

Multiple scenarios were evaluated with varying contributions to total production by each of the three types of equipment listed above to estimate the range of potential GHG emissions. The estimated emissions range from zero GHG associated with the 100% electrolysis and the 100% biomass gasification scenarios to the potential for some GHG emissions for the 100% RNG SMR scenario as detailed below. These estimates are draft and can be refined as more detailed project information from third-party producers becomes available, particularly regarding production processes and the proportions of hydrogen produced from different methods. Estimated GHG emission results are provided for the Low and High Demand Scenarios in Table 3.

Table 3 presents the projected GHG emissions from hydrogen production technologies based on the Low and High Demand Scenarios. This table categorizes emissions into minimum and maximum estimates in five year increments from 2030 to the year 2045. For the Low Demand Scenario, the estimates range from 1,120 MT CO2e in 2030 to 16,245 MT CO2e in 2045, based on 100% use of Steam Methane Reforming (SMR) with Renewable Natural Gas (RNG). For the High Demand Scenario, the estimates range from 9,448 MT CO2e in 2030 to 50,080 MT CO2e by 2045 under the 100% RNG SMR scenario. In contrast, the low estimates demonstrate zero emissions across all years, reflecting scenarios where 100% of hydrogen production is achieved through electrolysis or biomass gasification—both processes that emit zero GHGs.

Table 3
Potential Direct GHG Emissions from Hydrogen Production Based on Demand Scenarios

Demand Scenario	Emissions (MT CO2e/yr)				Production Scenario
	2030	2035	2040	2045	
Low Max	1,120	4,448	9,552	16,245	100% SMR (Max Case)
Low Min	0	0	0	0	100% Electrolysis or Biomass Gasification
High Max	9,448	19,565	33,369	50,080	100% SMR (Max Case)
High Min	0	0	0	0	100% Electrolysis or Biomass Gasification

5.1.2 Storage (Third Party) and Transmission

For the storage and transmission of hydrogen, the following three types of compressors were evaluated. Further details regarding compressors being considered are available in the parallel Phase 1 Pipeline Sizing and Routing Study.

1. Electric Motor-Driven Compressors: These utilize electricity from renewable sources, resulting in zero GHG emissions.
2. Hydrogen-Fueled Reciprocating Engine Driven Compressors: Emits no CO_2. However, trace amounts of N_2O could form from the nitrogen present in the combustion air at specific temperatures.
3. Hydrogen-Fueled Turbine Driven Compressors: Similar to reciprocating engines, these compressors could also emit trace amounts of N_2O.

Emissions of GHG (as N_2O) from hydrogen fueled reciprocating engine driven compressors and from turbine driven compressors were conservatively estimated using equation 1:

*Fuel Throughput x Emissions Factor * GWP = GHG Emissions (equation 1)*

The first equation (equation 1) multiplies the quantity of clean renewable hydrogen by the N_2O emission factor assumed in this Study for hydrogen. The emissions for N_2O are then multiplied by the GWP as shown in Table 1 to determine GHG emissions in units of CO2e.

This evaluation assumed that storage requirements would be similar between hydrogen and natural gas to accommodate fluctuations in fuel supply and demand. Data from 2022 from the "2023 California Gas Report Supplement"[85] was used to estimate a California-specific value for the fraction of annual hydrogen demand that would be stored. From this source, it was determined that the average quantity of supplied natural gas in California during 2022 was 6,023 MMcf/day, which equates to approximately 2,198 Bcf/yr. This source also indicated that in 2022 California had a natural gas storage capacity of approximately 304 Bcf. Dividing these two values yielded a maximum (conservative) fraction of annual natural gas demand that would be stored: 13.8%. This value was applied to hydrogen; therefore, it was assumed that annually 13.8% of hydrogen demand would be stored.

The Study evaluates two storage pressure scenarios—290 psi (low pressure) and 2,900 psi (high pressure). These were developed based on an article that presented a variety of hydrogen storage options and their corresponding pressures. The highest and lowest pressures from this publication were utilized to represent the full range of potential storage pressures, and therefore storage compressor energy demands, from this project. These low and high storage pressure scenarios were 20 bar (290 psi) and 200 bar (2,900 bar) respectively.[86] The energy needed to store hydrogen at 290 psi and 2,900 psi was determined to be 4 megajoules (MJ)/kg and 14 MJ/kg, respectively.

The Study also assumed a transmission distance of 450 miles based on information provided by the Pipeline Sizing and Routing Study. Efficiency values for reciprocating engines and turbines were also sourced from scientific literature to convert fuel energy in units of MMBtu to energy supplied by power sources for compression in units of MJ. These efficiency values were 60.3% and 51.9% for hydrogen fueled reciprocating engines and turbines respectively. Please refer to the Pipeline Sizing and Routing Study for additional information.

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[85] CPUC, 2023, 2023 California Gas Report Supplement prepared per Decision D.95-01-039, https://www.socalgas.com/sites/default/files/Joint_Biennial_California_Gas_Report_2023_Supplement.pdf

[86] Tahan, M., 2022, Recent advances in hydrogen compressors for use in large-scale renewable energy integration, International Journal of Hydrogen Energy 47(83): 35275-35292, https://doi.org/10.1016/j.ijhydene.2022.08.128

These parameters are preliminary assumptions being used since detailed design data is not available for this feasibility study. Future refinements in GHG emission estimates could incorporate more specific details on compressor types, sizes, and quantities, as well as assumptions about storage volumes and pressures. Additionally, development of assumptions regarding above ground and underground storage volumes and pressures can support development of refinement of GHG emission estimates.

Results for storage and transmission for GHG emissions are provided for the Low Demand Scenario in Tables 4 and 5, respectively. Table 4 displays the emissions from hydrogen storage at two pressure levels based on the Low Demand Scenario. For high-pressure storage using turbine-driven compressors, emissions rise from 204 MT CO2e in 2030 to 2,959 MT CO2e in 2045. Based on the High Demand Scenario, the values range from 1,200 MT CO2e in 2030 to 10,599 MT CO2e in 2045. When electric motor-driven compressors are used at any pressure, the emissions remain at zero throughout the study period.

Table 4
Potential Direct GHG Emissions from Hydrogen Storage Based on Demand Scenarios

Demand Scenario	Emissions (MT CO2e/yr)				Scenario	
	2030	2035	2040	2045	Storage Pressure	Power Source
Low Max	204	810	1,740	2,959	2,900 psi	Turbine
Low Min	0	0	0	0	All Pressures	Renewable Electricity
High Max	1,200	4,141	7,062	10,599	2,900 psi	Turbine
High Min	0	0	0	0	All Pressures	Renewable Electricity

Table 5 presents the emissions associated with using compressors to support transmission of hydrogen over a 450 mile distance. For hydrogen-fueled compressors, the emissions increase from 609 MT CO2e in 2030 to 8,829 MT CO2e by 2045 for the Low Demand Scenario. Emissions for hydrogen transmission using hydrogen-fueled compressors are estimated at 5,135 MT CO2e in 2030 and 27,220 MT CO2e by 2045 for the High Demand Scenario. When using electric motor-driven compressors powered by renewable electricity, the emissions are maintained at zero.

Table 5
Potential Direct GHG Emissions from Hydrogen Transmission Based on Demand Scenarios

Demand Scenario	Emissions (MT CO2e/yr)				Scenario	
	2030	2035	2040	2045	Transmission Distance	Power Source
Low Max	609	2,418	5,192	8,829	450 miles	Hydrogen
Low Min	0	0	0	0	All Distances	Renewable Electricity
High Max	5,135	10,634	18,137	27,220	450 miles	Hydrogen
High Min	0	0	0	0	All Distances	Renewable Electricity

5.2 END USERS

Consistent with the Decision, Angeles Link is intended to transport clean renewable hydrogen to multiple end user sectors. The focus of the GHG emissions study was on three sectors of end-users identified in the parallel Demand Study: mobility, power generation, and hard to electrify industrial sectors. The Demand Study estimated quantities of diesel and gasoline that may be displaced by hydrogen fuel cells in the mobility sector. The Demand Study also estimated quantities of natural gas that may be displaced by hydrogen fuel in the power generation and hard to electrify industrial sectors. The potential for leakage at end users was not quantified as part of this study.

5.2.1 Mobility

Mobility is the largest end-user sector for GHG emission reductions, accounting for 72.5% and 50.3% of overall reductions in Low and High Demand scenarios, respectively, due to the substitution of hydrogen fuel cells for fossil fuels. Potential sources of GHG emissions in this sector include on-road vehicles such as heavy-duty vehicles (HDV), medium-duty vehicles (MDV), and buses. For example, the 'Zero Emission Bus Transition Plan' specifically targets AC Transit in Oakland, California, focusing on deploying hydrogen fuel cells and electric buses to advance its long-standing public transit services.[87] The Mobility sector also includes off-road vehicles in Agriculture, Commercial Harbor Craft (CHC), Cargo Handling Equipment at ports (CHE), Construction and Mining, and Ground Support Equipment at airports (GSE).

- Low Demand Scenario
  - On-Road Vehicles account for 93.9% of Mobility GHG emission reductions
    - Heavy Duty Vehicles are 58.5% of Mobility GHG reductions
  - Off-Road Vehicles account for 6.1% of Mobility GHG emission reductions
- High Demand Scenario
  - On-Road Vehicles account for 95.6% of Mobility GHG emission reductions
    - Heavy Duty Vehicles are 62.8% of Mobility GHG reductions
  - Off-Road Vehicles account for 4.4% of Mobility GHG emission reductions

The assumptions for the Mobility sector are primarily that diesel and gasoline fuel will be displaced, and vehicles would convert to hydrogen fuel cells with zero emissions. Emission factors for GHG from displaced diesel and gasoline fuel were developed using EMFAC data. The EMFAC model contains sufficient data to estimate CO_2, CH_4, and N_2O emissions for on-road mobile sources, and CO_2 emissions for off-road mobile sources. The EMFAC model does not include CH_4 and N_2O emissions data for off-road mobile vehicles. Research was conducted to estimate the most representative CH_4 and N_2O emissions factors for off-road mobile sources. Fuel consumption was weighted by subcategory of vehicle types. The same two equations previously mentioned were used to conduct the GHG calculations, and the hydrogen emissions value in equation 2 is zero.

*Fuel Throughput x Emissions Factor * GWP = GHG Emissions (equation 1)*

GHG Emission Reductions = Fossil Fuel GHG Emissions – Hydrogen GHG Emissions (equation 2)

The total emissions were calculated by summing totals for each equipment type and are shown in Table 6. Figures 2A and 2B provide graphs for the Low and High Demand scenarios, respectively below. The GHG reductions estimated for the Low Demand Scenario in 2045 are equivalent to approximately 2.7 million gasoline passenger vehicles driven for one year per EPA Calculator. The GHG reductions estimated for the High Demand Scenario in 2045 are equivalent to over 4 million gasoline passenger vehicles driven for one year per EPA Calculator.

[87] AC Transit, Zero Emission Bus Transition Plan, 2022, 0162-22 ZEB Transition Plan_052022_FNL.pdf (actransit.org)

Table 6 Mobility Direct GHG Combustion Emission Reductions (million MT CO2e/yr)				
Demand Scenario	**2030**	**2035**	**2040**	**2045**
Low	0.94	3.81	7.84	12.14
High	4.44	9.04	13.97	17.98

Table 6 illustrates the expected reductions in GHG emissions within the mobility sector, under Low and High Demand Scenarios, spanning from 2030 to 2045. In the Low Demand Scenario, GHG reductions are substantial, beginning at approximately 939 thousand metric tons of CO_2 equivalent (MT CO2e) in 2030 and increasing by more than ten-fold to over 12 million MT CO2e by 2045. This increase reflects a growing adoption of hydrogen-fueled mobility solutions. Under the High Demand Scenario, the reductions are even more pronounced, starting at about 4.4 million MT CO2e in 2030 and escalating to nearly 18 million MT CO2e by 2045. These figures suggest a robust integration of hydrogen in transportation, significantly cutting GHG emissions as the Mobility sector transitions away from fossil fuels.

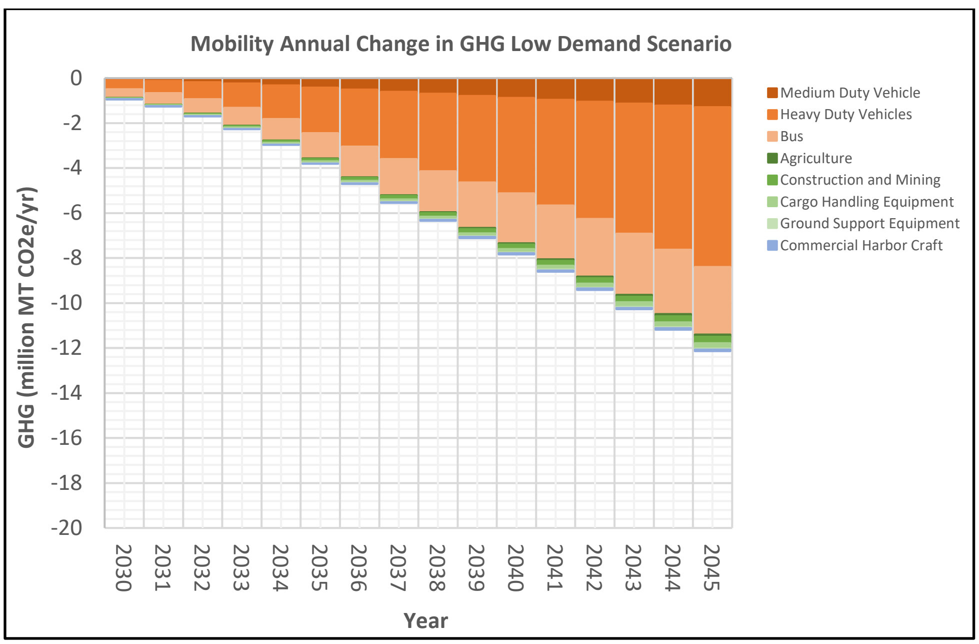

Figure 2A. Mobility Annual Change in GHG - Low Demand Scenario

Figure 2A visualizes the annual change in GHG emissions for the Mobility sector under the Low Demand Scenario over the period from 2030 to 2045. The chart shows a steady decline in GHG emissions, with the most significant reductions seen in heavy-duty vehicles. Medium-duty vehicles, buses, and other categories such as Agriculture and Construction contribute to the overall decrease but to a lesser extent. This trend reflects the potential impact of deploying clean hydrogen fuel cell technology in reducing emissions from various subsectors within mobility, with the most substantial effect seen in the heavy-duty vehicle category.

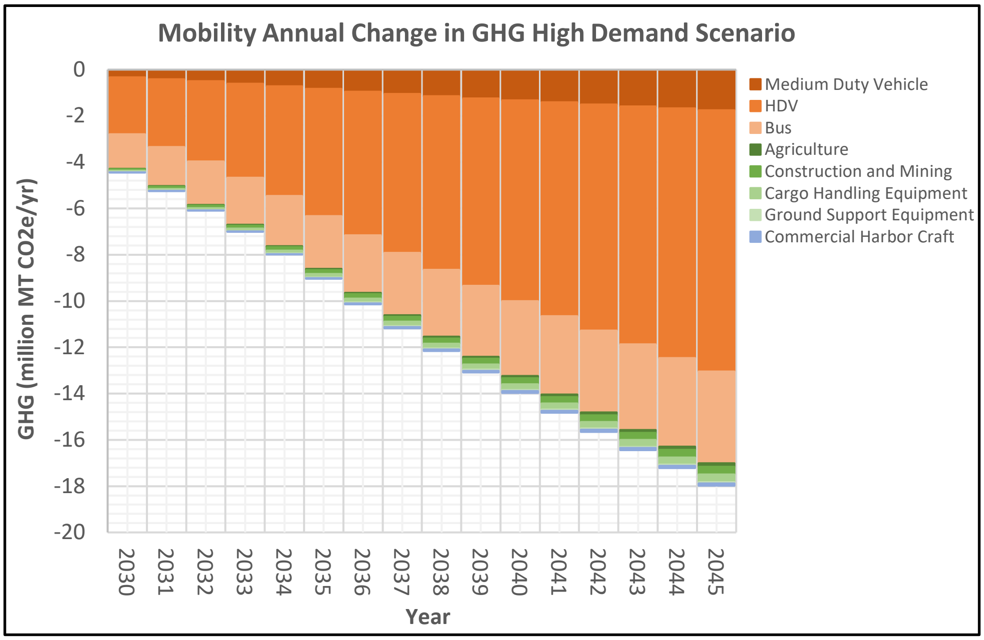

Figure 2B. Mobility Annual Change in GHG - High Demand Scenario

Figure 2B presents the changes in GHG emissions in a High Demand Scenario, which assumes higher shift towards hydrogen fuel cell vehicles across the Mobility sector. The decreasing stacked bars, which represent different vehicle categories, indicate an even more pronounced annual decrease in GHG emissions compared to the Low Demand Scenario. Heavy-duty vehicles remain the largest contributors to GHG reductions, followed by medium-duty vehicles and buses. The chart illustrates a potential future where a high demand for hydrogen in the mobility sector could lead to significantly lower GHG emissions, showcasing the Mobility sector's pivotal role in achieving broader climate targets.

5.2.2 Power Generation

The draft results for the anticipated GHG emissions reductions based on the Low and High Demand Scenarios data in 2045 are that the Power Generation sector accounts for 23.6% and 41.7% of overall GHG reductions, respectively. The assumptions that were applied to develop the GHG emissions calculations include that hydrogen will displace natural gas as a fuel with increasing amounts over time (from 2030 to 2045). The potential for leakage at power generation end users such as when hydrogen is transferred from onsite storage or pipelines to onsite hydrogen combustion equipment is acknowledged but was not quantified as part of this study.

This Study is focused on estimating GHG emissions reductions anticipated to be associated with use of clean renewable hydrogen as a fuel in the power generation sector relating to the development of Angeles Link. At the time of this Study, there is not sufficient detailed project information to estimate the quantity of electricity anticipated to be produced using 100% clean renewable hydrogen as the future annual average utilization and the capacity factor for thermal power plant generation is not known.

For each emission source type identified, calculations to estimate GHG emissions were prepared using the same two equations previously mentioned.

*Fuel Throughput x Emissions Factor * GWP = GHG Emissions (equation 1)*

GHG Emission Reductions = Fossil Fuel GHG Emissions – Hydrogen GHG Emissions (equation 2)

The first equation (equation 1) multiplies the quantity of fuel by the GHG emission factor specific to the fuel for each GHG pollutant. These pollutants are CO_2, CH_4, and N_2O for combustion of fossil fuels and trace amounts of N_2O for combustion of hydrogen. Each GHG has a specific fuel dependent emission factor and a unique GWP as shown in Table 1. The emissions for each of CO_2, CH_4, and N_2O are multiplied by their respective GWP and then summed to obtain the total GHG emissions in units of CO2e.

The second equation (equation 2) calculates the GHG emission reductions in CO2e by subtracting the GHG emissions for hydrogen (either for N_2O from combustion of hydrogen or zero for hydrogen fuel cells) from the GHG emissions for combustion of displaced fossil fuels. The GHG emissions for combustion of hydrogen and for combustion of fossil fuels are both derived from equation 1.

As previously noted, for combustion of clean renewable hydrogen, GHG is comprised entirely of N_2O from the nitrogen present in the combustion air at specific temperatures, and since the GWP 20 and GWP 100 for N_2O are both 273, the expected impacts in both short term and long term should be similar. The total emissions were calculated by summing totals for each equipment type and are shown in Table 7. Detailed information is available in the excel spreadsheets found in Appendix C.

Table 7
Power Generation Direct GHG Combustion Emission Reductions (million MT CO2e/yr)

Demand Scenario	2030	2035	2040	2045
Low	0.04	0.61	1.87	3.95
High	0.16	2.30	7.06	14.90

Table 7 quantifies the projected reductions in GHG emissions within the Power generation sector for both Low and High Demand Scenarios from 2030 to 2045. In the Low Demand Scenario, the reductions begin modestly at 0.04 million MT CO2e in 2030, gradually escalating to 3.95 million MT CO2e by 2045, accounting for 23.6% of the overall anticipated GHG reductions. For the High Demand Scenario, the reductions are more significant, starting at 0.16 million MT CO2e and surging to 14.90 million MT CO2e by 2045, contributing to 41.7% of the total expected reductions. These estimates reflect the impact of transitioning to clean renewable hydrogen in Power generation, highlighting the sector's potential contribution to reducing GHG emissions.

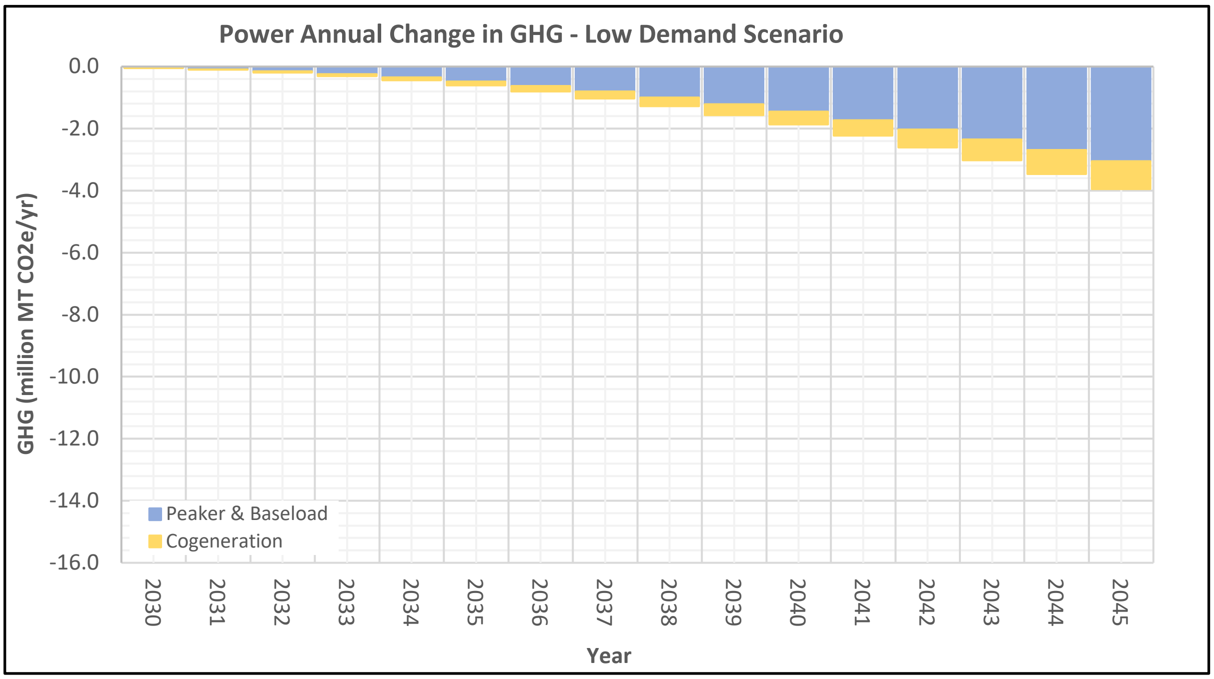

Figure 3A. Power Annual Change in GHG - Low Demand Scenario

Figure 3A represents the annual change in GHG emissions for the Power sector under the Low Demand Scenario. It features two distinct segments in each bar: the larger, representing base load and peaker power generation units, and the smaller, cogeneration units. Together, they depict a downward trend in emissions, signaling a reduction in GHG as the sector pivots towards clean renewable hydrogen use. By 2045, this shift equates to the GHG emissions of over 769,537 households' annual electricity consumption, demonstrating a significant environmental impact through the incorporation of clean renewable hydrogen in power generation.

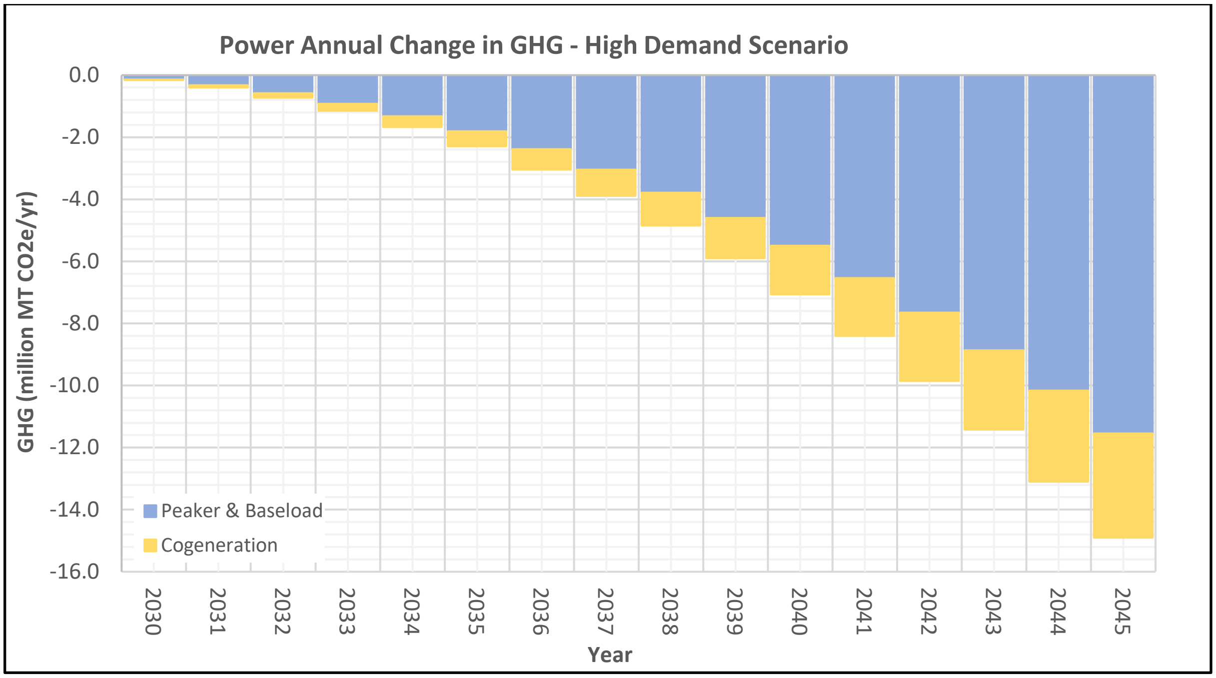

Figure 3B. Power Annual Change in GHG - High Demand Scenario

Figure 3B illustrates the Power sector's annual GHG emissions changes under the High Demand Scenario, showing deeper reductions than the Low Demand Scenario. This scenario implies a faster adoption of clean renewable hydrogen as a fuel source, with the dark blue and yellow bars representing peaker and base load and cogeneration units, respectively. The staggered bars mirror an increased decline in emissions year over year, culminating in a decrease comparable to the annual electricity use of nearly 2.91 million homes by 2045. This emphasizes the transformative potential of a high-demand shift to clean renewable hydrogen fuel, substantially lowering the Power sector's carbon footprint.

5.2.3 Hard to Electrify Industrial

Hard to Electrify Industrial sectors include energy-intensive industries such as refining; food and beverage manufacturing; primary and fabricated metals; stone, clay, and glass (including cement); chemical manufacturing; wood and paper; petroleum products; mining; ammonia production; industrial launderers; co-generation; and textile manufacturing. These sectors are anticipated to initially blend hydrogen with natural gas in 2030 and then eventually transition to pure hydrogen by 2050. Source types with the potential for GHG emissions in the Hard to Electrify Industrial sectors include hot water boilers, steam generating units, process heaters, furnaces/kilns, reciprocating internal combustion engines, turbines, and miscellaneous combustion equipment.

The draft results for the anticipated GHG emissions reductions associated with the Industrial sector based on the Low and High Demand Scenario data in 2045 are that the Industrial sector accounts for 3.9% and 8.1% of overall GHG reductions, respectively. The assumptions that were applied to develop the GHG emissions calculations include that clean renewable hydrogen will displace natural gas as a fuel with increasing amounts over time (from 2030 to 2045). It should be noted that consistent with the Decision, Angeles Link is intended as a project to transport only 100% clean renewable hydrogen in the pipeline, and any analysis of hydrogen blending refers strictly to "behind-the-meter" operations, not within SoCalGas control. This Study does not dictate if end users will blend hydrogen with natural gas and makes assumptions regarding adoption rates based on currently available information regarding equipment and the anticipated evolution of adoption over time. Since only 100% clean renewable hydrogen will be delivered, to estimate GHG reductions at end users, assumptions regarding hydrogen adoption rates were made as shown in Tables 2A and 2B. The estimated emissions are based on these assumptions.

The potential for leakage at hard to electrify industrial end users such as when hydrogen is transferred from onsite storage or pipelines to onsite hydrogen combustion equipment is acknowledged but was not quantified as part of this study.

For each emission source type identified, calculations to estimate emissions were prepared using the same two equations previously mentioned.

*Fuel Throughput x Emissions Factor * GWP = GHG Emissions (equation 1)*

GHG Emission Reductions = Fossil Fuel GHG Emissions – Hydrogen GHG Emissions (equation 2)

The first equation (equation 1) multiplies the quantity of fuel by the GHG emission factor specific to the fuel for each GHG pollutant. These pollutants are CO_2, CH_4, and N_2O for combustion of fossil fuels and N_2O for combustion of hydrogen. Each GHG has a specific fuel dependent emission factor and a unique GWP as shown in Table 1. The emissions for each of CO_2, CH_4, and N_2O are multiplied by their respective GWP and then summed to obtain the total GHG emissions in units of CO2e.

The second equation (equation 2) calculates the GHG emission reductions in CO2e by subtracting the GHG emissions for hydrogen (either for N_2O from combustion of hydrogen or zero for hydrogen fuel cells) from the GHG emissions for combustion of displaced fossil fuels. The GHG emissions for combustion of hydrogen and for combustion of fossil fuels are both derived from equation 1.

As previously mentioned, for combustion of clean renewable hydrogen with GHG emissions comprised entirely of N_2O, since the GWP 20 and GWP 100 for N_2O are both 273, the expected impacts in both short term and long term should be similar.

The total emissions were calculated by summing the totals for each equipment type and are shown in Table 8. Figures 4A and 4B provide graphs for the Low and High Demand scenarios, respectively below. The GHG reductions predicted for the Low Demand Scenario in 2045 are equivalent to 139,007 homes' electricity use for one year per EPA Calculator. The GHG reductions predicted for the High Demand Scenario in 2045 are equivalent to 603,582 homes' electricity use for one year per EPA Calculator. Detailed information is available in Appendix C.

Table 8
Hard-to-Electrify Industrial Direct GHG Combustion Emission Reductions (million MT CO2e/yr)

Demand Scenario	2030	2035	2040	2045
Low	0.28	0.45	0.56	0.65
High	1.13	1.91	2.45	2.89

Table 8 focuses on the GHG emission reductions in the industrial sector, a variety of energy-intensive industries facing challenges in electrification. The table reflects emission reductions from 2030 through 2045 under Low and High Demand Scenarios. Under the Low Demand Scenario, reductions start at 0.28 million MT CO2e in 2030, modestly increasing to 0.65 million MT CO2e by 2045. This change represents a steady progression towards cleaner energy usage within these industries, accounting for 3.9% of the overall GHG reduction. In contrast, the High Demand Scenario starts at 1.13 million MT CO2e in 2030, ramping up to 2.89 million MT CO2e by 2045, indicating more aggressive adoption rates of clean renewable hydrogen as a replacement for natural gas, contributing to 8.1% of total GHG reductions. The trajectory of both scenarios suggests an evolving industrial landscape where clean renewable hydrogen plays a key role in reducing emissions.

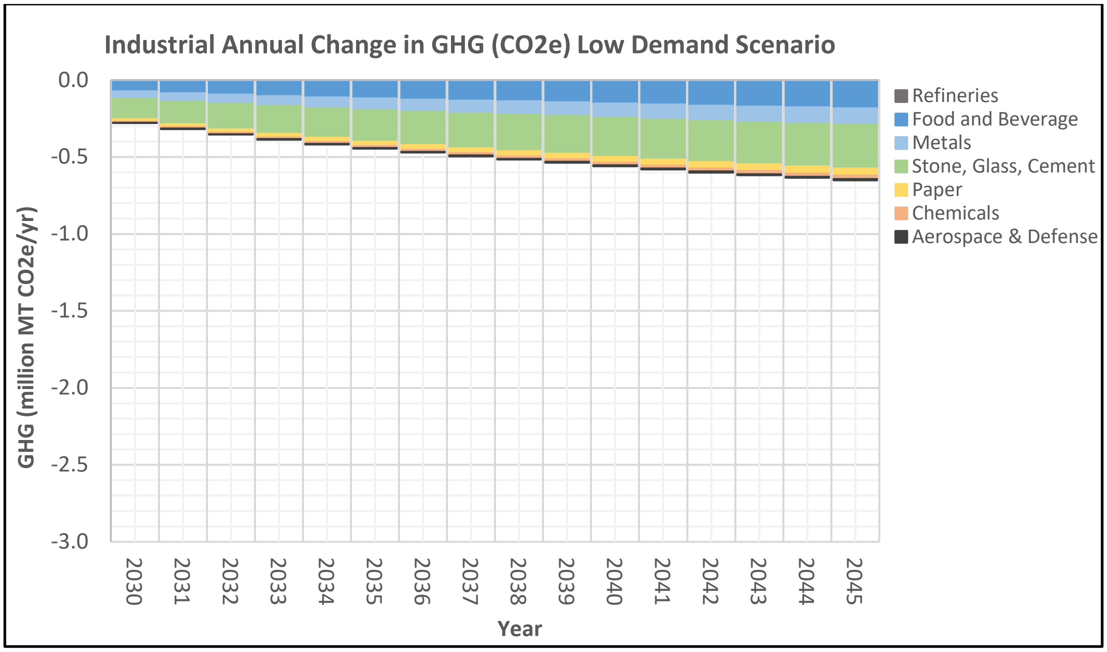

Figure 4A. Industrial Annual Change in GHG - Low Demand Scenario

Figure 4A visualizes the decline in GHG emissions across various sub-sectors in the industrial sector for the Low Demand Scenario. It showcases how industries like refineries, food and beverage, metals, and others are expected to reduce their emissions over the years, with the most substantial decreases projected in the refining sector. The total projected GHG emission reductions in 2045 are equivalent to the annual electricity usage of about 139,000 homes.

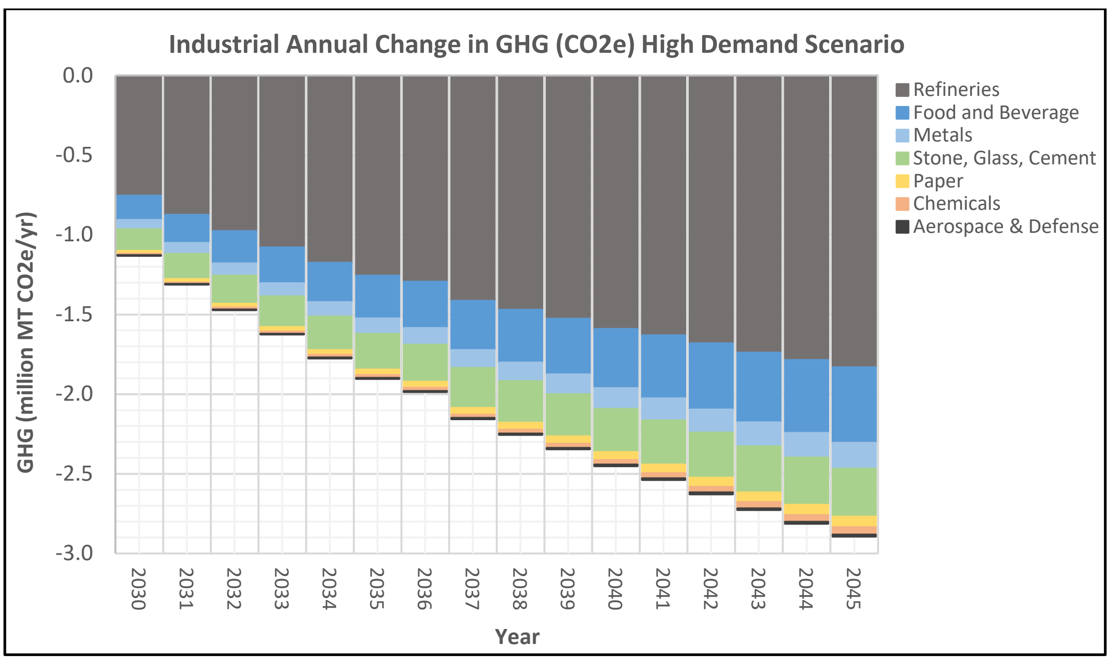

Figure 4B. Industrial Annual Change in GHG – High Demand Scenario

Figure 4B depicts a more significant reduction in GHG emissions within the industrial sector under the High Demand Scenario. The larger scale of reductions mirrors a more robust transition to clean renewable hydrogen fuel, with the refining sector again making up the largest proportion of decreases. The graph indicates that the industrial sector could achieve GHG reductions in 2045 equating to the yearly electricity use of 603,582 homes. This scenario emphasizes the sector's potential for substantial contributions to overall emission reductions with an intensified hydrogen adoption rate.

6 OVERALL RESULTS BASED ON DEMAND STUDY SCENARIOS

The anticipated potential minor GHG emissions associated with the new infrastructure were added to the overwhelmingly large anticipated GHG emissions reductions associated with potential end users of clean renewable hydrogen as defined by the Demand Study. The total GHG reductions predicted for the Low Demand Scenario in 2045 for end-users are equivalent to more than 3,255,000 homes' electricity use for one year per EPA Calculator. The total GHG reductions predicted for the High Demand Scenario in 2045 for end-users are equivalent to more than 6,961,000 homes' electricity use for one year per EPA Calculator. The results are provided in Table 9 and in Figures 5A and 5B below. Detailed information is available in the excel spreadsheets found in Appendix C.

In summary:

- Projected up to nearly 17 and 36 million metric tons of CO2e removed per year from SoCalGas territory geographic area by end users by 2045 for Low and High Demand Scenarios, respectively.
- Infrastructure GHG emissions are significantly smaller than end-user reductions.
    - The highest potential infrastructure GHG emissions estimated are 0.17% and 0.25% the magnitude of overall end-user reductions for Low and High Demand Scenarios, respectively.
- Mobility GHG emissions would be eliminated with clean renewable hydrogen substitution when fossil fuels are replaced with hydrogen fuel cells. In the Mobility sector, hydrogen fuel cells offer a substantial reduction in GHG emissions by replacing diesel and gasoline in vehicles. This sector shows the highest reduction potential due to the large contributions to emissions by heavy-duty and medium-duty vehicles using traditional fuels.
    - Mobility comprises 72.5% and 50.3% of overall GHG reductions for Low and High Demand Scenarios, respectively.
- Industrial and Power Generation GHG emissions are almost entirely eliminated when fossil fuels are replaced by clean renewable hydrogen as a fuel in combustion equipment. Hard-to-Electrify Industrial sectors benefit from clean renewable hydrogen in reducing emissions from processes that are currently reliant on high-temperature operations and fossil fuels. The smaller percentage in overall reductions compared to mobility and power generation reflects the complex challenges and slower transition expected in these sectors.
    - Power generation comprises 23.6% and 41.7% of overall GHG reductions for Low and High Demand Scenarios, respectively.
    - Industrial comprises 3.9% and 8.1% of overall GHG reductions for Low and High Demand Scenarios, respectively.

Table 9 Annual Change in Direct GHG Emissions for Demand Scenarios (MT CO2e/yr)					
Category	**Demand Scenario**	**2030**	**2035**	**2040**	**2045**
End-Users	Low	-1,261,530	-4,864,767	-10,265,012	-16,731,269
	Mid	-2,762,724	-7,948,981	-15,674,833	-24,958,279
	High	-5,729,290	-13,244,418	-23,490,552	-35,776,958
Infrastructure	High - Low	1,966	7,807	16,765	28,512
	High - Mid	4,234	13,363	27,657	46,447
	High - High	16,583	34,339	58,568	87,899
	Low - Low	0	0	0	0
	Low - Mid	0	0	0	0
	Low - High	0	0	0	0
Total	Low	-1,259,565	-4,856,960	-10,248,247	-16,702,756
	Mid	-2,758,490	-7,935,593	-15,647,156	-24,911,832
	High	-5,712,707	-13,210,054	-23,431,964	-35,689,059

Table 9 presents a comprehensive view of the anticipated yearly change in GHG emissions across different scenarios, capturing the transformational impact of clean renewable hydrogen adoption by end-users within the SoCalGas territory by 2045. In the Low Demand Scenario, end-user emissions reductions start at 1.26 million metric tons (MT) of CO2e per year in 2030 and expand to a reduction of 16.70 million MT CO2e by 2045. The Mid and High scenarios show even more dramatic decreases, with the High scenario projecting reductions of over 35.8 million MT CO2e annually by 2045. Conversely, infrastructure related GHG emissions represent a minimal increase in the overall emissions profile, peaking at just 0.29% of the magnitude of end-user reductions. The analysis shows the potential for GHG emission reductions, equating to the annual power usage of over 3.25 million homes for the Low Demand Scenario and more than 6.96 million homes for the High Demand Scenario, emphasizing the significant role of end-users in driving down GHG emissions through hydrogen use.

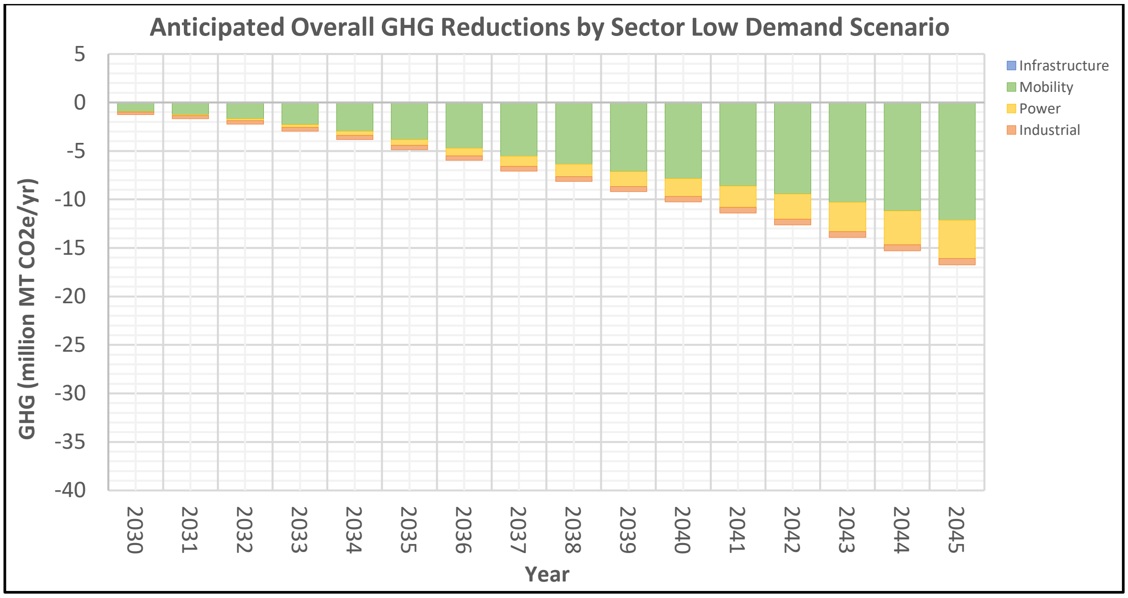

Figure 5A. Anticipated Overall GHG Reductions by Sector - Low Demand Scenario

Figure 5A depicts the anticipated GHG reductions by sector under the Low Demand Scenario. It shows that the Mobility sector would account for the lion's share of reductions, making up 72.5% of the total decrease in emissions. This sector's change is depicted as the largest portion, underscoring the impact of replacing traditional vehicle fuels with hydrogen fuel cells. Power generation and industrial sectors follow, illustrating the transition from fossil fuels to clean hydrogen and their respective contributions to the total reduction in emissions. The clear delineation of contributions across sectors highlights the critical importance of sector-specific strategies in achieving GHG emission targets.

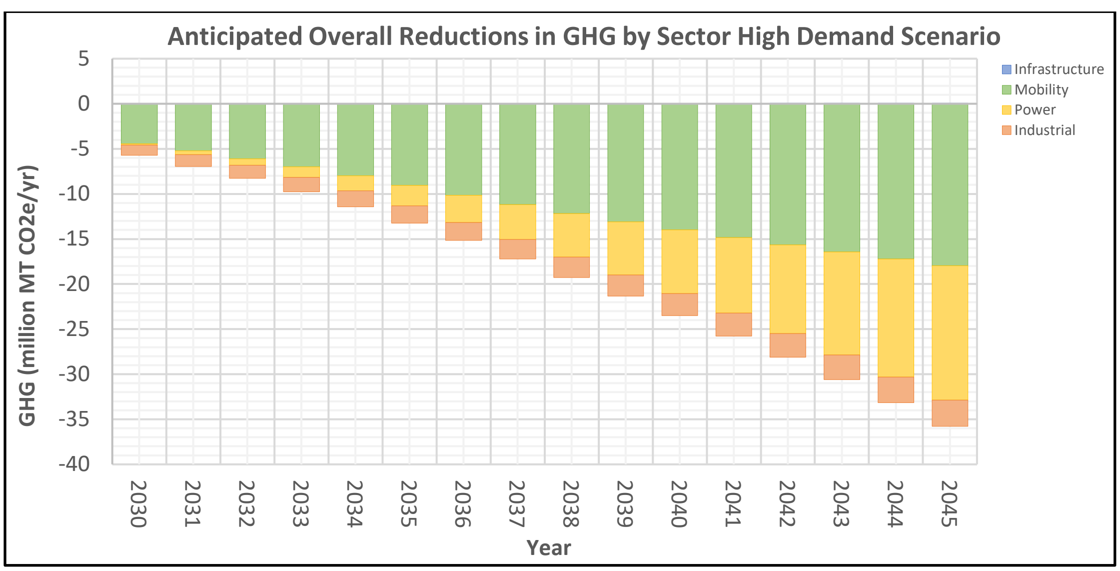

Figure 5B. Anticipated Overall GHG Reductions by Sector - High Demand Scenario

In Figure 5B, the reductions in GHG emissions are presented under the High Demand Scenario, indicating a faster approach to hydrogen integration. The scale of reductions is more substantial compared to the Low Demand Scenario, with Mobility again constituting the bulk of the decrease but at a relatively lower percentage, suggesting a broader distribution of clean hydrogen usage across sectors. The Power sector's contribution is markedly increased, consistent with the larger role of clean hydrogen in high-demand futures. The Industrial sector, while smaller in percentage, also shows a significant decrease in emissions, reaffirming the potential of hydrogen to transform even the most challenging sectors. The collective representation of sectors in this figure reflects a dynamic shift towards a low-carbon economy with substantial GHG emissions reductions.

7 ASSUMPTIONS AND RESULTS FOR ANGELES LINK THROUGHPUT SCENARIOS

Draft emissions calculation results including assumptions are provided for the following categories that were evaluated for the Angeles Link Throughput Scenarios. The projected GHG emissions reductions totals for each end-user subsector were summed to estimate totals for each sector; and then totals for each sector were summed and added to anticipated GHG emissions associated with new infrastructure to estimate the overall annual GHG emissions reductions based upon the Angeles Link Throughput Scenarios and anticipated for each year 2030 to 2045.

- Infrastructure: production, storage, and transmission of hydrogen to end-users
- End-Users: mobility, power generation, and hard-to-electrify industrial sectors projected to use hydrogen

This document provides the results of the GHG study. Detailed emission calculations based on the Angeles Link Throughput Scenarios will be provided in the draft report.

7.1 INFRASTRUCTURE

The draft results for potential GHG emission increases associated with the new Angeles Link-related infrastructure based on the data for 2045 project that such are up to 0.17% and 0.25% the magnitude of end-user reductions for Angeles Link Low and High Throughput Scenarios, respectively.

7.1.1 Hydrogen Production (Third Party)

Three equipment options were evaluated for hydrogen production to meet the definition of clean renewable hydrogen:

1. Electrolyzers powered by renewable electricity (zero GHG)
2. Biomass gasification (zero GHG)
3. RNG SMR (residual GHG due to N_2O)

Multiple scenarios were evaluated with varying contributions to total production by each of the three types of equipment listed above to estimate the range of potential GHG emissions. The range extends from zero GHG associated with 100% electrolysis and 100% biomass gasification scenarios to the potential for some GHG emissions for the 100% RNG SMR scenario. GHG emission estimates can be refined once further project details are developed, including assumptions regarding anticipated production processes and proportions of hydrogen intended to be produced from different methods have been identified. Draft results are provided for the Low and High Throughout Scenarios in Table 10. Detailed information is available in the excel spreadsheets found in Appendix C.

Table 10 Potential Direct GHG Emissions from Hydrogen Production Based on Angeles Link Throughput Scenarios					
Angeles Link Throughput Scenario	**Emissions (MT CO2e/year)**				
	2030	**2035**	**2040**	**2045**	**Production Scenario**
Low Min	0	0	0	0	100% Electrolysis or 100% Biomass Gasification
Low Max	301	1,194	2,564	4,361	100% SMR (Max Case)
High Min	0	0	0	0	100% Electrolysis or 100% Biomass Gasification
High Max	2,396	4,962	8,463	12,701	100% SMR (Max Case)

Table 10 depicts the estimated GHG emissions from hydrogen production related to the throughput scenarios. For both low and high throughput scenarios, the minimum potential emissions are zero, representing methods like electrolysis and biomass gasification that do not produce GHG emissions. In contrast, the maximum emissions under the low throughput scenario rise from about 301 MT CO2e in 2030 to 4,361 MT CO2e by 2045 for 100% SMR. Similarly, under the high throughput scenario, maximum emissions increase from 2,396 MT CO2e to 12,701 MT CO2e within the same timeframe for the 100% SMR option.

7.1.2 Storage (Third Party) and Transmission

Compressors will be needed for storage and transmission of hydrogen. Three options for types of compressors were evaluated.

1. Electric motor driven compressors (zero GHG emissions)
2. Clean renewable hydrogen fueled reciprocating engine driven compressors (some GHG emissions)
3. Clean renewable hydrogen fueled turbine driven compressors (some GHG emissions)

Emissions of GHG (as N_2O) from hydrogen fueled reciprocating engine driven compressors and from turbine driven compressors were conservatively estimated using equation 1.

*Fuel Throughput x Emissions Factor * GWP = GHG Emissions (equation 1)*

The first equation (equation 1) multiplies the quantity of clean renewable hydrogen by the N_2O emission factor assumed in this Study for hydrogen. The emissions for N_2O are then multiplied by the GWP as shown in Table 1 to determine GHG emissions in units of CO2e.

Two storage pressure scenarios were evaluated - a low pressure scenario at 290 psi and a high-pressure scenario at 2,900 psi. A total transmission distance of 450 miles was evaluated. These assumptions were made for this Study and additional information is available in the parallel Pipeline Sizing and Routing Study. GHG emission estimates can be refined once the types, sizes, and quantities of compressors have been further developed. Additionally, development of assumptions regarding above ground and underground storage volumes and pressures will support refinement of potential GHG emission estimates for third-party storage. Draft results for storage and transmission for GHG emissions are provided in Tables 11 and 12, respectively. Detailed information is available in the excel spreadsheets found in Appendix C.

Table 11
Potential Direct GHG Emissions from Hydrogen Storage Based on Angeles Link Throughput Scenarios

Angeles Link Throughput Scenario	Emissions (MT CO2e/yr)				Scenario	
	2030	**2035**	**2040**	**2045**	**Storage Pressure**	**Power Source**
Low Min	0	0	0	0	NA	Renewable Electricity
Low Max	64	253	543	923	2,900 psi	Turbine Engine
High Min	0	0	0	0	NA	Renewable Electricity
High Max	507	1,050	1,791	2,688	2,900 psi	Turbine Engine

Table 11 outlines the potential GHG emissions from hydrogen storage under different Angeles Link throughput scenarios. The table presents a range from zero emissions, which would occur when using renewable electricity for all storage pressures, to a maximum emission scenario where hydrogen is stored at high pressure (2,900 psi) using turbine engines. The maximum emissions for the low throughput scenario grow from about 64 MT CO2e in 2030 to 923 MT CO_2e by 2045. In the high throughput scenario, the projected maximum emissions are greater, starting at 507 MT CO2e in 2030 and reaching approximately 2,688 MT CO2e by 2045.

Table 12 Potential Direct GHG Emissions from Transmission Based on Angeles Link Throughput Scenarios						
Angeles Link Throughput Scenario	**Emissions (MT CO2e/yr)**				**Scenario**	
	2030	**2035**	**2040**	**2045**	**Transmission Distance**	**Power Source**
Low Min	0	0	0	0	NA	Renewable Electricity
Low Max	163	649	1,394	2,371	450 miles	NA
High Min	0	0	0	0	NA	Renewable Electricity
High Max	1,302	2,697	4,600	6,903	450 miles	NA

Table 12 presents the anticipated GHG emissions from the transmission of hydrogen, varying by Angeles Link throughput scenarios over a set distance of 450 miles. Similar to the hydrogen production and storage tables, the emissions for transmission are presented as ranging from zero—using renewable electricity—to a maximum calculated based on undefined sources (NA). For the low throughput scenario, maximum emissions estimates increase from about 163 MT CO2e in 2030 to 2,371 MT CO2e by 2045. The high throughput scenario starts with 1,302 MT CO2e in 2030 and climbs to 6,903 MT CO2e by 2045. These figures provide an insight into the anticipated GHG emissions associated with hydrogen transmission. Detailed information is available in the excel spreadsheets found in Appendix C.

7.2 END USERS

Consistent with the Decision, Angeles Link is intended to transport clean renewable hydrogen to the end users. The focus of the GHG emissions study was on three sectors of end-users: mobility, power generation, and hard to electrify industrial. The Throughput Scenarios estimated quantities of diesel and gasoline that may be displaced by hydrogen fuel cells in the mobility sector. The Throughput Scenarios also estimated quantities of natural gas that may be displaced by hydrogen fuel in the power generation and hard to electrify industrial sectors. The potential for leakage at end users is acknowledged but was not quantified as part of this Study.

7.2.1 Mobility

Summary of draft results for the anticipated GHG emission reductions associated with the Mobility sector based on the Low and High Throughput Scenarios for Angeles Link in 2045 are the following.

- Mobility is the largest end-user sector of GHG reductions at 72.5% and 50.3% of overall reductions for Low and High Throughput Scenarios, respectively. These reductions are due to hydrogen fuel cell substitution for fossil fuels nearly eliminating GHG emissions. The potential for leakage such as during refueling of vehicles is acknowledged but was not quantified as part of this study.
    - Low Throughput Scenario
        - On-Road Vehicles account for 93.9% of Mobility GHG reductions
            - Heavy Duty Vehicles are 58.5% of Mobility GHG reductions
        - Off-Road Vehicles account for 6.1% of Mobility GHG reductions
    - High Throughput Scenario
        - On-Road Vehicles account for 95.6% of Mobility GHG reductions
            - Heavy Duty Vehicles are 62.8% of Mobility GHG reductions
        - Off-Road Vehicles account for 4.4% of Mobility GHG reductions

On-Road Vehicles, Heavy Duty Vehicles, and Off-Road Vehicles have distinct roles in the mobility sector's GHG reductions, with on-road vehicles leading in both scenarios due to their higher contributions to emissions. The assumptions associated with the Mobility sector are primarily that diesel and gasoline fuel will be displaced, and vehicles would convert to hydrogen fuel cells with zero emissions. Emission factors for GHG from displaced diesel and gasoline fuel were developed using EMFAC data. The EMFAC model contains sufficient data to estimate CO_2, CH_4, and N_2O emissions for on-road mobile sources, and CO_2 emissions for off-road mobile sources. The EMFAC model does not include CH_4 and N_2O emissions data for off-road mobile vehicles. Research was conducted to estimate the most representative CH_4 and N_2O emissions factors for off-road mobile sources. Fuel consumption was weighted by subcategory of vehicle types. The same two equations previously mentioned were used to conduct the GHG calculations, and the hydrogen emissions value in equation 2 is zero.

*Fuel Throughput x Emissions Factor * GWP = GHG Emissions (equation 1)*

GHG Emission Reductions = Fossil Fuel GHG Emissions – Hydrogen GHG Emissions (equation 2)

The first equation (equation 1) multiplies the quantity of fuel by the GHG emission factor specific to the fuel for each GHG pollutant. These pollutants are CO_2, CH_4, and N_2O for combustion of fossil fuels and N_2O for combustion of hydrogen. Each GHG has a specific fuel dependent emission factor and a unique GWP as shown in Table 1. The emissions for each of CO_2, CH_4, and N_2O are multiplied by their respective GWP and then summed to obtain the total GHG emissions in units of CO2e.

The second equation (equation 2) calculates the GHG emission reductions in CO2e by subtracting the GHG emissions for hydrogen (either for N_2O from combustion of hydrogen or zero for hydrogen fuel cells) from the GHG emissions for combustion of displaced fossil fuels. The GHG emissions for combustion of hydrogen and for combustion of fossil fuels are both derived from equation 1.

The total emissions were calculated by summing totals for each equipment type and are shown in Table 13. Figures 6A and 6B provide graphs for the Low and High Throughput Scenarios, respectively below. The GHG reductions estimated for the Low Throughput Scenario in 2045 are equivalent to 775,000 gasoline passenger vehicles driven for one year per EPA Calculator. The GHG reductions estimated for the High Throughput Scenario in 2045 are equivalent to about 1,085,300 gasoline passenger vehicles driven for one year per EPA Calculator. Detailed information is available in the excel spreadsheets found in Appendix C.

Table 13
Mobility Direct GHG Emission Reductions Associated with Angeles Link Throughput Scenarios (million MT CO2e/yr)

Scenario	2030	2035	2040	2045
Low	0.25	1.02	2.10	3.26
High	1.13	2.29	3.54	4.56

Table 13 presents the GHG emission reductions within the mobility sector as a result of the Angeles Link Throughput Scenarios from 2030 to 2045. In the Low Throughput Scenario, the reductions begin at 0.25 million MT CO2e in 2030 and increase over the years to reach 3.26 million MT CO2e by 2045. This indicates a steady increase in the use of hydrogen as a fuel, replacing traditional carbon-intensive fuels in vehicles. The High Throughput Scenario predicts reductions starting with 1.13 million MT CO2e in reductions in 2030 and expanding to 4.56 million MT CO2e by 2045. These substantial figures suggest aggressive displacement of fossil fuels with hydrogen fuel cells, reflecting the potential for large GHG reductions in the transportation sector with the adoption of clean renewable hydrogen technology.

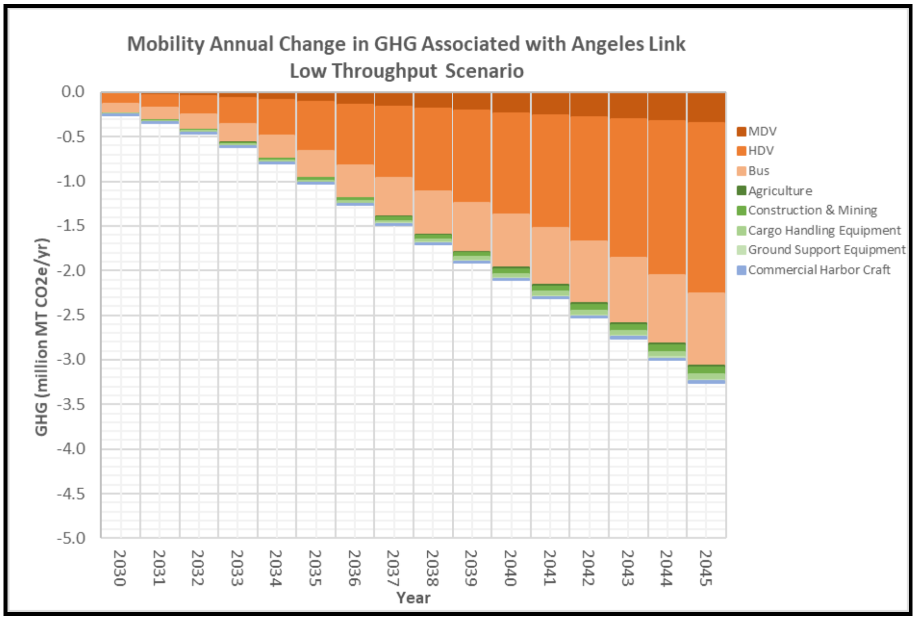

Figure 6A. Mobility Annual Change in GHG for Angeles Link - Low Throughput Scenario

Figure 6A illustrates the projected yearly reductions in GHG emissions from various subsectors of mobility, such as Medium Duty Vehicles (MDV), Heavy Duty Vehicles (HDV), Buses, and Agriculture from 2030 to 2045. The dominant segments, representing MDVs, indicate that this subsector is expected to contribute the largest share to GHG reductions, particularly as we approach 2045. The figure reflects an increased rate of emission reductions over time, aligning with the anticipated broader adoption of clean hydrogen fuel cells in these vehicle categories.

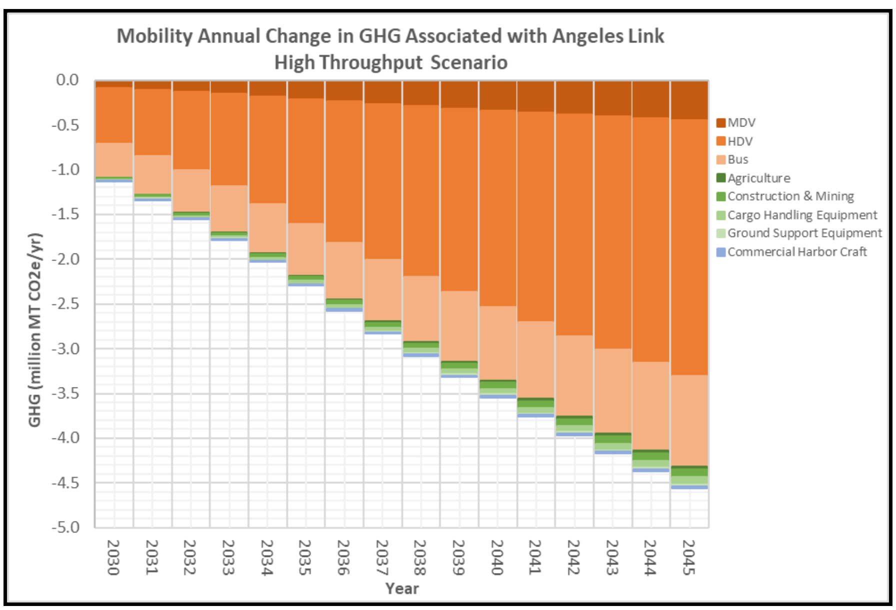

Figure 6B. Mobility Annual Change in GHG for Angeles Link - High Throughput Scenario

In Figure 6B, we see a similar trend of GHG reduction across the mobility sector, albeit with smaller absolute numbers compared to the high throughput scenario. This chart shows that even with a more conservative adoption of hydrogen fuel cell technology, significant emission reductions are projected, especially from MDVs and buses, which make up the majority of the reductions. The gradual increase in the size of the colored segments over the years suggests the growing impact of transitioning to hydrogen-powered transportation within the lower demand framework. The graph indicates that by 2045, the shift to hydrogen in mobility could yield emission reductions comparable to taking a large number of traditional vehicles off the road.

7.2.2 Power Generation

Draft results for anticipated GHG emissions reductions based on the Angeles Link Low and High Throughout Scenarios in 2045 are that the Power Generation sector accounts for 24% and 42% of overall GHG emissions reductions, respectively. The assumptions that were applied to develop the GHG emissions calculations include that hydrogen will displace natural gas as a fuel with increasing amounts over time (from 2030 to 2045). The potential for leakage at power generation end users such as when hydrogen is transferred from onsite storage or pipelines to onsite hydrogen combustion equipment is acknowledged but was not quantified as part of this study.

This Study is focused on estimated GHG reductions anticipated to be associated with use of hydrogen as a fuel in the power generation sector relating to the development of Angeles Link. At the time of this study report, there is not sufficient detailed project information to estimate the quantity of electricity that is anticipated to be produced using 100% clean renewable hydrogen as a fuel to electric generating equipment as the future annual average utilization or the capacity factor for thermal power plant generation is not known. For each emission source type identified, calculations to estimate GHG emissions were prepared using the same two equations previously mentioned.

*Fuel Throughput x Emissions Factor * GWP = GHG Emissions (equation 1)*

GHG Emission Reductions = Fossil Fuel GHG Emissions – Hydrogen GHG Emissions (equation 2)

The first equation (equation 1) multiplies the quantity of fuel by the GHG emission factor specific to the fuel for each GHG pollutant. These pollutants are CO_2, CH_4, and N_2O for combustion of fossil fuels and N_2O for combustion of hydrogen. Each GHG has a specific fuel dependent emission factor and a unique GWP as shown in Table 1. The emissions for each of CO2, CH_4, and N_2O are multiplied by their respective GWP and then summed to obtain the total GHG emissions in units of CO2e.

The second equation (equation 2) calculates the GHG emission reductions in CO2e by subtracting the GHG emissions for hydrogen (either for N_2O from combustion of hydrogen or zero for hydrogen fuel cells) from the GHG emissions for combustion of displaced fossil fuels. The GHG emissions for combustion of hydrogen and for combustion of fossil fuels are both derived from equation 1.

As previously mentioned, for combustion of clean renewable hydrogen with GHG comprised entirely of N_2O, since the GWP 20 and GWP 100 for N_2O are both 273, the expected impacts in both short term and long term should be similar.

The total emissions were calculated by summing totals for each equipment type and are shown in Table 14. Figures 7A and 7B provide graphs for the Angeles Link Low and High Throughput Scenarios, respectively below. The GHG reductions estimated for the Low Throughput Scenario in 2045 are equivalent to 206,101 homes' electricity use for one year per EPA Calculator. The GHG reductions estimated for the High Throughput Scenario in 2045 are equivalent to 735,486 homes' electricity use for one year per EPA Calculator. Detailed information is available in the excel spreadsheets found in Appendix C.

Table 14
Power Generation GHG Combustion Emission Reductions Associated with Angeles Link Throughput Scenarios (million MT CO2e/yr)

Throughput Scenario	2030	2035	2040	2045
Low	0.12	0.16	0.50	1.06
High	0.41	0.58	1.79	3.78

Table 14 offers a detailed account of the projected GHG emission reductions within the power generation sector under the Angeles Link Throughput Scenarios. For the Low Throughput Scenario, the table shows a ten-fold increase in GHG reductions over time, starting at 0.12 million MT CO2e in 2030 and increasing to 1.06 million MT CO2e by 2045. In the High Throughput Scenario, the GHG emission reductions begin at 0.41 million MT CO2e in 2030 and ramping up to 3.78 million MT CO2e by 2045.

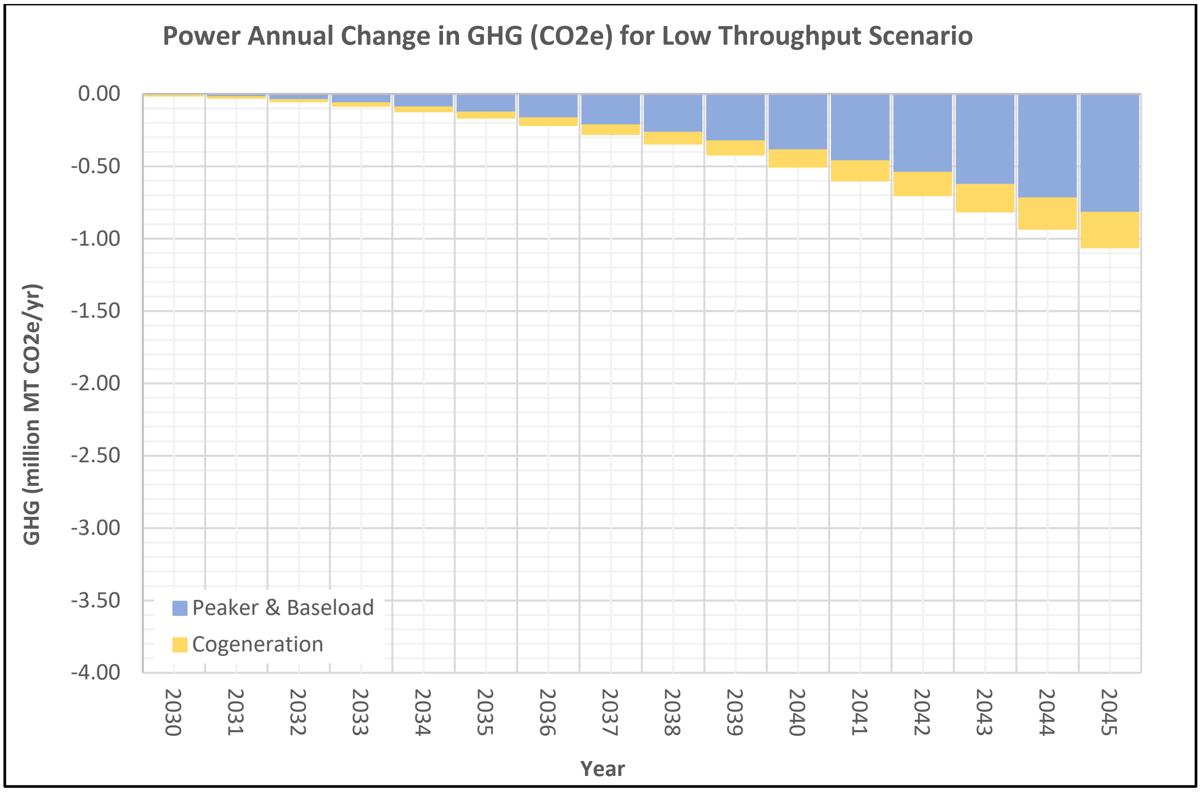

Figure 7A. Power Annual Change in GHG for Angeles Link - Low Throughput Scenario

Figure 7A displays the expected annual reductions in GHG emissions for the Power sector from 2030 to 2045. The stacked bars depict a significant year-over-year decrease in GHG emissions. This visualization highlights the large-scale impact of transitioning to hydrogen-fueled power generation, with cogeneration units also showing notable reductions. The clear decline in emissions over the years signifies the increasing role of clean hydrogen in achieving emissions targets within the Power sector.

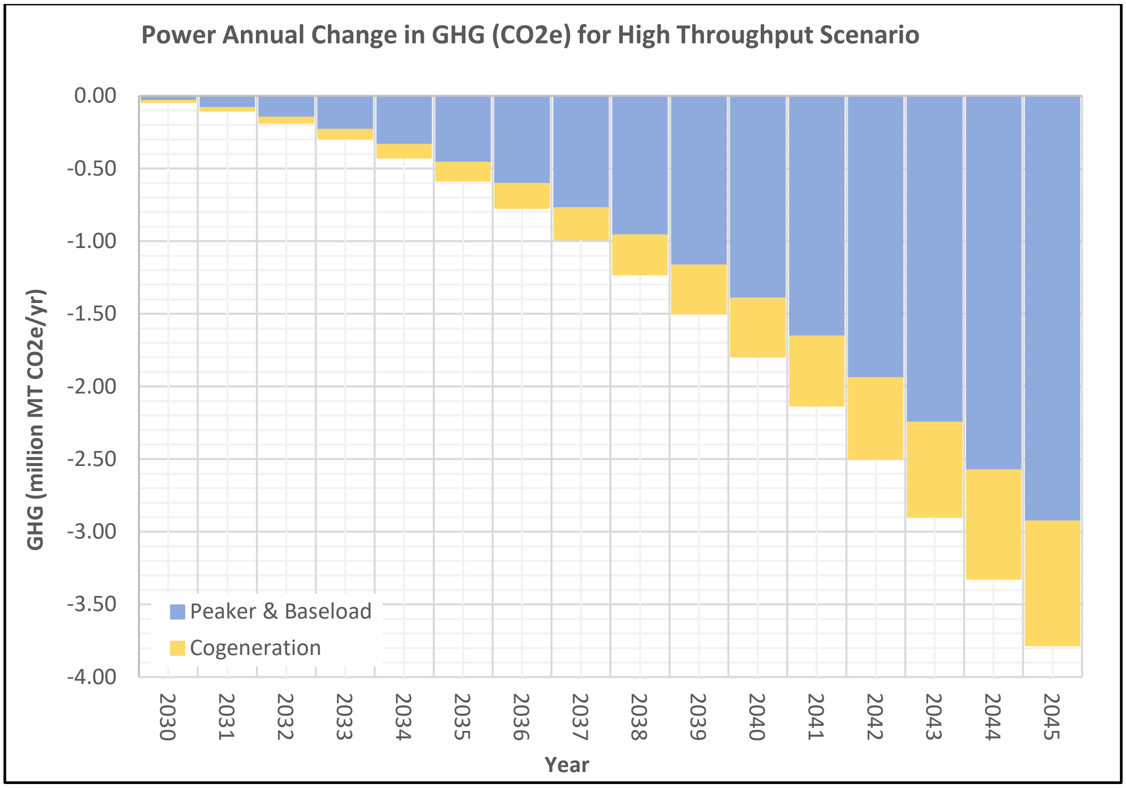

Figure 7B. Power Annual Change in GHG for Angeles Link - High Throughput Scenario

In Figure 7B, the estimated GHG reductions are showcased for the power sector with a less aggressive but steady transition towards hydrogen. The peaker baseload and cogeneration are again represented, showing a consistent trend of decreasing emissions over time. The color coding of the bars clearly shows the contributions from each type of generation unit to the overall reduction, with a trajectory pointing towards a significant environmental benefit by 2045. The chart underlines the potential of hydrogen to substantially lower GHG emissions even with lower adoption rates, indicating the effectiveness of hydrogen as a clean alternative to fossil fuels in Power generation.

7.2.3 Hard to Electrify Industrial

The draft results for the anticipated GHG emissions reductions associated with the Industrial sector based on the Angeles Link Low and High Throughput Scenario data in 2045 are that the Industrial sector accounts for 4% and 8% of overall GHG emissions reductions, respectively. The assumptions that were applied to develop the GHG emissions calculations include that hydrogen will displace natural gas as a fuel with increasing amounts over time (from 2030 to 2045). It should be noted that consistent with the Decision, Angeles Link is intended to transport clean renewable hydrogen, and any analysis of hydrogen blending refers strictly to “behind-the-meter” operations, not within SoCalGas control. This Study does not dictate if end users will blend hydrogen with natural gas and makes assumptions regarding adoption rates based on currently available information regarding equipment and the anticipated evolution of adoption over time. Since only 100% clean renewable hydrogen will be delivered, to estimate GHG reductions at end users, assumptions regarding hydrogen adoption rates were made as shown in Tables 2A and 2B. The estimated emissions are based on these assumptions.

The potential for leakage at hard to electrify industrial end users such as when hydrogen is transferred from onsite storage or distribution to onsite hydrogen combustion equipment is acknowledged but was not quantified as part of this study.

For each emission source type identified, calculations to estimate emissions were prepared using the same two equations previously mentioned.

*Fuel Throughput x Emissions Factor * GWP = GHG Emissions (equation 1)*

GHG Emission Reductions = Fossil Fuel GHG Emissions – Hydrogen GHG Emissions (equation 2)

The first equation (equation 1) multiplies the quantity of fuel by the GHG emission factor specific to the fuel for each GHG pollutant. These pollutants are CO_2, CH_4, and N_2O for combustion of fossil fuels and N_2O for combustion of hydrogen. Each GHG has a specific fuel dependent emission factor and a unique GWP as shown in Table 1. The emissions for each of CO_2, CH_4, and N_2O are multiplied by their respective GWP and then summed to obtain the total GHG emissions in units of CO2e.

The second equation (equation 2) calculates the GHG emission reductions in CO2e by subtracting the GHG emissions for hydrogen (either for N_2O from combustion of hydrogen or zero for hydrogen fuel cells) from the GHG emissions for combustion of displaced fossil fuels. The GHG emissions for combustion of hydrogen and for combustion of fossil fuels are both derived from equation 1.

As previously noted, for combustion of clean renewable hydrogen with GHG emissions comprised entirely of N_2O, since the GWP 20 and GWP 100 for N_2O are both 273, the expected impacts in both short term and long term should be similar.

Total emissions were calculated by summing totals for each equipment type and are shown in Table 15. Figures 8A and 8B provide graphs for the Angeles Link Low and High Throughput Scenarios, respectively below. The GHG emissions reductions predicted for the Low Throughput Scenario in 2045 are equivalent to about 35,500 homes' electricity use for one year per EPA Calculator. The GHG emissions reductions predicted for the High Throughput Scenario in 2045 are equivalent to about 144,000 homes' electricity use for one year per EPA Calculator. Detailed information is available in the excel spreadsheets found in Appendix C.

Table 15 Hard-to-Electrify Industrial GHG Combustion Emission Reductions Associated with Angeles Link Throughput Scenarios (million MT CO2e/yr)				
Throughput Scenario	**2030**	**2035**	**2040**	**2045**
Low	0.075	0.12	0.15	0.18
High	0.29	0.48	0.62	0.73

Table 15 quantifies the GHG emission reductions within the industrial sector influenced by the Angeles Link project under Low and High Throughput Scenarios. Starting in 2030, the Low Scenario estimates a reduction of 0.75 million MT CO2e, with a steady increase over time, reaching 0.18 million MT CO2e by 2045. The High Scenario projects more substantial reductions beginning at 0.29 million MT CO2e in 2030 and culminating at 0.73 million MT CO2e in 2045.

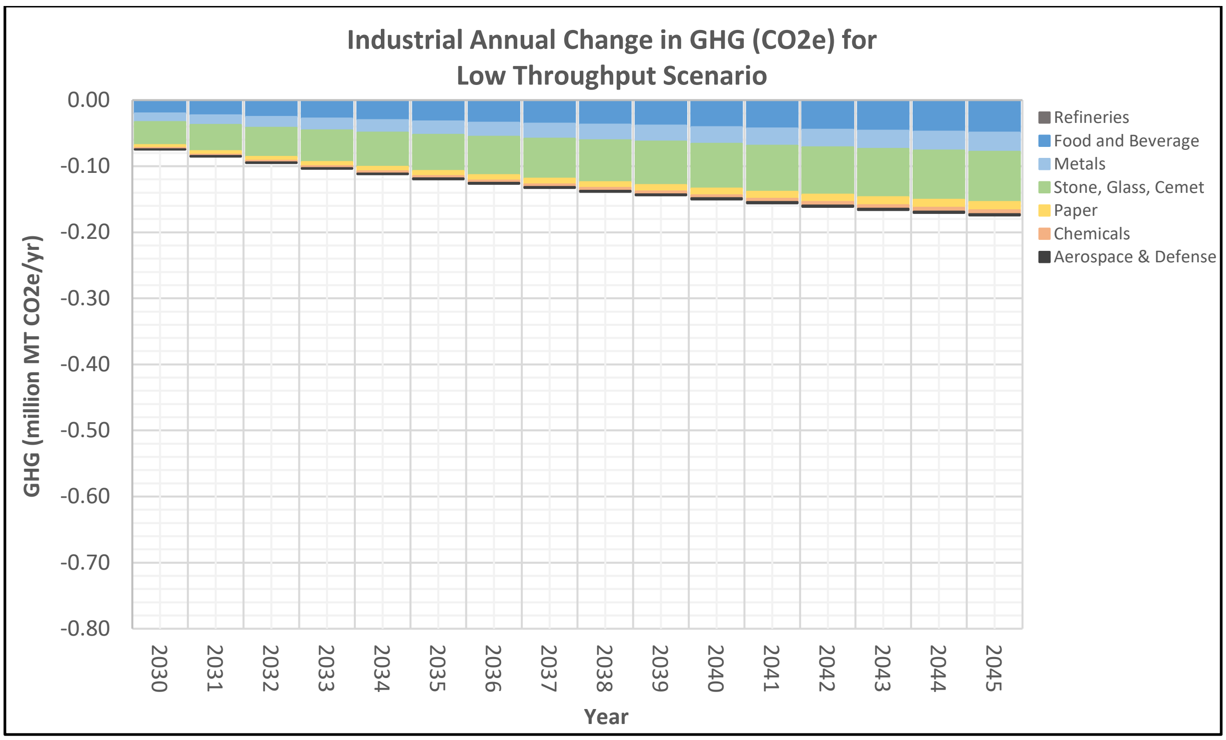

Figure 8A. Industrial Annual Change in GHG for Angeles Link - Low Throughput Scenario

Figure 8A depicts significant yearly reductions in GHG emissions across various industrial subsectors from 2030 to 2045. The largest decreases are seen in the refineries and the metals sectors, shown by the deepest layers in the chart. As years progress, GHG emissions continue to fall, reflecting the increased adoption of hydrogen as a clean fuel alternative to natural gas, particularly in energy-intensive industries. By 2045, the emissions reduction is most pronounced, demonstrating the cumulative effect of the transition to hydrogen in high-demand scenarios.

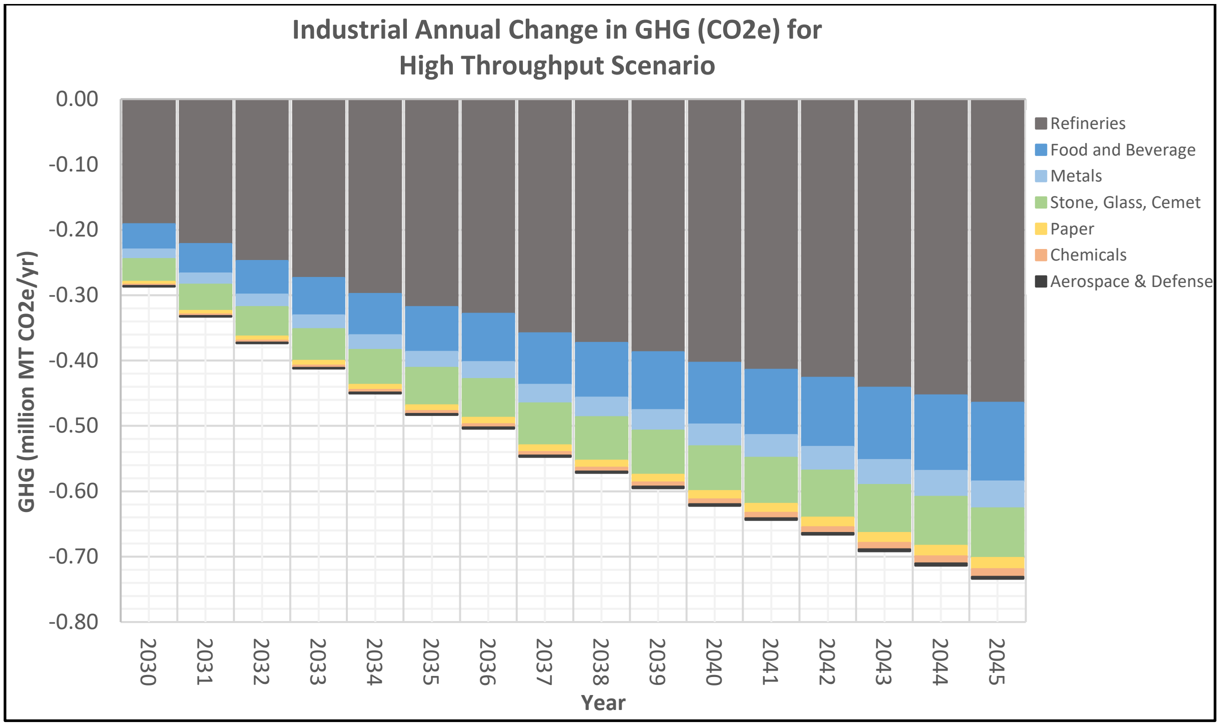

Figure 8B. Industrial Annual Change in GHG for Angeles Link - Low Throughput Scenario

Figure 8B illustrates a conservative yet steady decline in GHG emissions within the industrial sector over the same period. In this scenario, refineries, food and beverage, and metals are also leading contributors to GHG reductions. Although the overall decrease in emissions is less aggressive than in the high throughput scenario, the continued year-over-year reductions indicate that even with a lower rate of hydrogen adoption, the industrial sector can achieve meaningful emissions reductions.

8 OVERALL RESULTS FOR ANGELES LINK THROUGHPUT SCENARIOS

Anticipated potential minor GHG emissions associated with new hydrogen infrastructure were added to the potential large anticipated GHG emissions reductions associated with potential end users of hydrogen as defined by the Demand Study. The total GHG emissions reductions projected for the Low Throughput Scenario in 2045 for end-users are equivalent to more than 874,000 homes' electricity use for one year per EPA Calculator. The total GHG emissions reductions predicted for the High Throughput Scenario in 2045 for end-users are equivalent to more than 1,760,000 homes' electricity use for one year per EPA Calculator. The results are provided in Table 16 and in Figures 9A and 9B below. Detailed information is available in the excel spreadsheets found in Appendix C.

In summary:

- Projected about 4.5 and 9 million metric tons of CO2e per year removed from SoCalGas territory geographic area by end users by 2045 in Angeles Link Low and High Throughput Scenarios.
- Projected new infrastructure GHG emissions are significantly smaller than end-user reductions.
    - The highest potential infrastructure GHG emissions estimated are 0.17% and 0.25% the magnitude of overall end-user reductions for Angeles Link Low and High throughput scenarios, respectively.
- Mobility GHG emissions are almost entirely eliminated with hydrogen substitution when fossil fuels are replaced with hydrogen fuel cells.
    - Mobility comprises 72.5% and 50.3% of overall GHG reductions for Angeles Link Low and High throughput scenarios, respectively.
- Industrial and Power Generation GHG emissions are almost entirely eliminated when fossil fuels are replaced by hydrogen as a fuel in combustion equipment.
    - Power generation comprises 23.6% and 41.7% of overall GHG emissions reductions for Angeles Link Low and High throughput scenarios, respectively.
    - Industrial comprises 3.9% and 8.1% of overall GHG emissions reductions for Angeles Link Low and High Throughput Scenarios, respectively.

Table 16 Annual Change in GHG Emissions for Angeles Link Throughput Scenarios (MT CO2e/yr)					
Category	**Throughput Scenario**	**2030**	**2035**	**2040**	**2045**
End-Users	Low	-338,689	-1,306,066	-2,755,894	-4,491,919
	Mid	-859,849	-2,473,978	-4,878,512	-7,767,819
	High	-1,453,026	-3,358,957	-5,957,517	-9,073,521
Infrastructure	Max - Low	528	2,096	4,501	7,655
	Max - Mid	1,318	4,159	8,608	14,456
	Max - High	4,206	8,709	14,854	22,292
	Min - Low	0	0	0	0
	Min - Mid	0	0	0	0
	Min - High	0	0	0	0
Total	Low	-338,161	-1,303,970	-2,751,393	-4,484,264
	Mid	-858,531	-2,469,812	-4,869,898	-7,753,363
	High	-1,448,820	-3,350,248	-5,942,663	-9,051,228

Table 16 reflects the changes in GHG emissions due to the Angeles Link project, which indicate a significant decline in emissions from end-users, particularly in the High scenario with nearly 9 million MT CO2e reduction by 2045. These figures represent a shift toward cleaner energy and indicate a major potential for emissions reduction through clean renewable hydrogen adoption. Infrastructure-related emissions, while present, are minimal compared to the gains from end-user reductions.

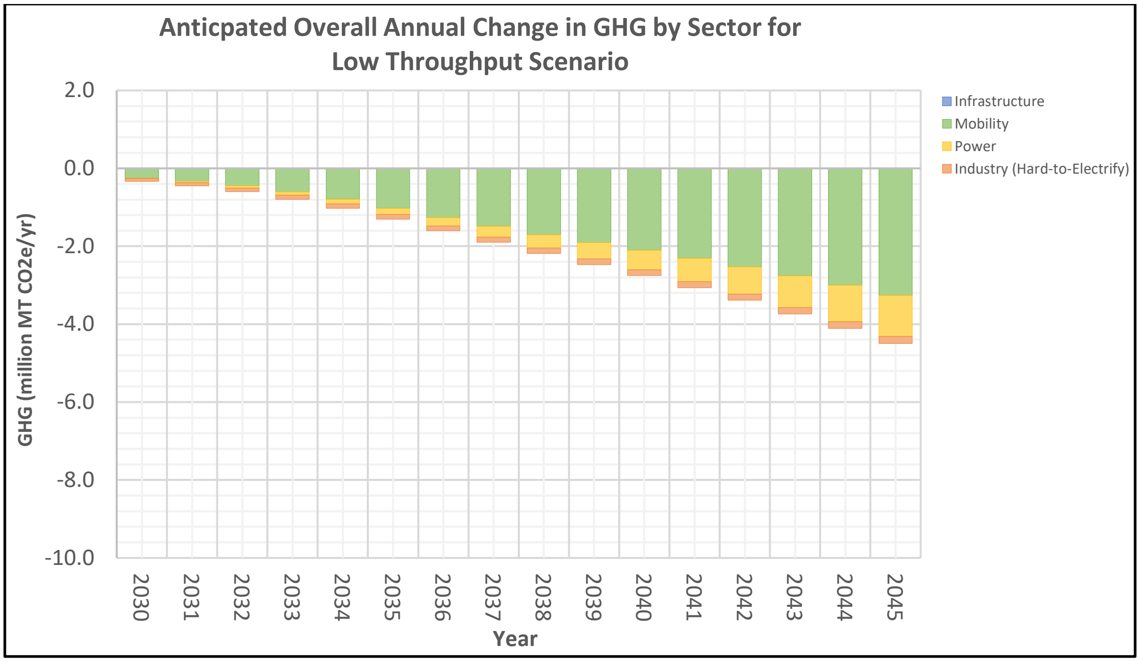

Figure 9A. Annual Change in GHG for Angeles Link - Low Throughput Scenario

In Figure 9A featuring the High Throughput Scenario, the stacked bar chart demonstrates a substantial decline in GHG emissions across all sectors, with the Mobility sector leading the reductions, followed by Power, and with Industry having the least, yet still notable GHG emission reductions. This visualizes a strategic and impactful cut in emissions through hydrogen adoption, especially in the Mobility sector.

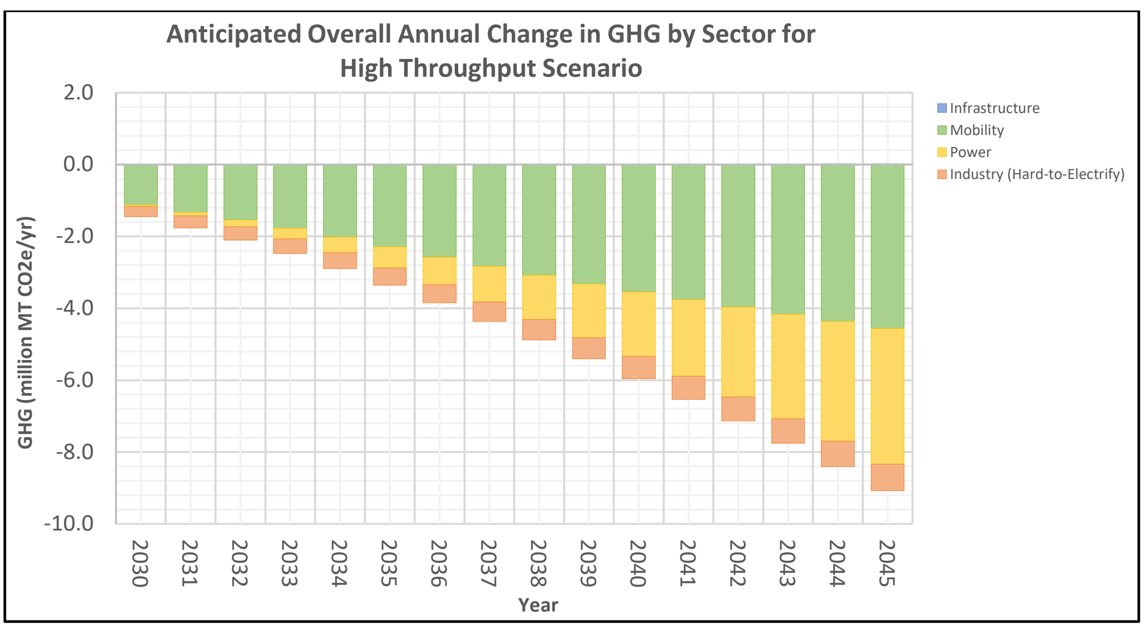

Figure 9B. Annual Change in GHG for Angeles Link - Low Throughput Scenario

In Figure 9B, for the Low Throughput Scenario, the trend is similar but with smaller reductions. Mobility still shows the most considerable decline, underscoring the role of cleaner transportation methods in reducing overall emissions. The consistent year-over-year decrease in all sectors reaffirms the value of even modest shifts toward clean renewable hydrogen for a significant environmental benefit.

9 Hydrogen Leakage Impact to GHG Reductions

This Study broadens its scope to address concerns raised by stakeholders regarding hydrogen leakage, which represents a risk factor that could reduce a small percentage of the overall expected GHG reductions projected for Angeles Link. Addressing both direct and indirect GHG emissions, as raised by stakeholders, is essential for accurately assessing hydrogen's overall effectiveness as a means to achieve GHG reductions.

9.1 HYDROGEN AS INDIRECT GHG EMISSIONS

As outlined earlier in this document, this draft GHG report specifically estimates potential direct emissions of greenhouse gases such as CO_2, CH_4, and N_2O that can occur during fossil fuel or hydrogen combustion. It is important to note that hydrogen is not classified as a direct greenhouse gas by leading environmental organizations and governing bodies, including CARB, EPA, or the IPCC, due to the absence of globally recognized warming potentials. The research on global warming potential of hydrogen is evolving and there is not yet consensus among academic, regulatory, and climate organizations on the extent of the global warming impact of hydrogen. However, some analytical studies using atmospheric chemistry models estimate that hydrogen, if emitted to the atmosphere, will have an indirect global warming effect.[88]

Similar to methane, hydrogen's climate impacts are short-lived, with near-term climate change impacts from hydrogen expected to be 3 to 8 times higher than long-term impacts. Additionally, hydrogen's indirect impact on methane in the atmosphere results in a longer atmospheric lifetime for methane which could result in climate effects for about 10 years longer.[89]

Hydrogen's global warming impact may be caused by increasing methane residence time in the atmosphere, increasing production of tropospheric ozone (O_3) and altering stratospheric O_3, increasing the production of stratospheric water vapor, and changing the production of some aerosols.[90] These impacts are largely driven by the reaction of hydrogen and OH to form H_2O and H. OH is an atmospheric sink for methane and other atmospheric compounds.

Hydrogen combustion primarily results in the production of water vapor and very small amounts of N_2O may indirectly result from the nitrogen present in the combustion air at specific temperatures. While water vapor is a greenhouse gas due to its ability to trap heat in the atmosphere, hydrogen combustion does not directly emit carbon-based greenhouse gases like CO_2 or CH_4, because hydrogen lacks carbon content. Therefore, the climate-related concerns

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[88] Bertagni, M.B., Pacala, S.W., Paulot, F. et al. Risk of the hydrogen economy for atmospheric methane. Nat Commun 13, 7706 (2022). https://doi.org/10.1038/s41467-022-35419-7

[89] Ocko, Ilissa & Hamburg, Steven. (2022). Climate consequences of hydrogen emissions. Atmospheric Chemistry and Physics, 2022. https://acp.copernicus.org/articles/22/9349/2022/

[90] Bertagni, M.B., Pacala, S.W., Paulot, F. et al. Risk of the hydrogen economy for atmospheric methane. Nat Commun 13, 7706 (2022). https://doi.org/10.1038/s41467-022-35419-7

associated with hydrogen primarily stem from its indirect effects rather than direct emissions. Key indirect effects of hydrogen combustion include:

- **Hydroxyl Radical Reduction:** Hydrogen can lower the concentration of hydroxyl radicals (OH) in the atmosphere. These radicals play a crucial role in breaking down methane, a significant greenhouse gas. When the levels of hydroxyl radicals are reduced, methane's atmospheric lifetime increases, which in turn amplifies its warming effect on the climate.
- **Ozone Formation:** When hydrogen is emitted, it can react with other compounds in the atmosphere under the influence of sunlight, leading to the formation of tropospheric ozone. This substance is not only a potent greenhouse gas but also a harmful air pollutant, contributing further to climate change.
- **Water Vapor Impact:** The oxidation of hydrogen leads to an increase in stratospheric water vapor, which can intensify the greenhouse effect. However, the impact of this increase is highly variable and complex to model accurately due to the intricate dynamics of the atmosphere.

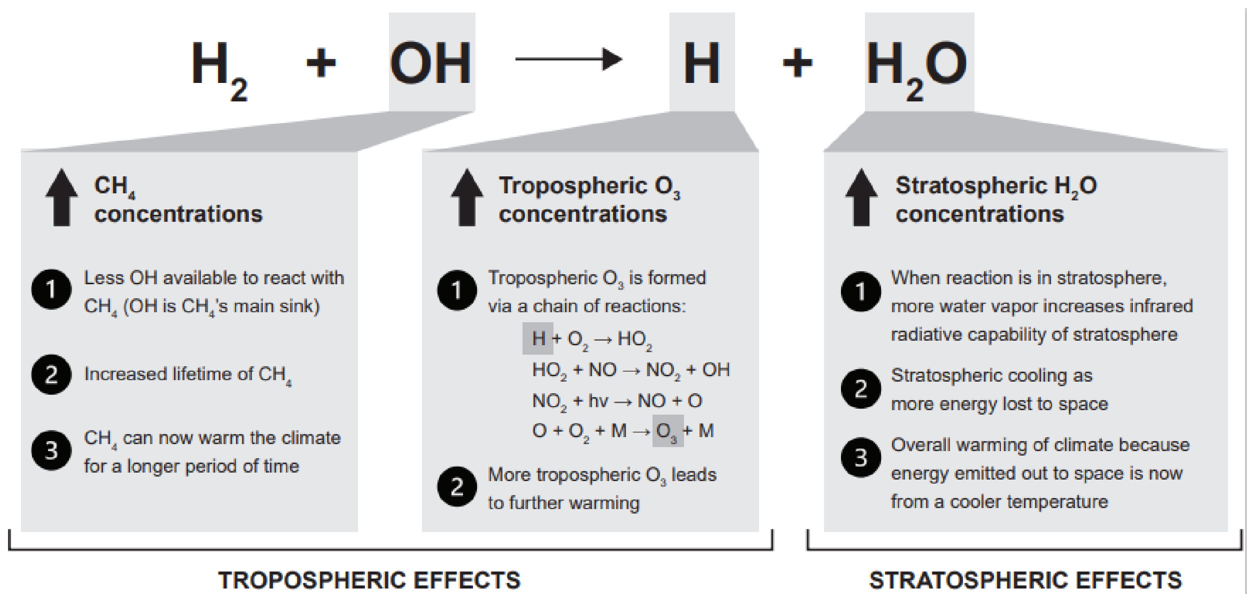

Figure 10. Estimated tropospheric and stratospheric effects of hydrogen

As shown in Figure 10[91], scientific literature has identified potential climate impact considerations: 1) reduction in available hydroxyl radicals to react with methane, potentially prolonging methane's lifetime in the atmosphere; 2) increased tropospheric concentrations of ozone; and 3) increased concentrations of water vapor.

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[91] Ocko, Ilissa & Hamburg, Steven. (2022). Climate consequences of hydrogen emissions. Atmospheric Chemistry and Physics, 2022. https://acp.copernicus.org/articles/22/9349/2022/

Research on hydrogen's global warming potential has evolved, with key findings consolidated in recent studies.[92] [93] Derwent's March 2023 article in the International Journal of Hydrogen Energy standardized earlier research, narrowing hydrogen's GWP to 7.1 to 9.3 over 100 years.[94] In contrast, Sand et al.'s June 2023 study, using five atmospheric chemistry models, proposed a GWP of 11.6 ± 2.8, focusing on emissions and potential infrastructure leakages.[95] This study highlighted the higher GWPs projected over shorter, 20-year horizons.[96] Notably, green hydrogen[97] could reduce GWPs by over 95% compared to fossil fuels over 20 to 100 years, based on leakage rates of 1 to 3%.[98] The primary uncertainties in developing a GWP for hydrogen continue to be the lack of data around the removal rate of atmospheric hydrogen by soil and potential future changes in atmospheric concentrations of other GHG such as methane.[99]

Table 17 presents a range of GWP values for hydrogen from various studies. These values can be used for developing effective GHG emission rates for hydrogen leakage as CO_2e.

- GWP100 Range of Estimates: This column lists the GWP for a 100-year time horizon, which is the standard measure used to compare the impacts of different GHGs. The "+/-" values indicate the uncertainty or range in these estimates.
- GWP20 Range of Estimates: This column provides GWP values for a 20-year time horizon, which highlights the short-term climate impact of the gases. Not all studies provide a 20-year GWP.

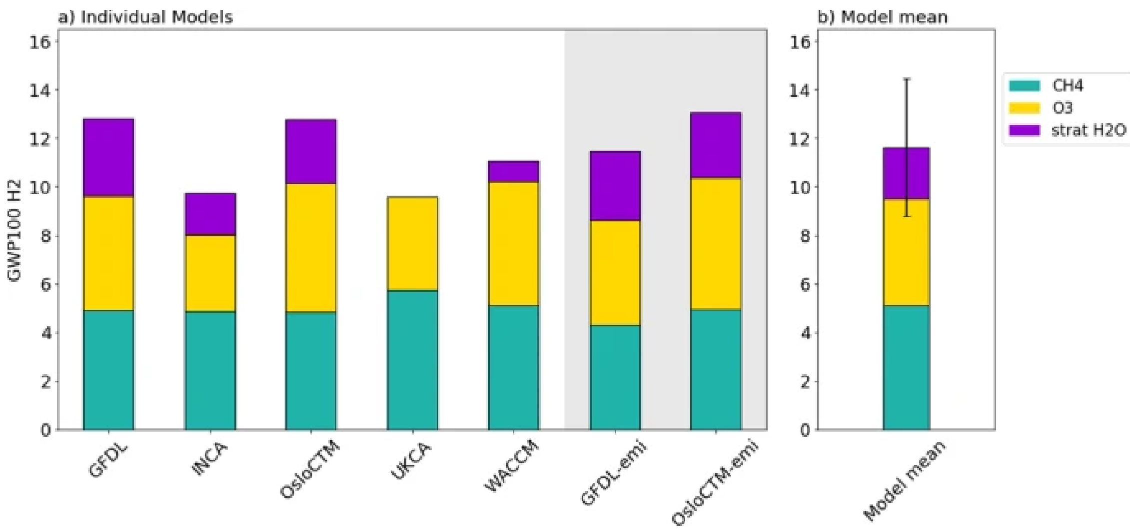
[92] Derwent, R.G. et al. 2020, Global modelling studies of hydrogen, Ibid
[93] Field, R.A. and Derwent 2021, Global warming consequences, Ibid
[94] Derwent, R.G. et al. 2020, Global modelling studies of hydrogen, Ibid
[95] Sand, M. et al. 2023 Ibid
[96] Paulot F., D. Paynter, V. Naik, S. Malyshev, R. Menzel, L. W. Horowitz, Global modeling of hydrogen using GFDL-AM4.1: Sensitivity of soil removal and radiative forcing, International Journal of Hydrogen Energy, 46, Issue 24, 2021. 13446-13460, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2021.01.088
[97] Green hydrogen defined as produced by electrolysis using renewable electricity.
[98] Hauglustaine, D., F. et al, 2022, Climate benefit, Ibid
[99] Sun, Tianyi, et al. "Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales." Environmental Science & Technology, American Chemical Society, Feb. 2024, https://doi.org/10.1021/acs.est.3c09030

Table 17 Summary of GWP 20 and GWP 100 Estimates for Hydrogen			
GWP100 Range of Estimates	**GWP20 Range of Estimates**	**Date of Article**	**Article Authors**
5 +/- 1	---	January 2020	R. G. Derwent, et al
3.3 +/- 1.4	---	August 2021	R.A. Field, R.G. Derwent
12.8 +/- 5.2	40.1 +/- 24.1	November 2022	D. Hauglustaine, et al
8 +/- 2	---	March 2023	R. G. Derwent
11.6 +/- 2.8	**37.3 +/- 15.1**	**June 2023**	**M. Sand et al**
11.5 +/- 6	34.8 +/- 19	October 2023	N. J. Warwick, et al

Understanding Multi-model Assessments of the Global Warming Potential of Hydrogen

To demonstrate that a number of data sources are typically evaluated to develop the values shown in Table 17 above, one row was selected (highlighted) and a deep-dive into the data was performed. For the row with the information from M. Sand et al. in June 2023[100], the authors evaluated the following information to develop the result in the study which estimates hydrogen's GWP100 to be 11.6, with a standard deviation of ±2.8 as shown in Table 17 above.

[100] Sand, M., R.B. Skeie, M. Sandstad, S. Krishnan, G. Myhre, H. Bryant, R. Derwent, D. Hauglustaine, F. Paulot, M. Prather and D. Stevenson, 2023, A multi-model assessment of the Global Warming Potential of hydrogen, Communications Earth & Environment V.4 Article number: 203, https://doi.org/10.1038/s43247-023-00857-8



GFDL Geophysical Fluid Dynamics Laboratory Model	**OSLOCTM** Oslo Chemical Transport Model
The **GFDL** model operates with a resolution of approximately 100 km and 49 vertical levels. This model conducts experiments focused on meteorological aspects with a set of experiments that involve a control run with fixed H2 and CH4 concentrations, and several scenarios with different levels of increased H2 and CH4 concentrations. It uses its own meteorology for simulations which are conducted over a period of 20 years, focusing on atmospheric dynamics and climate processes. The **GFDL-emi** is a variant with a specific focus on emission scenarios. It retains the same resolution and vertical levels as the GFDL model but explores the impacts of increased H2 emissions (200 Tg yr−1) along with a significant increase in CH4 concentrations. This model's experiments span 50 years, making it particularly valuable for studying long-term climatic effects of emission changes.	**OsloCTM** features a resolution of roughly 2.25° x 2.25° with 60 vertical levels and conducts experiments under fixed H2 concentrations, along with increased H2 and CH4 scenarios. This model, using ECMWF OpenIFS 3 hr forecast data for meteorology, covers 20 years, **focusing** on the transport and transformation of chemical species in the atmosphere. The **OsloCTM-emi** similarly maintains the same resolution and vertical levels and includes a scenario with increased H2 emissions (14 Tg yr−1). Its experiments also focus on the interaction between these emissions and atmospheric chemistry, using the same meteorological data and spanning 25 years.
INCA Interactive Chemistry and Aerosols	**UKCA** United Kingdom Chemistry and Aerosols
The **INCA** model utilizes a resolution of 2.5° × 1.25° with 39 vertical levels. It focuses on interactive chemistry, conducting experiments on present-day control scenarios with fixed H2 concentrations and simulations examining increases in H2 and CH4. INCA uses ECMWF OpenIFS 3 hr forecast data for meteorology and spans 20 years in simulation, emphasizing atmospheric chemistry and climate interactions.	The **UKCA** model operates with a resolution of 1.250° × 1.875° and 85 vertical levels. It performs experiments involving fixed H2 concentrations and a 10% increase in H2 and CH4 concentrations. The UKCA uses its own meteorology and runs simulations for 18 years, focusing on the study of atmospheric chemistry, aerosols, and their impact on climate.
WACCM Whole Atmosphere Community Climate Model	
WACCM6 utilizes a resolution of 1.875° × 2.5° with 88 vertical levels and conducts experiments focusing on fixed H2 concentrations, and a 10% increase in both H2 and CH4 concentrations. It uses its own meteorological data and its simulation covers 20 years, integrating atmospheric chemistry with climate dynamics to model the whole atmosphere comprehensively.	

The article "Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales,"[101] published recently in Environmental Science & Technology, explores the complexities surrounding the assessment of climate impacts associated with hydrogen energy systems. The article discusses the global warming potential of hydrogen over shorter periods, driven by its indirect effects on methane, tropospheric ozone, and stratospheric water vapor. Two methods were used to quantify the relative climate impacts of the pathway for hydrogen as compared to that of the fossil fuels being replaced. The first is technology warming potential (TWP)[102] which compares the cumulative radiative forcing from continuous emissions for the two pathways considering 10, 20, 50, and 100 year timeframes. The second method is a comparison of the total emissions in CO2e using GWP for the 20 and 100 year time scales. The results indicate that green hydrogen pathways consistently reduce warming impacts from fossil fuel technologies by more than 60% for all time scales regardless of emission rate; and when emission rates are around 1%, the climate benefits jump to greater than 90%. The article also mentions that displacement of fossil fuels with hydrogen may reduce other co-emitted pollutants such as carbon monoxide (CO) and N_2O and volatile organic compounds (VOC) that are indirect GHGs that impact atmospheric chemistry. Finally, the article advocates for broader temporal analysis in climate impact assessments to capture both long-term and significant near-term effects and emphasizes the need for comprehensive assessments in hydrogen technology deployment to accurately evaluate its role in decarbonization strategies.

The EDF blog post[103] “New research reaffirms hydrogen’s impact on the climate, provides consensus,” discusses that maintaining leakage of hydrogen at a minimum will depend on technological advancements related to direct measurement technologies that detect even small leaks. Minimal leakage will support the full advantages of the benefits of switching from fossil fuels to hydrogen.

The article "Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales"[104] also highlights hydrogen's potential for leakage. Additionally, the article "Wide Range in Estimates of Hydrogen Emissions

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[101] Sun, Tianyi, et al. “Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales.” Environmental Science & Technology, American Chemical Society, Feb. 2024, https://doi.org/10.1021/acs.est.3c09030

[102] Alvarez, R. A., Pacala, S. W., Winebrake, J. J., Chameides, W. L., and Hamburg, S. P. (2012). Greater focus needed on methane leakage from natural gas infrastructure. PNAS 109, 6435–6440. doi:10.1073/pnas.1202407109

[103] Ocko. I and S. Hamburg, EDF Blog, July 19, 2023, New research reaffirms hydrogen’s impact on the climate, provides consensus, https://blogs.edf.org/energyexchange/2023/07/19/new-research-reaffirms-hydrogens-impact-on-the-climate-provides-consensus/

[104] Sun, Tianyi, et al. “Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales.” Environmental Science & Technology, American Chemical Society, Feb. 2024, https://doi.org/10.1021/acs.est.3c09030

from Infrastructure,"[105] published in Frontiers and recommended by stakeholders, notes that emission rates can vary widely across different components of the value chain, such as transmission and distribution pipelines and storage systems, reflecting significant variability.

The recent National Petroleum Council (NPC) Report[106] mentions that initial research shows that hydrogen leakage across the global value chain could reduce the climate benefits of hydrogen with greater climatic impact in the near term. Specifically, the report indicates that recent studies suggest that every 1% of value chain hydrogen leakage would reduce the climate benefit by 1.2% to 4.2% in the near term (20 years) and 0.4% to 1.3% in the long-term (100 years). The Report also suggests that to completely understand the climate impacts of hydrogen leakage, highly sensitive hydrogen direct measurement tools that are not yet widely available are needed to quantify leakage at real world facilities.

The article "Global modeling of hydrogen using GFDL-AM4.1: Sensitivity of soil removal and radiative forcing," mentions that hydrogen is the second most abundant reactive trace gas in the atmosphere with a global mean concentration of approximately 530 ppbv. Source of hydrogen are approximately 30% from fossil fuel combustion and 55% from formaldehyde photolysis. Over 80% of hydrogen removal from the atmosphere is attributed to soil uptake.[107]

Collectively, these studies underscore the importance of a comprehensive temporal analysis of GHG emissions from hydrogen sources. They advocate for the integration of these findings into policy and commercial decisions to minimize hydrogen's climate footprint. This includes designing infrastructure to minimize the potential for leakage and GHG emissions, enhancing the accuracy of direct hydrogen measurements, and expanding estimation methodologies to include short-term and long-term impacts. The ongoing research efforts are crucial for refining our understanding of hydrogen's role in climate dynamics and developing robust strategies to manage its emissions in the context of global climate goals. Given the variability observed across these models, scholarly research stresses the critical need for stringent controls on hydrogen leakage during its production, storage, and transport processes to mitigate its unintended climatic effects. These implications are being carefully considered and opportunities to minimize the potential for leakage is discussed in the parallel Phase One Leakage Study.

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[105] Alvarez, R. A., Pacala, S. W., Winebrake, J. J., Chameides, W. L., and Hamburg, S. P. (2012). Greater focus needed on methane leakage from natural gas infrastructure. PNAS 109, 6435–6440. doi:10.1073/pnas.1202407109

[106] National Petroleum Council, April 23, 2024, "Harnessing Hydrogen: A Key Element of the U.S. Energy Future https://harnessinghydrogen.npc.org/downloads.php

[107] Paulot F., D. Paynter, V. Naik, S. Malyshev, R. Menzel, L. W. Horowitz, Global modeling of hydrogen using GFDL-AM4.1: Sensitivity of soil removal and radiative forcing, International Journal of Hydrogen Energy, 46, Issue 24, 2021. 13446-13460, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2021.01.088

9.2 HYDROGEN LEAKAGE IMPACT ON PROJECTED OVERALL GHG EMISSIONS REDUCTIONS

In response to stakeholder input, the parallel Draft Leakage Study Report provides a high-level estimate of potential leakage scenarios for general hydrogen infrastructure and for anticipated Angeles Link infrastructure. This estimation remains preliminary as detailed design and engineering data is not yet available for either the general or Angeles Link infrastructure.

9.2.1 General Infrastructure

For general infrastructure, the Draft Leakage Study Report compiles leakage data across various stages of hydrogen infrastructure—including production, compression, aboveground storage, underground storage, and transmission—utilizing 25 distinct data points. From this compilation, a median leakage rate of 0.24% and an average rate of 0.92% were identified. These rates were then applied to estimate potential leakage across low, medium, and high throughput scenarios for Angeles Link. This modeling provides an initial quantitative framework for understanding potential losses due to leakage, albeit with uncertainty pending further infrastructure specification and development.

The Draft Leakage Study Report provides high-level estimates of potential hydrogen leakage. These estimates range from 1,200 MT/yr for the low demand scenario using the median leakage estimate to 13,800 MT/yr for the high demand scenario using the average leakage estimate.

To estimate the potential impact to climate change, a conservative method is used involving the range of estimated volumetric leakage rates, as well as the range of effective GWP 100 estimated for hydrogen from existing scientific studies. For the purposes of this analysis, the estimated amounts are assumed to be equivalent to GHG emissions. This assumption allows for evaluating the potential environmental impact relative to the GHG emission reduction estimates discussed in this Draft GHG Study Report.

The Global Warming Potentials for hydrogen are used to convert the amount of leaked hydrogen into CO_2e. The GWP values specifically for a 100-year horizon range from 1.9 to 18, according to different studies summarized in Table 17. Using these GWP values, the potential GHG impact from leakage is calculated as follows:

- Lower Estimate: 1,200 MT/yr of hydrogen x 1.9 (minimum GWP100) = 2,280 MT CO_2e/yr
- Upper Estimate: 13,800 MT/yr of hydrogen x 18 (maximum GWP100) = 248,400 MT CO_2e/yr

These GHG values, ranging from 2,280 MT CO_2e/yr to 248,400 MT CO_2e/yr, are then compared to the projected overall GHG reductions from the project (end-user reductions minus infrastructure emissions), which are estimated at 9.0 million MT/yr (as shown in Table ES-1). This comparison shows that the impact of hydrogen leakage on the overall GHG reductions ranges from about 0.03% to 2.8%. In other words, this high-level methodology indicates that the impact from combustion associated with new hydrogen infrastructure to the predicted overall GHG emissions reductions would be very low (i.e., less than 3% for high throughput scenario).

9.2.2 Angeles Link Infrastructure

For Angeles Link infrastructure, the Draft Leakage Study Report compiles leakage data for compression and transmission using 10 distinct data points. From this compilation, a median leakage rate of 0.17% and an average rate of 0.27% were identified. These rates were then applied to estimate potential leakage across low, medium, and high throughput scenarios for Angeles Link. This modeling provides an initial quantitative framework for understanding potential losses due to leakage, albeit with uncertainty pending further infrastructure specification and development.

The Draft Leakage Study Report provides high-level estimates of potential hydrogen leakage. These estimates range from 850 MT/yr for the low throughput scenario using the median leakage estimate to 4,065 MT/yr for the high throughput scenario using the average leakage estimate.

To estimate the potential impact to climate change, a conservative method is used involving the range of estimated volumetric leakage rates, as well as the range of effective GWP 100 estimated for hydrogen from existing scientific studies. For the purpose of this analysis, the estimated amounts are assumed to be equivalent to GHG emissions. This assumption allows for evaluating the potential environmental impact relative to the GHG emission reduction estimates discussed in this Draft GHG Study Report.

The Global Warming Potentials for hydrogen are used to convert the amount of leaked hydrogen into CO_2e. The GWP values specifically for a 100-year horizon range from 1.9 to 18, according to different studies summarized in Table 17. Using these GWP values, the potential GHG impact from leakage is calculated as follows:

- Lower Estimate: 850 MT/yr of hydrogen x 1.9 (minimum GWP100) = 1,615 MT CO_2e/yr
- Upper Estimate: 4,065 MT/yr of hydrogen x 18 (maximum GWP100) = 73,170 MT CO_2e/yr

These GHG values, ranging from 1,615 MT CO_2e/yr to 73,170 MT CO_2e/yr, are then compared to the projected overall GHG reductions from the project (end-user reductions minus infrastructure emissions), which are estimated at 9.0 million MT/yr (as shown in Table ES-1). This comparison shows that the impact of hydrogen leakage on the overall GHG reductions ranges from about 0.02% to 0.8%. In other words, this high-level methodology indicates that the impact to the predicted overall GHG emissions reductions would be very low (i.e., less than 1% for high throughput scenario) when considering the addition of potential GHG emissions from the two leakage sectors evaluated in the parallel Draft Leakage Study Report. Scientific studies indicate that maintaining value chain leakage rates below 1% will increase climate benefits of clean renewable hydrogen to greater than 90%.[108]

As the project progresses, further refinements in infrastructure design, better information from end users, and technological advancements will likely provide more accurate data. This can help in more precisely quantifying the leakage and its impact on overall GHG emissions reductions. Additionally, further studies and data will allow a better understanding of the atmospheric effects of hydrogen, particularly through advanced modeling techniques.

[108] Sun, Tianyi, et al. "Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales." Environmental Science & Technology, American Chemical Society, Feb. 2024, https://doi.org/10.1021/acs.est.3c09030

10 CONCLUSIONS

The draft direct GHG combustion emission estimates were developed from data from both the Demand Study Demand Scenarios and Angeles Link Throughput Scenarios and are set forth in this Study. The draft GHG combustion emission estimates associated with Angeles Link set forth in this study are informative for Phase 1. This study acknowledges that based on available scientific research preliminarily reviewed, there is uncertainty about the potential tropospheric and atmospheric effects associated with leakage of hydrogen. Preliminary high-level estimates indicate that the potential for hydrogen leakage from infrastructure as compared to the overall GHG reductions may range from 0.03% to 2.8%. In other words, this high-level methodology indicates that the impact to the predicted overall GHG emissions reductions (end users minus infrastructure emissions) would be very low (i.e., less than 3% for high throughput scenario). The design details of the hydrogen infrastructure and the Angeles Link infrastructure as the project is further refined, and more details regarding third-party production, third-party storage, and end users, may further inform future quantification estimates of GHG emissions.

10.1 UNCERTAINTY

Global warming potentials from IPCC's AR6 report were utilized to calculate CO2e emissions within this study. While these AR6 values are the most recently published global warming potentials from the IPCC, it is likely that these values will continue to evolve as new science is published. There is uncertainty in how these global warming potential values will change in the future.

10.1.1 Infrastructure

Design of the new hydrogen infrastructure and Angeles Link infrastructure will be refined in future project stages, and as a result assumptions related to transmission of hydrogen, in addition to assumptions regarding third-party production and third-party storage, formed the basis of the GHG emissions estimates. Details regarding the hydrogen production process, and proportions of hydrogen intended to be produced from different methods, if more than one method is used, would reduce the uncertainty with respect to the estimated hydrogen production emissions estimates. Estimates were developed based on hypothetical electrolysis, biomass gasification, and biogas in steam methane reforming scenarios where the combustion equipment is fueled by hydrogen. Details regarding quantity of hydrogen storage, location, and types (above ground versus below ground) of storage will inform refinement of these initial estimates. Additionally, distances and locations (primarily below ground, and above ground where necessary) of transmission pipelines will also provide details to refine the emission estimates. More accurate GHG emissions estimates related to infrastructure can be developed as designs evolve and details emerge.

10.1.2 End Users

As discussed previously in this report, there is a lack of data and clarity around a N_2O emissions factor for hydrogen combustion and therefore uncertainty regarding associated GHG emissions. There are many variables that may affect N_2O formation including different operating modes, lean combustion, control options, and lower combustion temperatures possible with hydrogen. Using a conservative value in these calculations may result in higher N_2O estimates than actual N_2O emissions. The conservative value of 2 ppm was selected for the calculations within this study developed based on information in the literature and incorporation of a margin of safety of 2, by doubling of the value.

There is uncertainty within the correction factor calculation approach for converting a mass basis emissions limitation for natural gas combustion to a mass basis emissions limitation for hydrogen combustion. One source of uncertainty arises from the lack of information around how the fuel type (including blended fuels) impacts the oxygen levels in the exhaust gas, and how that impacts the required oxygen correction factors in the conversion from volumetric to mass emissions for hydrogen combustion exhaust.

There is uncertainty in the correction factor calculation approach for converting natural gas emissions to a representative value for hydrogen. A source of uncertainty in this approach is the lack of information about how oxygen levels in the exhaust gas may vary between natural gas, hydrogen, and blends. In this study, it was assumed that a particular type of equipment combusting natural gas, hydrogen, or a blend would have the same exhaust oxygen concentration for all fuels. In-practice combustion characteristics for hydrogen turbines may result in higher or lower exhaust oxygen concentrations than what is observed in natural gas equipment. If exhaust oxygen concentration is higher for hydrogen than natural gas, emissions from hydrogen will increase compared to what is forecasted in this study.

Fossil fuel displacement volumes for diesel and gasoline from the Demand Study were utilized in the calculations within this study directly as provided for the mobility sector. Natural gas displaced by hydrogen and hydrogen demand projections were provided by the Demand Study and utilized in the calculations within this study as provided for the power generation and hard to electrify industrial sectors.

On-road vehicle GHG emissions factors were developed from the current EMFAC model, and off-road vehicle CO_2 emissions factors were developed from the current EMFAC model, while emissions factors from EPA were utilized for off-road vehicle CH_4 and N_2O emissions. The EMFAC model may be updated in the future, and EPA routinely updates their recommended emissions factors for GHG inventories document. It is uncertain how these emissions factors might change in the future.

10.2 KEY FINDINGS

Draft key findings for GHG emission reductions based on the Demand Study Scenarios are as follows.

The key findings for GHG emission reductions based on the Demand Study Scenarios are as follows and are discussed further herein.

- Projected up to nearly 17 and 36 million metric tons of CO2e per year removed from SoCalGas geographic service territory by end users by 2045 in low and high demand scenarios of the Demand Study, respectively. ("Low Demand Scenario" and "High Demand Scenario"). The reductions are equivalent to the annual GHG emissions of approximately 45 and 96 natural gas-fired power plants, respectively per EPA Calculator.
    - Mobility sector comprises 72.5% and 50.3% of overall GHG reductions based on the Low and High Demand Scenarios, respectively. The GHG reductions estimated for the Low and High Demand Scenarios in 2045 are equivalent to removing approximately 2.7 million and 4.3 million gasoline passenger vehicles off the roads per year, respectively.[109]
    - Power generation and hard to electrify industrial sectors comprise 41.7% and 8.1% of the overall GHG reductions, respectively, based on the High Demand Scenario.
    - Power generation and hard to electrify industrial sectors comprise 23.6% and 3.9% of overall GHG reductions, respectively, based on the Low Demand Scenario.
    - Infrastructure GHG emissions are projected to be negligible when compared to overall emission reductions, at 0.17% and 0.25% of end-user reductions for Low and High Demand Scenarios, respectively.

Key Findings: Angeles Link Throughput Scenarios

The key findings for GHG emission reductions for Angeles Link Throughput Scenarios, which accounts for emissions from not just transmission of hydrogen, but also from third-party production and storage as well as end users, are as follows and are discussed further herein.

- Projected about 4.5 and 9 MMT of CO2e per year removed from SoCalGas's geographic territory by end users by 2045 in Angeles Link Low and High Throughput Scenarios, respectively.
- Mobility sector comprises 72.5% and 50.3% of overall GHG reductions based on the Angeles Link Low and High Throughput value scenarios, respectively. The GHG reductions

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[109] US EPA, 2023c, Greenhouse Gas Equivalencies Calculator, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results

estimated for the Low and High Throughput Scenarios in 2045 are equivalent to 725,000 and more than 1 million gasoline passenger vehicles driven for one year, respectively.[110]

- Power generation and hard to electrify industrial sectors comprise 41.7% and 8.1% of overall GHG emission reductions, respectively, based on the High Throughput Scenario.
- Power generation and hard to electrify industrial sectors comprise 23.6% and 3.9% of overall GHG emission reductions, respectively, based on the Low Throughput Scenario.
- Infrastructure GHG emissions are projected to be negligible when compared to overall emission reductions at 0.17% and 0.25% of end-user reductions for Low and High Throughput Scenarios, respectively.

Additional details related to both the Demand Scenarios and Angeles Link Throughput Scenarios are provided below.

2030 High Demand Scenario: In 2030, the High Demand Scenario predicts a reduction of about 6 MMT/yr of CO2e due to hydrogen replacing fossil fuels. This reduction includes the emissions from producing, storing, and transmitting hydrogen. This amount of reduction is comparable to the energy use of about 740,000 homes for one year, according to the EPA's greenhouse gas (GHG) calculator.[111] In terms of specific contributions, Angeles Link is expected to meet about 25% of the projected hydrogen demand identified in the Demand Study. This means that the specific GHG reductions attributed to Angeles Link under the High Throughput Scenario are estimated at about 1.45 million MT CO2e per year, which is equivalent to the energy use of approximately 189,000 homes for one year.

2045 High Demand Scenario: By 2045, the scenario estimates an overall reduction in CO2e emissions of about 36 MMT/yr, again due to the displacement of fossil fuels by hydrogen. These reductions are equivalent to the annual electricity usage of over 4.6 million homes, as per the EPA's calculator. Angeles Link is expected to supply the same percentage (about 25%) of the total hydrogen demand in SoCalGas service territory, as projected in the High Demand Scenario. As a result, the GHG emissions reductions specifically associated with Angeles Link in the High Throughput Scenario for 2045 are estimated at about 9.0 million MT CO2e per year. This would correspond to the energy use of roughly 1.1 million homes for one year.

Mobility Sector: In the Mobility sector, the estimated CO2e reductions under the High Demand Scenario are approximately 4.4 million MT in 2030 and about 18 million MT by 2045. The reductions by 2045 are equivalent to the emissions from around 4.3 million gasoline-powered

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110 US EPA, 2023c, Greenhouse Gas Equivalencies Calculator, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results

111 US EPA, 2023c, Greenhouse Gas Equivalencies Calculator, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results

passenger vehicles driven for a year. The sector accounts for between 50% to 83% of total GHG emissions reductions, varying by scenario and year. The largest contributors are heavy-duty vehicles (55.5% in 2030 and 62.8% in 2045), followed by buses (33.6% in 2030 and 22.0% in 2045), and medium-duty vehicles (7.3% in 2030 and 9.7% in 2045). Reductions from on-road vehicles significantly outweigh those from off-road vehicles, mainly due to the higher displacement of fossil fuels. In the High Throughput Scenario, the reductions for 2030 are about 1.1 million MT CO2e per year, increasing to about 4.6 million MT CO2e by 2045. The 2045 reductions would be equivalent to the emissions from 1 million gasoline-powered vehicles driven for a year.

Power Generation Sector: In the Power Generation sector, it's projected that by 2030, there could be a reduction of 0.16 million MT of CO2e under the High Demand Scenario, and by 2045, this could increase to about 15 million MT CO2e. Over 78% of these reductions are expected from the peaker and baseload plant sub-sectors in all years under this scenario with the remaining reductions attributable to the cogeneration sub-sector. By 2045, these reductions are equivalent to the yearly electricity consumption of approximately 1.9 million homes, according to the EPA's calculator. Under the High Throughput Scenario, the reductions are estimated at about 41,000 MT CO2e per year for 2030 and about 3.8 million MT CO2e per year by 2045. The reductions for 2045 under this scenario are comparable to the energy use of around 480,000 homes for one year.

Hard to Electrify Industrial Sectors: In the industrial sectors that are difficult to electrify, the estimated CO2e reductions under the High Demand Scenario are around 1.1 million MT in 2030 and could rise to about 2.9 million MT by 2045. The 2045 reductions would be equal to the annual electricity usage of about 365,000 homes. In this scenario, refineries are the largest contributors, accounting for 65.5% of reductions in 2030, followed by the Food and Beverage sector (13.4%), Stone, Glass, and Cement (12.1%), and Metals (5.3%). These percentages remain consistent from 2030 to 2045. In the High Throughput Scenario, the reductions are estimated at about 290,000 MT CO2e per year for 2030 and about 730,000 MT CO2e per year by 2045. The 2045 reductions equate to the energy use of around 96,000 homes for one year.

Hydrogen Infrastructure Emissions: Emissions associated with new hydrogen infrastructure are evaluated. The results of the conservative estimate prepared represent a small fraction of the emissions reductions achieved by end-users adopting hydrogen in the study region.

Specifically, in the High Demand Scenario:

- By 2030, emissions from the new hydrogen infrastructure are estimated at about 16,600 MT of CO2e per year. This accounts for 0.29% of total CO2e reductions expected from end-users based on hydrogen usage projections.
- By 2045, these emissions increase to about 87,900 MT per year of CO2e, which constitutes 0.25% of the total CO2e reductions from end-users. This accounts for 0.25% of total CO2e reductions expected from end-users based on hydrogen usage projections.

For Angeles Link, under the High Throughput Scenario:

- In 2030, the estimated emissions attributed to the new infrastructure are estimated to be around 4,200 MT of CO2e per year. This accounts for 0.29% of total CO2e reductions expected from end-users based on hydrogen usage projections.
- By 2045, this figure is projected to rise to 22,300 MT of CO2e per year. This accounts for 0.25% of total CO2e reductions expected from end-users based on hydrogen usage projections.

11 STAKEHOLDER COMMENTS

The input and feedback from stakeholders including the Planning Advisory Group (PAG) and Community Based Organization Stakeholder Group (CBOSG) has been essential to the development of this draft GHG Study Report. Some of the feedback that has been received related to this Study is summarized below. All feedback received is included, in its original form, in the quarterly reports submitted to the CPUC and published on SoCalGas' website.[112] Feedback topics that were not incorporated into the Study are also identified.

Quarter 1 to Quarter 4 2023 Reports

- **PAG/CBOSG Feedback Themes**
    - Interest in an independent study.
    - Concerns surrounding the tracking of duplicative emissions reductions and whether research would look at the net impact of positive GHG emissions and the effect of hydrogen.
    - Suggestion for study to include carbon intensity and lifecycle emissions. Specifically, to estimate GHG from water conveyance, from feed preparation and transport of biomass, and from use of non-renewable electricity.
    - Clarification questions on carbon measurements.
    - Emphasis on proper infrastructure design and maintenance to prevent continuous emissions.
    - Importance of using both GWP 100 and GWP 20 and examining climate impacts of different hydrogen leakage rates.
    - Request to have the climate risks of projected GHG emissions be evaluated.
    - Questions regarding the type of evaluation that will be conducted to determine the indirect warming potential of hydrogen leakage.
- **EDF Comments**
    - Hydrogen emissions should be included and/or considered in the GHG emissions impact calculations.
- **SCAQMD Feedback**

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[112] https://www.socalgas.com/sustainability/hydrogen/angeles-link

- The Study should specify whether the estimates are for direct GHG emissions or for an entire life cycle analysis. Carbon intensity of delivered hydrogen based on production and transport scenarios should be included.

Preliminary Data & Findings Document

- Six comment letters were received from Environmental Defense Fund, Communities for a Better Environment (CBE), Food and Water Watch, Protect Playa Now, and Physicians for Social Responsibility – Los Angeles, and Air Products
    - The letters from the first five listed entities requested volumetric leakage estimates and associated impacts to climate change be discussed and a volumetric analysis be included in the leakage and GHG study reports.
- CBE also requested clarification regarding assumptions and resulting GHG emissions associated with the three analyzed production options – electrolysis, biomass gasification, and steam methane reforming.
- Air Products expressed in interest in understanding the GHG emissions associated with water conveyance and with transportation of feed associated with biomass gasification. Additionally, a stakeholder indicated that GHG emissions from grid electricity used for production should be included.

Summary of How Comments were Addressed

- This draft GHG report includes analysis based on both (1) the three scenarios from the Demand Study and (2) the three scenarios of currently projected throughput for Angeles Link.
- This GHG Study evaluates direct GHG emissions associated with hydrogen combustion associated with new infrastructure, specifically production, storage, and transmission of hydrogen, as well as GHG emissions reductions associated with displaced fossil fuels by end users in the mobility, power generation, and hard-to-electrify industrial sectors.
    - Lifecycle assessments rely on a level of detail that is beyond the scope of this feasibility study and have therefore not been included.
    - Details regarding specific locations of renewable electricity generation sites and compressor stations was not available and therefore was not included.
- As noted in the executive summary, hydrogen has been identified in the literature as having indirect climate impacts. A detailed discussion on this topic is included in Section 9 of this document.

- Although the Intergovernmental Panel on Climate Change (IPCC) has not assigned a Global Warming Potential (GWP) for hydrogen, scientific literature indicates that hydrogen behaves as an indirect GHG.
- A summary of the estimated GWP 20 and GWP 100 values for hydrogen based on a review of the literature is provided in Table 17 of this document.

- The range of preliminary high-level volumetric estimates of the potential for leakage in the parallel Draft Leakage Study Report is used in this draft GHG report to predict a high-level range of potential impacts to the estimated overall GHG reductions associated with general new hydrogen infrastructure and Angeles Link infrastructure using the potential for leakage. The results are presented in Section 9.3.
  - The leakage estimates were based on a summary of values found during a literature review. Conducting empirical leakage measurements is beyond the scope of the Phase 1 feasibility studies.
- The draft GHG report assumes that production of hydrogen will use renewable electricity which has zero GHG emissions regardless of production method.
- This Study does not evaluate the GHG associated with water conveyance or the transportation of other materials such as biomass to the production site or biomass feed preparation, as those details are beyond the scope of this feasibility study. An assumption was made that biomass would be procured ready for combustion and removal of moisture would not be required on-site.
- This study evaluated GHG associated with Steam Methane Reforming using Renewable Natural Gas as a feedstock and clean renewable hydrogen as a fuel for the heating equipment.

Parallel Angeles Link Phase 1 Study Reports may be reviewed for additional information including Demand, Production, Pipeline Sizing and Routing, and Options and Alternatives.

Summary of Literature Provided by Stakeholders

Specific literature provided has been evaluated and relevant information has been incorporated, as appropriate, including, but not limited to:

- AC Transit, Zero Emission Bus Transition Plan, 2022, 0162-22 ZEB Transition Plan_052022_FNL.pdf (actransit.org)
- Bertagni, M.B., Pacala, S.W., Paulot, F. et al. Risk of the hydrogen economy for atmospheric methane, Nat Commun 13, 7706 (2022). https://doi.org/10.1038/s41467-022-35419-7
- CARB, Innovative Clean Transit Regulation, https://ww2.arb.ca.gov/our-work/programs/innovative-clean-transit/about
- Ocko. I and S. Hamburg, EDF Blog, July 19, 2023, New research reaffirms hydrogen's impact on the climate, provides consensus, https://blogs.edf.org/energyexchange/2023/07/19/new-research-reaffirms-hydrogens-impact-on-the-climate-provides-consensus/
- Paulot F., D. Paynter, V. Naik, S. Malyshev, R. Menzel, L. W. Horowitz, Global modeling of hydrogen using GFDL-AM4.1: Sensitivity of soil removal and radiative forcing, International Journal of Hydrogen Energy, 46, Issue 24, 2021. 13446-13460, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2021.01.088.
- Sand, M., R.B. Skeie, M. Sandstad, S. Krishnan, G. Myhre, H. Bryant, R. Derwent, D. Hauglustaine, F. Paulot, M. Prather and D. Stevenson, 2023, A multi-model assessment of the Global Warming Potential of hydrogen, Communications Earth & Environment V.4 Article number: 2003, https://doi.org/10.1038/s43247-023-00857-8
- Sun, Tianyi, et al. "Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales." Environmental Science & Technology, American Chemical Society, Feb. 2024, https://doi.org/10.1021/acs.est.3c09030

12 GLOSSARY

Aftertreatment – An exhaust gas aftertreatment system is a device that reduces combustion emissions.

Air-to-fuel ratio – The ratio of the mass of air to fuel present in a combustion reaction.

Ambient air – Ambient air refers to atmospheric air in its natural state. Ambient air typically consists of 78% nitrogen and 21% oxygen. The remaining 1% is a combination of carbon, helium, methane, argon, and hydrogen.

Anthropogenic causes - Anthropogenic causes are causes of environmental problems that are a result of human activities. Examples of anthropogenic causes are energy-related activities, such as combustion of fossil fuels in the electric utility and transportation sectors, and the anthropogenic greenhouse effect, which is due to greenhouse gases emitted by humans, leading to global warming.

Autoignition (ignition) temperature – The minimum temperature that a substance mixed with air will ignite and burn without an ignition source.

Blended fuels – Blended fuels are mixtures of traditional and alternative fuels in varying percentages. Blends can be thought of as transitional fuels. The lowest-percentage blends are being marketed and introduced to work with current technologies while paving the way for future integration, in this case, eventual usage of 100% hydrogen fuel.

Carbon-based fuel (also includes fossil fuel) – Hydrocarbon materials of biological origin. Carbon-based fossil fuel includes decomposing plants and other organisms, buried beneath layers of sediment and rock. These fuels have taken millennia to become the carbon-rich deposits we now call fossil fuels. These fuels include coal, oil, and natural gas.

Clean renewable hydrogen – Clean renewable hydrogen is defined as hydrogen that does not exceed 4 kilograms of CO_2e produced on a lifecycle basis per kilogram of hydrogen produced and does not use fossil fuel in the hydrogen production process where fossil fuel is defined as a mixture of hydrocarbons including coal, petroleum, or natural gas, occurring in or extracted from underground deposits per Decision 22-12-055 dated December 15, 2022.

Cogeneration or combined heat and power (CHP) – CHP is the use of a heat engine or power station to generate electricity and useful heat at the same time. Cogeneration is a more efficient use of fuel or heat, because otherwise-wasted heat from electricity generation is put to some productive use. Combined heat and power (CHP) plants recover otherwise wasted thermal energy for heating. This is also called combined heat and power district heating. Small CHP plants are an example of decentralized energy.

Compressors – A compressor is a mechanical device that increases the pressure of a gas by reducing its volume. Compressors are similar to pumps: both increase the pressure on a fluid and both can transport the fluid through a pipe. The main distinction is that the focus of a compressor is to change the density or volume of the fluid, which is mostly only achievable on gases. Gases are compressible, while liquids are relatively incompressible, so compressors are rarely used for liquids. The main action of a pump is to pressurize and transport liquids.

Combustion units – A combustion unit generates mechanical power by combustion of a fuel. Combustion units are of two general types: internal combustion engines and external combustion units.

Decarbonize – Decarbonization can mean moving away from energy systems that produce carbon dioxide (CO_2) and other greenhouse gas emissions. Energy decarbonization involves shifting the entire energy system in an attempt to stop carbon emissions from entering the atmosphere before they are ever released — this involves decarbonizing power grids, decarbonizing supply chains, and utilizing carbon sequestration in the pursuit of net-zero emissions and a carbon-neutral global economy.

Density – the mass per unit volume of a substance.

Diffusivity – Diffusivity is a measure of the capability of a substance or energy to be diffused or to allow something to pass by diffusion. Diffusivity refers to the spreading of something or making it less concentrated.

Drayage trucks – Drayage trucking involves shipping goods a short distance using ground freight. You see drayage loads commonly in intermodal shipping, such as moving large containers from a ship to rail for delivery.

Electrolyzer – An electrolyzer uses electrolysis as a method for carbon-free hydrogen production (green hydrogen) from renewable and nuclear resources. Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in an electrolyzer that can range in size from small, appliance-sized equipment that is well-suited for small-scale distributed hydrogen production to large-scale, central production facilities that could be tied directly to renewable or other non-greenhouse-gas-emitting forms of electricity production.

End-users – An end-user uses the hydrogen delivered by Angeles Link.

Engine – a machine that converts thermal energy into useful work (e.g., electricity of shaft power) to produce force and motion.

External combustion – The process of combining heat, fuel, and oxygen without the use of a combustion chamber to produce thermal energy.

Feasibility study – A feasibility study is an assessment of the practicality of a proposed project plan or method. For example, asking “Is this feasible?” by analyzing implementation and operational factors.

Feedstock – Feedstock is the material that is used in some hydrogen production equipment and can renewable natural gas and biomass.

Flammability range – The range of air-to-fuel ratios for which a substance will burn when exposed to an ignition source. The low end of this range is "rich" combustion where excess fuel inhibits combustion. The high end of this range is "lean" combustion where excess air inhibits combustion.

Flame speed – The rate of expansion of a flame front in a combustion reaction. This is the speed that unburned gas must move relative to an unmoving flame to supply it with fuel.

Global Warming Potential (GWP) – Global warming potential (GWP) is a measure of how much infrared thermal radiation a greenhouse gas added to the atmosphere would absorb over a given time frame, as a multiple of the radiation that would be absorbed by the same mass of added carbon dioxide (CO_2). GWP is 1 for CO_2. For other gases it depends on how strongly the gas absorbs infrared thermal radiation, how quickly the gas leaves the atmosphere, and the time frame being considered.

Green hydrogen – Green hydrogen is produced through water electrolysis process by employing renewable electricity. The reason it is called green is that there is no CO_2 emission during the production process. Water electrolysis is a process which uses electricity to decompose water into hydrogen gas and oxygen.

Heavy-duty transportation – Heavy-duty transportation includes flatbed trailers, wide load hauling, large trucks, and freight trucks.

Hydrogen – Hydrogen is a colorless, odorless, tasteless, flammable gaseous substance that is the simplest member of the family of chemical elements. Hydrogen is the most flammable of all the known substances.

Hydrogen fuel cell - A hydrogen fuel cell is an electrochemical cell that produces a current that can work using a spontaneous redox reaction. The combination of the two half-cell potentials for the electrochemical reaction creates a positive potential for cells. In general, fuel cells are different from most batteries in that they require a continuous source of fuel and oxygen (usually from air) to sustain the chemical reaction, whereas in a battery the chemical energy usually comes from substances that are already present in the battery. Fuel cells can produce electricity continuously for as long as fuel and oxygen are supplied. The only byproduct of a hydrogen fuel cell is water vapor.

Ignition energy – The minimum energy required to initiate the self-sustained combustion of a substance.

Infrastructure – Infrastructure are the resources such as pipelines and compressors required for an activity such as transmission of hydrogen.

Internal combustion – The process of combining heat, fuel, and oxygen within a combustion chamber where the combustion gasses themselves are the working fluid.

Methane – Methane is a chemical compound with the chemical formula CH_4 (one carbon atom bonded to four hydrogen atoms). It is the main component of natural gas.

Methodology – Methodology is the general research strategy that outlines the way in which research is to be undertaken and, among other things, identifies the methods to be used in it. These methods, described in the methodology, define the means or modes of data collection or, sometimes, how a specific result is to be calculated.

N_2O – N_2O is nitrous oxide, a greenhouse gas commonly known as laughing gas or nitrous, and is a chemical compound, an oxide of nitrogen. At room temperature, it is a colorless non-flammable gas, and has a slightly sweet scent and taste.

NOx – NOx is shorthand for nitrogen oxides (comprised of NO and NO_2) which is an air pollutant subject to air quality regulations formed during combustion of fossil fuels and a precursor to ozone.

Project scenario – A project scenario is a description of what a project proposal will look like when it is completed. This allows companies to identify potential problems that may occur along the way so they can be addressed in project planning for a smooth and productive outcome. Scenario planning, sometimes called scenario thinking or scenario analysis, is used by organizations as part of their strategic planning process.

Reciprocating compressors – A reciprocating compressor uses a linear drive to move a piston or a diaphragm back and forth to compress a gas. This motion compresses the gas by reducing the volume it occupies. Reciprocating compressors are the most used compressors for applications that require a very high compression ratio (compression ratio is the ratio of the pressure at the outlet of the compressor over the pressure at the inlet of the compressor).

Refining – Refining is removing impurities or unwanted elements from a substance, typically as part of an industrial process.

Stationary source – A stationary source refers to a qualitative term used to describe any fixed emitter of air pollutants, such as power plants, oil refineries, and heavy industrial facilities.

Steam generating units – Industrial/commercial/institutional steam generating units are boilers that are capable of combusting over 10 million international British thermal units per hour (MMBtu/hr) of fuel. A boiler or steam generator is a device used to create steam by applying heat energy to water.

Stoichiometric ratios/calculations – Stoichiometric ratios/calculations are used to analyze the relationship between the weights of reactants and products before, during, and following chemical reactions. Stoichiometry is founded on the law of conservation of mass where the total mass of the reactants equals the total mass of the products, leading to the insight that the relations among quantities of reactants and products typically form a ratio of positive integers. This means that if the amounts of the separate reactants are known, then the amount of the product can be calculated. Conversely, if one reactant has a known quantity and the quantity of the products can be empirically determined, then the amount of the other reactants can also be calculated.

Throughput – Throughput is the amount of a product or service that is provided.

Turbines - A turbine is a rotary mechanical device that extracts energy from a fluid flow and converts it into useful work. The work produced can be used for generating electrical power when combined with a generator. A turbine is a turbomachine with at least one moving part called a rotor assembly, which is a shaft or drum with blades attached. Moving fluid acts on the blades so that they move and impart rotational energy to the rotor. In a gas turbine, the turbine is driven by expansion of hot gases. In a steam turbine, expanding steam drives the turbine. The turbine can do mechanical work or be used to generate electricity.

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Appendix A: Development and Application of GHG Emission Factor for Hydrogen Combustion

Combustion of hydrogen is anticipated to have zero or potentially trace GHG emissions. To account for the potential N_2O emissions that may form during combustion since N_2O is a GHG, in the absence of published N_2O emissions factors for hydrogen combustion, the following approach was used to develop hydrogen emissions factors based on studies. Details regarding assumptions made to apply the N_2O emission factor are also discussed below.

Development of GHG Emission Factor

Studies evaluating the formation of N_2O from the combustion of hydrogen typically fall into two categories: modeling or direct measurement. For the modeling studies, various models, variable inputs, and boundary conditions are used to account for the unique properties of hydrogen and minimization of air pollutant emissions. Direct measurement studies addressing N_2O formation from the combustion of hydrogen are typically performed on equipment that was not originally designed to account for the unique combustive properties of hydrogen.

A paper published in the International Journal of Hydrogen Energy in 2017 by a team at UCI investigated whether N_2O emission could be formed and emitted by the combustion of various fuels that did not contain nitrogen.[113] The study evaluated natural gas with up to 70% hydrogen added (by volume). The results indicated that direct N_2O emissions were observed in greater volumes during transient events such as ignition and blowoff. It also found that steady state combustion of hydrogen-enriched natural gas flames can lead to the direct emissions of N_2O when operated at very lean conditions, made possible by the stabilizing effects of hydrogen. The study measured N_2O concentrations at various fuel–air equivalence ratios, phi. The fuel–air equivalence ratio is defined as the ratio of the fuel-to-oxidizer ratio to the stoichiometric fuel-to-oxidizer ratio. If the fuel-air equivalence ratio is less than 1, the mixture is considered lean (air is in excess). The study compared the lean burnoff experimental measurements with GRI 3.0 and University of California San Diego (UCSD) chemical reaction mechanisms,[114] with the UCSD mechanism following the experimental trends. The USCD San Diego Mechanism is used for modeling combustion applications as a chemical-kinetic mechanism with 57 species in 268 reactions.[115] GRI 3.0 is a mechanism for modeling natural gas combustion, including 325

[113] Colorado, A., V. McDonell and S. Samuelsen, 2017, Direct Emissions of Nitrous Oxide from Combustion of Gaseous Fuels, International Journal of Hydrogen Energy 42(1): 711-719, https://doi.org/10.1016/j.ijhydene.2016.09.202

[114] UCSD, 2023, Chemical-Kinetic Mechanisms for Combustion Applications, University of California at San Diego Mechanical and Aerospace Engineering (Combustion Research), San Diego Mechanism web page, https://web.eng.ucsd.edu/mae/groups/combustion/mechanism.html

[115] CERFACS (Centre Euorpéen de Recherche et de Formation Avancée en Calcul Scientifique), 2023, CANTERA User's Guide - Hydrogen/Air Combustion, https://cerfacs.fr/cantera/mechanisms/hydro.php

reactions and 53 species.[116] As noted in this study, N_2O is rapidly consumed at high temperatures or when equivalence ratio is close to the stoichiometric point (φ= 1). Therefore, combustion parameters such as a higher ratio of air-to-fuel (leaner combustion) and lower combustion temperatures that are utilized to minimize the formation of NOx emissions from the combustion of hydrogen fuels may potentially have the opposite effect on direct N_2O emissions. These effects need to be studied further since hydrogen combustion allows for leaner mixtures and stable operation at lower temperatures.

In a white paper prepared by the National Energy Technology Laboratory (NETL), hydrogen combustion emissions are evaluated. Similar to other literature, it is noted that thermal NOx is the prevalent form of NOx emissions for most high-temperature combustion (higher than 1,500°C). It is noted that in regions of the flame where there is a lack of oxygen, N_2O can also be formed from the under-oxidation of nitrogen. N_2O formation through this intermediate mechanism during combustion is generally very rare compared to other NOx compounds according to the paper "A Literature Review of Hydrogen and Natural Gas Turbines: Current State of the Art with Regard to Performance and NOx Control."[117]

A 1994 paper by Kramlich et al. indicates that in most nitrogen free gas fuel combustion systems the flame temperature is sufficiently high that any N_2O formed in the flame zone is destroyed before the gases are emitted.[118]

A modeling study completed by Duan et al. published in 2017 studied the mechanisms for NOx formation in a hydrogen internal combustion engine under high load found that the N_2O concentration increased significantly during the period of combustion. However, N_2O concentration at the end of the modeled process was less than 1 ppm. [119]

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[116] Smith, G.P., D.M. Golden, M. Frenklach, N.W. Moriarty, B. Eiteneer, M. Goldenberg, C.T. Bowman, R.K. Hanson, S. Song, W.C. Gardiner, Jr., V.V. Lissianski, and Zhiwei, 2023, GRI-Mech 3.0 webpage, Qin http://www.me.berkeley.edu/gri_mech/

[117] National Energy Technology Laboratory, 2022, A Literature Review, Ibid

[118] Kramlich, J.C. and W.P. Linak, 1994, Nitrous oxide behavior in the atmosphere, and in combustion and industrial systems, Progress in Energy and Combustion Science 20(2): 149-202, https://doi.org/10.1016/0360-1285(94)90009-4

[119] Duan, J., F. liu, Z. Yang, B. Sun, W. Chen, and L. Wang, 2017, Study on the NOx emissions mechanism of an HICE under high load, International Journal of Hydrogen Energy 42(34): 22027-22035, https://doi.org/10.1016/j.ijhydene.2017.07.048

Table A-1
Summary of Experimental Data of Hydrogen Combustion by Fuel Type

Fuel (Equipment)	Metric	Value	Units	Author
H_2:NG Blend (Burner)	Experimental	0.55	ppm (wet)	Colorado et al., 2017
H_2 (HICE)	Model Transient	6	ppmvd	Duan et al., 2017
H_2 (HICE)	Model Typical	1	ppmvd	Duan et al., 2017
H_2 (Residential Boiler)	Experimental	0.41	ppmvd	Galbraith, 2023[120]

As discussed above, data on N_2O emissions from 100% hydrogen combustion is sparse. In the table above, experimental data for blended hydrogen fuel, N_2O modeled data, and experimental data for hydrogen combustion are summarized. While data was available for ignition and transient combustion, the focus was on establishing a N_2O emission factor for steady-state combustion to best reflect anticipated combustion emissions. In collaboration with UCI, an evaluation of the available data was conducted. An average of the experimental data including the standard deviation was considered, but in effort to avoid the potential of underestimating N_2O emissions, the worst-case modeling data was chosen as the basis for estimated N_2O emissions from hydrogen combustion. It was further decided to add an additional layer of conservatism by applying a margin of safety of two. This approach utilizes the best data currently available and the inclusion of a margin of safety accounts for the uncertainty and the limited dataset. The conclusion is that a N_2O emission factor of 2 ppmvd was used for this study.

Application of GHG Emission Factor

The N_2O emission factor was used to estimate GHG from hydrogen combustion for the following:

- Infrastructure: Production, Storage, and Transmission
- End-Users: Mobility, Power Generation, and Hard to Electrify Industrial

Production

Electrolysis Powered by Renewable Electricity

The process of electrolysis is not a combustion process and therefore N2O emissions are zero.

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[120] Galbraith, John, 2023, Nitrous Oxide Emissions Associated with 100% Hydrogen Boilers: Research, Energy and Climate Change Directorate, https://www.gov.scot/publications/nitrous-oxide-emissions-associated-100-hydrogen-boilers/ [gov.scot]

Biomass Gasification

No method for calculating greenhouse gas emissions was identified for biomass gasification, nor were any directly measured emissions from the process. Based on the scientific literature, biomass gasification is likely a "carbon neutral" process and may have negative life cycle greenhouse gas emissions.[121] It is assumed for the purposes of this study, that a "carbon neutral" source of biomass will be selected for the production of hydrogen to be distributed by Angeles Link. Therefore, no CO_2 or CH_4 emissions are assumed from the biomass gasification process. Biomass gasification is not a true combustion process, and it occurs at relatively low temperatures of 700-1400 degrees Celsius in a low oxygen environment. As such, it was assumed that N_2O formation during biomass gasification is negligible. However, very little scientific literature is available that addresses the potential formation of N_2O from biomass gasification. A study completed by Sikarwar et al. in 2016 notes that there is the potential for nitrogen contamination in the outlet of the biomass gasification system if there is fuel nitrogen is present.[122] For the purposes of this study, it was assumed that no nitrogen is contained in the biomass or any other fuel source, as hydrogen is the preferred fuel source within the Angeles Link supply chain. Therefore, for the purposes of this study, it was assumed that N_2O emissions from biomass gasification were negligible.

The biomass gasification process requires dry biomass. It is possible to obtain biomass containing moisture that would require drying on-site. However, this is dependent on the biomass available in the area and the supply chain and procurement for the specific facility. Due to the level of uncertainty around whether on-site drying would be required for each specific biomass gasification facility, this study assumed that biomass would be procured ready to utilize and would not require moisture removal on-site.

The syngas formed through biomass gasification can potentially be utilized in steam reforming to obtain additional hydrogen from the remaining hydrocarbons. Biomass gasification using steam as the oxidizing agent can achieve efficiencies of up to 44%.[123] Running the syngas through the steam reforming process improves the overall efficiency and converts any remaining hydrocarbons, primarily CH_4, to hydrogen.

SMR Utilizing RNG as Feedstock and Hydrogen as Fuel for Heat Generation

For the purposes of this study, it was assumed that renewable natural gas generated from dairy farms would be the feedstock for the SMR process. Renewable natural gas, as it is referred to in

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[121] Yaser Khojasteh Salkuyeh, Bradley A. Saville, Heather L. MacLean, International Journal of Hydrogen Energy Volume 43, Issue 20, 17 May 2018, Pages 9514-9528, Techno-economic analysis and life cycle assessment of hydrogen production from different biomass gasification processes

[122] Sikarwar, V.S., M. Zhao, P. Clough, J. Yao, X. Zhong, M. Zaki Memon, N. Shah, E.J. Anthony and P.S. Fennell, 2016, An overview of advances in biomass gasification, Energy and Environmental Science 9(10): 2927-3304, https://pubs.rsc.org/en/content/articlepdf/2016/ee/c6ee00935b

[123] Rödl, A., C. Wulf, M. Kaltschmitt, 2018 Ibid

this study, is a useable feedstock for the SMR process as it generally has a methane content of 96% to 98%.[124] Biomethane is a type of renewable natural gas which is typically developed by the anaerobic digestion of manure and/or food wastes at a dairy farm or similar facility. The anaerobic digestion of these waste products generates a gaseous and a liquid product. The gaseous product is known as biogas and is subsequently sent through a cleaning skid where pollutants and impurities are removed resulting in renewable natural gas. The liquid product is called digestate and may be used as fertilizer in agriculture.

Steam reforming of renewable natural gas does have the potential to produce direct GHG emissions. Potential point sources of direct GHG emissions from combustion within a hypothetical steam reforming process include a furnace or external combustion unit for heat generation and a flare for use during maintenance, upset, and startup/shutdown operations. Given that pure hydrogen will be used as fuel for the combustion process, there is no potential for the formation of CO_2 or CH_4 emissions from the combustion hydrogen within the SMR process. However, there is the potential for N_2O formation from the combustion of hydrogen.

To calculate N_2O emissions from the external combustion unit within the steam reforming process, a heat rating per unit of hydrogen produced was required. To estimate an appropriate heat rating for the steam reforming process, air permits for existing steam methane reforming plants were reviewed. Only standalone SMR production facilities, external combustion units with a given heat rating rather than a “not-to-exceed", and facilities with no more than 2 external combustion units were reviewed.

The external combustion unit heat rating was compared against the plant hydrogen production capacity to develop a ratio of (MMBtu/hr) / (MMscf/day hydrogen production) ratio. For facilities where the plant hydrogen production capacity was not stated in the air permit, the facility hydrogen production capacity was gathered from the Pacific Northwest National Laboratory (PNNL) Hydrogen Analysis Resource Center North American Merchant Hydrogen Plant Production Capacity list.[125] Of these facilities considered, the highest (MMBtu/hr) / (MMscf/day hydrogen production) ratio was 3.71 MMBtu/hr per MMscf/day hydrogen production, and the average was 2.97 MMBtu/hr per MMscf/day hydrogen production. Three calculation cases were established, the maximum case using the average plus standard deviation for the ratio value (3.62 MMBtu/hr per MMscf/day H2 production), the mid case using the average ratio value (2.97 MMBtu/hr per MMscf/day H2 production), and the minimum case using the average minus the standard deviation for the ratio value (2.32 MMBtu/hr per MMscf/day H2 production).

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[124] USEPA, 2024, Renewable Natural Gas, agency webpage, https://www.epa.gov/lmop/renewable-natural-gas

[125] Pacific Northwest National Laboratory (PNNL), 2016, North American Merchant Hydrogen Plant Production Capacities, data available on the Hydrogen Tools website, https://h2tools.org/hyarc/hydrogen-data/merchant-hydrogen-plant-capacities-north-america

For the purposes of this study, it is assumed that the external combustion unit would operate using hydrogen as fuel. It was assumed that some of the hydrogen produced by SMR would be siphoned off to use as fuel. As such, the volume of hydrogen produced was increased based on the amount of hydrogen that would be needed as fuel. To calculate the amount of hydrogen that would be required for use as fuel to generate the necessary total volume of hydrogen to meet end-user demand, the end-user demand was converted to an MMscf/day value and the maximum MMBtu/hr case of 3.62 MMBtu/hr per MMscf/day of hydrogen production was utilized to determine an appropriate MMBtu/hr rating to meet the demand. The MMBtu/hr values were multiplied by 8,760 (hours/year) to calculate the maximum annual MMBtu value for the hydrogen fuel. This annual MMBtu value was added to the end-user MMBtu demand values for each Demand Scenario to determine the total estimated annual production volumes.

A thermal efficiency was then applied to account for the fact that energy conversion is generally less than 100%. Research was completed to determine an appropriate thermal efficiency for a hydrogen-fired external combustion unit. No single value was discovered that would be representative for all hydrogen-fired external combustion units. Therefore, an average of multiple values was utilized. Values were obtained from US DOE, a study completed by Gupalo et al. (2023), and an article by Gerardo Lara in Power Engineering.[126] [127] [128] Based on these articles, an efficiency of 73% was applied within this study.

Based on this methodology, roughly 38% of the hydrogen produced would be utilized as fuel for heat generation. As a note, this is likely a high estimate due to the use of only the maximum MMBtu/hr per MMscf/day hydrogen production ratio to determine fuel requirements. Utilizing the average case ratio yields a hydrogen use percent of total production of 31%, where the minimum case ratio yields 24%.

N_2O emissions factors for external combustion were calculated utilizing the same process as outlined for stationary combustion end-users and the conservative value of 2 ppmvd (equivalent to 0.0265 kg CO_2e/kg H_2 combusted) was conservatively utilized for external combustion. The calculations within this study assumed that hydrogen was the fuel for the external combustion unit within the SMR operations.

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[126] US DOE, Purchasing Energy-Efficient Large Commercial Boilers, https://www.energy.gov/femp/purchasing-energy-efficient-large-commercial-boilers

[127] Gupalo, O., 2023, Study of the efficiency of using renewable hydrogen in heating equipment to reduce carbon dioxide emissions, from IOP Conference Series: Earth and Environmental Science, doi:10.1088/1755-1315/1156/1/012035, https://iopscience.iop.org/article/10.1088/1755-1315/1156/1/012035/pdf

[128] Lara, G., 2022, Boilers running on hydrogen: What you need to know, from Power Engineering, https://www.power-eng.com/hydrogen/boilers-running-on-hydrogen-what-you-need-to-know/

Storage and Transmission

A two-step calculation approach was utilized to determine N_2O emissions from storage and transmission:

1. Estimate the total energy requirements to power compressors.
2. Calculate emissions from reciprocating engines and turbines associated with this energy.

The total energy requirement to power compressors for storage and transmission were developed from Bossel and Eliasson (2003)[129], a widely cited scientific paper. The first figure below, is a chart from this publication of compression energy (MJ/kg) to compress hydrogen at various pressures. Using this figure, the amount of energy required to store hydrogen can be calculated given a particular quantity of hydrogen (kg) and storage pressure (bar). The second chart from this this publication, the second figure below is a chart of the percentage of hydrogen that would be consumed to power compressors to transport hydrogen over a particular distance of pipeline. This figure can be used to calculate the amount of hydrogen (and therefore energy) required to transport hydrogen a distance via pipeline. Using these two data sources, the total energy required to power compressors used for storage and transmission could be determined.

[129] Bossel, U., and B. Eliasson, 2003, Energy and the Hydrogen Economy, https://afdc.energy.gov/files/pdfs/hyd_economy_bossel_eliasson.pdf

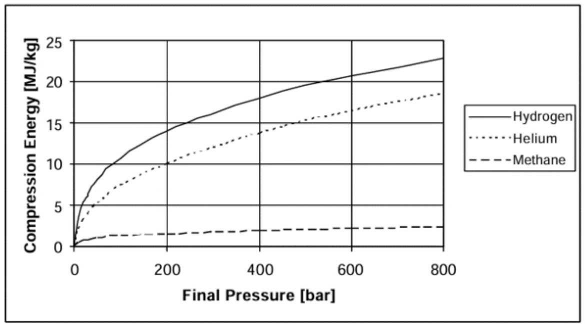

Figure A-1. Adiabatic Compression Work for Hydrogen, Helium, and Methane

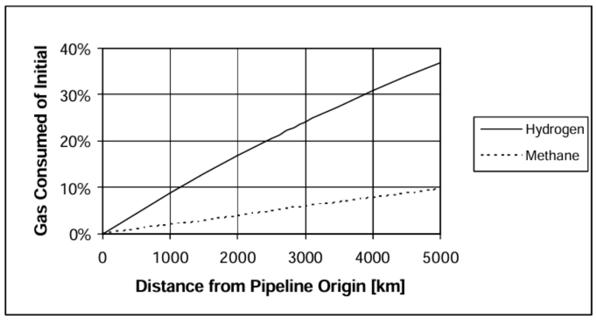

Figure A-2 Fraction of Gas Consumed to Energize the Pumps Corresponds to the Relative Energy Consumption of the Transported Gas

Based on data from Bossel and Eliasson (2003), the following information was required to determine N_2O emissions from transmission and third-party storage:

– Hydrogen storage pressure

– Hydrogen storage quantity

– Hydrogen transmission distance

– N_2O emissions factors for reciprocating engines and turbines

A range of possible N_2O emissions scenarios were evaluated related to new hydrogen infrastructure. A total of four scenarios were evaluated (per Demand Scenario) representing each combination of two (2) storage pressure scenarios, (2) compressor power source scenarios, and one (1) transmission distance scenarios. Annual N_2O emissions estimates were developed for each of these four storage and transmission scenarios for each of the three Demand Scenarios (Low, Medium, High).

Storage pressure scenarios were developed based on storage pressures from Tahan (2022).[130] This publication presented a variety of hydrogen storage options at a high-level and their corresponding pressures. The highest and lowest pressures from this publication were utilized to represent the full range of potential storage pressures, and therefore storage compressor energy demands, from this project. These high and low storage pressure scenarios were 200 and 20 bar respectively, corresponding to storage underground and in spherical pressure vessels respectively.

A conservative N_2O emissions factor of 2 ppmvd (equivalent to 0.0265 kg CO_2e/kg H_2) was utilized to represent the potential for N_2O formation from the combustion of hydrogen with air. This same factor was used for reciprocating engines and turbines. Efficiency values for reciprocating engines and turbines were also sourced from scientific literature to convert fuel energy (MMBtu) to energy supplied by power sources for compression (MJ). These efficiency values were 60.3% and 51.9% for hydrogen fueled reciprocating engines and turbines respectively.[131] [132] A transmission distance of 450 miles of pipeline was assumed.

It was assumed that storage requirements would be similar between hydrogen and natural gas to accommodate fluctuations in fuel supply and demand. Data from 2022 from the "2023 California Gas Report Supplement" was used to estimate a California-specific value for the fraction of annual hydrogen demand that would be stored. From this source, it was determined that the average quantity of supplied natural gas in California during 2022 was 6,023 MMcf/day, which equates to approximately 2,198 Bcf/yr. This source also indicated that in 2022 California had a natural gas storage capacity of approximately 304 Bcf. Dividing these two values yielded a maximum (conservative) fraction of annual natural gas demand that would be stored: 13.8%. This value was applied to hydrogen; therefore, it was assumed that annually 13.8% of hydrogen demand would be stored.

Collectively, this information was used to determine the energy requirements for the compressors utilized in storage and transmission. N_2O emissions, as CO_2e, from storage and transmission were calculated by multiplying overall compressor energy demand by N_2O emissions factor by N_2O GWP (AR6).

Based on the figures above and information from the literature as summarized above, the compression needs for storage were determined to be 4 MJ/kg for storage pressure at 20 bar and 14 MJ/kg for storage pressure at 200 bar, Additionally, for transmission, the hydrogen that

[130] Tahan, M., 2022, Recent advances in hydrogen, Ibid

[131] Babayev, R., H.G. Im, A. Andersson, and B. Johansson, 2022, Hydrogen double compression-expansion engine (H2DCEE): A sustainable internal combustion engine with 60%+ brake thermal efficiency potential at 45 bar BMEP, Energy Conversion and Management 264: 115698, https://doi.org/10.1016/j.enconman.2022.115698

[132] Salam, Md A., Md. A. Ali Shaikh, and K. Ahmed, 2023, Green hydrogen based power generation prospect for sustainable development of Bangladesh using PEMFC and hydrogen gas turbine, Energy Reports 9: 3406-3416, https://doi.org/10.1016/j.egyr.2023.02.024

would be consumed by the reciprocating or centrifugal compressors, was determined to be 0.0093% of the volume in the pipelines per kilometer of transmission via pipelines.

The following emission factors were developed for reciprocating engine and turbine compressors combusting clean renewable hydrogen:

- Hydrogen combusted (reciprocating engine & turbine compressors)
  - 2.1673E-11 grams CO_2e per gram H_2
  - 0.0005988 MT CO_2e per MMBtu
- Hydrogen transported (reciprocating engine & turbine compressors)
  - 5.5886E-8 grams CO_2e per gram H_2 per kilometer
  - 2.0228E-15 MT CO_2e per MMBtu H_2 per kilometer
- Hydrogen stored at 290 psi (reciprocating engine compressor)
  - 0.01318 grams CO_2e per gram H_2
- Hydrogen stored at 2,900 psi (reciprocating engine compressor)
  - 0.003765 grams CO_2e per gram H_2
- Hydrogen stored at 290 psi (turbine compressor)
  - 0.01531 grams CO_2e per gram H_2
- Hydrogen stored at 2,900 psi (turbine compressor)
  - 0.004374 grams CO_2e per gram H_2

Collectively, this information was used to determine the energy requirements for the compressors utilized in transmission and storage. NO_x emissions were calculated by multiplying overall compressor energy demand by NO_x emissions factor. NO_x emissions were estimated for a total of 12 scenarios corresponding to 4 storage and transmission scenarios for each of the 3 Demand Scenarios. These 4 transmission and storage scenarios were based on each combination of two storage pressure scenarios, two pressure source scenarios, and one transmission distance scenarios. This was repeated for a total of 12 scenarios for each of the 3 Throughput Scenarios. These emissions scenarios are listed in the table below. In combination, these scenarios represent the range of possible transmission and storage characteristics and the corresponding NO_x emissions.

Table A-2 Storage and Transmission Calculation Scenarios Evaluated

Scenario	Storage Pressure	Transmission Distance	Compressor Driver	Demand
1	High (2,900 psi)	450 mi	Reciprocating Engine	Low
2	Low (290 psi)	450 mi	Reciprocating Engine	Low
3	High (2,900 psi)	450 mi	Turbine	Low
4	Low (290 psi)	450 mi	Turbine	Low
5	High (2,900 psi)	450 mi	Reciprocating Engine	Moderate
6	Low (290 psi)	450 mi	Reciprocating Engine	Moderate
7	High (2,900 psi)	450 mi	Turbine	Moderate
8	Low (290 psi)	450 mi	Turbine	Moderate
9	High (2,900 psi)	450 mi	Reciprocating Engine	High
10	Low (290 psi)	450 mi	Reciprocating Engine	High
11	High (2,900 psi)	450 mi	Turbine	High
12	Low (290 psi)	450 mi	Turbine	High

Mobility

The EMFAC model does not include CH_4 and N_2O emissions data for off-road mobile vehicles. As such, additional research was completed to establish the most representative CH_4 and N_2O emissions factors for off-road mobile sources. The US EPA Emission Factors for Greenhouse Gas Inventories document most recently modified on September 12, 2023 was selected as the most appropriate and representative source for CH_4 and N_2O emissions factors for off-road mobile sources. The document consolidates these emissions factors from the Annex tables in the US EPA (2022) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020. Table A-3 is a summary of the GHG emission factors that were developed for the mobility sector. Table A-4 summarizes the allocation of each mobility sub-sector to the two fossil fuels being displaced, diesel and gasoline, as a total for the fifteen-year study period.

Table A-3 GHG Emission Factors by Fuel Type for On-Road and Off-Road Vehicles

Vehicle Type	Fuel Type	CO_2 (MT/gal)	CH_4 (MT/gal)	N_2O (Mt/gal)
On-Road	Diesel	0.0102	2.2078E-08	1.6000E-06
On-Road	Gasoline	0.0086	2.7499E-07	3.2282E-07
Off-Road	Diesel	0.0100	2.1960E-06	7.8800E-07
Off-Road	Gasoline	0.0065	1.7100E-06	1.0560E-06

Table A-4 Percentage of Total Fuel Type Displaced for each Mobility Sub-sector 2030 to 2045

Subsector	BAU % Diesel	BAU % Gasoline
MDV	38.81%	61.19%
HDV	99.99%	0.01%
Bus	10.15%	89.85%
Ag	92.14%	7.86%
CHC	100.00%	0.00%
CHE	27.55%	72.45%
C&M	67.65%	32.35%
GSE	18.28%	81.72%

Power Generation and Hard to Electrify Industrial

The research completed for this study did not reveal any published hydrogen-specific GHG combustion emission factors. There is agreement within scientific literature that the formation of carbon GHGs (CO_2 and CH_4) will be zero from the combustion of hydrogen fuel. Reductions of CO_2 and CH_4 emissions will therefore be 100% when compared to the emissions calculated for the fossil fuels displaced by hydrogen. The combustion of hydrogen at lower temperatures does provide potential for the formation and emissions of N_2O. However, there is significant uncertainty around the contributing factors to the formation and N_2O emissions. This uncertainty was discussed in the N_2O development of emissions factor section above.

Appendix B: Carbon Intensity Evaluation of Third Party Production Options

This evaluation sought to gather existing data regarding potential lifecycle greenhouse gas emissions associated with electrolysis powered by renewable electricity, biomass gasification, and steam methane reforming (SMR) of renewable natural gas (RNG) using hydrogen as fuel for any combustion units. Lifecycle GHG emissions associated with hydrogen production include direct (Scope 1) and indirect emissions (Scope 2 and Scope 3).

At the time of this study, details regarding third party production for new hydrogen infrastructure are not complete, and therefore, it is not feasible to estimate Scope 3 greenhouse gas emissions for the specific processes. It is critical to note that none of the lifecycle carbon intensities referenced in this section were developed for Angeles Link, they are all hypothetical scenarios or based on existing facilities and therefore, are not necessarily representative of the third-party production options being evaluated. The carbon intensity values presented in this section were obtained from existing literature and do not represent the full range of potential carbon intensities for each hydrogen production methodology. Based on the assessment within this study and with the information currently available, it is not possible to determine which of the potential hydrogen production methodologies will best meet the CPUC definition for clean renewable hydrogen. However, based on existing data, it appears to be possible for all three of the methodologies being considered to meet the CPUC definition depending on operational variables.

Multiple studies found in the literature were prepared to assess the lifecycle carbon intensity (kg CO_2e/kg H_2 produced) for the various hydrogen production methodologies. While there is not a single standardized methodology and structure for Life Cycle Assessments (LCA), existing standards include International Organization for Standardization (ISO) 14040 and ISO 14044, and assessment methods such as ReCiPe2016.[133] [134] Key variables for assessing carbon intensity for each methodology include the type and amount of feedstock required, type and amount of process fuels required, electricity required, water required for each of the various production methods, and the full supply chain for the required feedstock and fuel. The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model[135] is a publicly available tool that estimates "well-to-gate" (WTG) or "well-to-wheel" carbon intensity for hundreds of pathways, including hydrogen production, and was also utilized to assess potential life cycle carbon intensities.

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[133] Cho, H.H., V. Strezov, and T.J. Evans, 2022, Environmental impact assessment of hydrogen production via steam methane reforming based on emissions data, Energy Reports 8: 13585-13595, https://doi.org/10.1016/j.egyr.2022.10.053

[134] Mehmeti, A., A. Angelis-Dimakis, G. Arampatzis, S.J. McPhail and S. Ulgiati, 2018, Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies, Environments 5(2), https://doi.org/10.3390/environments5020024

[135] Argonne National Laboratory, 2022a, GREET Ibid

For this analysis, an evaluation was conducted to determine the "well-to-gate" carbon intensity for the following hydrogen production methods:

- Electrolysis powered by renewable electricity
- Biomass gasification
- Steam methane reforming (SMR) of feedstock renewable natural gas (biomethane)

Carbon intensity can be presented in multiple ways. For this study, emissions are presented in kilograms of carbon dioxide equivalent per kilograms of hydrogen produced (kg CO_2e/kg H_2) for comparison with the carbon intensity of 4 kg CO_2e/kg H_2 which is part of the CPUC definition of clean renewable hydrogen. The table below presents a summary of life cycle carbon intensities for the various production methodologies from existing literature which are discussed in more detail in the sections below.

Table B-1 Summary of Hydrogen Production Carbon Intensity Estimates from Existing Research

Production	Feedstock	Carbon Intensity Cradle-to-Gate (kg CO_2e/kg H2)	Study
Electrolysis	Renewable Electricity	0	GREET
Electrolysis	Solar-powered Electricity	2.3	Cho et al. 2022
Biomass Gasification	Not Specified	1.61	GREET
Biomass Gasification	Average of five biomass types	2.46	Cho et al. 2022
Steam Methane Reforming	Landfill Gas	3.57	Cho et al. 2022

<u>Electrolysis Powered by Renewable Electricity</u>

Per the GREET model, GHG emissions associated with electrolysis powered by renewable electricity are zero. GREET does not account for embedded carbon associated with solar panels or wind turbines. A study by Cho et al. published in 2022 found that solar-powered electrolysis may have a carbon intensity of 2.3 kg CO_2e/kg H_2 largely due to the manufacture of the solar cells.[136] As demonstrated, carbon intensity for electrolysis powered by renewable electricity will vary based on how the required technology is manufactured, even when Scope 1 and Scope 2 emissions are zero. Research has also noted that electrolysis requires high quality water as a feedstock, which may require treatment on site potentially increasing the energy demand[137] and impact overall carbon intensity.

<u>Biomass Gasification</u>

In the direct GHG emission calculations, we assume that biomass gasification is a "carbon neutral" process with no combustion, therefore, no pathway for GHG formation. Assuming no grid electricity usage or natural gas combustion, GREET was used to calculate indirect GHG

[136] Cho, H.H. et al. 2022, Environmental impact assessments, Ibid
[137] Mehmeti, A.et al. 2018, Life Cycle Assessment, Ibid

emissions associated with biogas gasification, assuming that 36.3 kg of biomass is needed to produce 1 kg H_2.[138] Approximately 1.61 kg CO_2e/kg H_2 is emitted by Scope 3 indirect sources (cultivation, harvesting, transport, drying, and chipping) for the biomass gasification process. Cho et. al (2022) calculated a cradle-to-gate carbon intensity of 2.46 kg CO_2e/kg H_2 for biomass gasification as an average of carbon intensity values from six different studies encompassing the following types of biomass: corn stover, unspecified forest residue, poplar, spruce, and willow.[139]

The carbon intensity of biomass gasification can vary based on a variety of key inputs including, but not limited to, type of biomass feedstock, whether fossil energy is used in the biomass lifecycle, biomass transport, pre-treatment such as drying and chipping, and the use of synthetic fertilizers. Fossil energy may be used in the agricultural process such as diesel fuel in agricultural machinery and vehicles. The use of synthetic fertilizers during the biomass lifecycle can cause acidification which can significantly impact the carbon intensity of that biomass.[140]

Steam Methane Reforming

In the SMR process, hydrogen is produced through a reaction of gaseous methane and steam to produce a carbon monoxide (CO) – hydrogen synthetic gas (syngas). The CO in the syngas is then further reacted with steam to produce CO_2 and additional hydrogen. Note that if the steam is exported for other uses, a process credit may be calculated, assuming emissions avoidance from a natural gas boiler that would have produced an equal amount of steam. SMR being considered would use renewable natural gas as feedstock. The direct emissions calculations completed within this study assume that the produced hydrogen is utilized as fuel for heat generation in the SMR process. However, no studies were identified that assume the use of hydrogen as fuel.

Cho et al. evaluated cradle-to-gate carbon intensity for utilizing landfill gas as feedstock for the SMR process. They took an average of the carbon intensities from three landfill gas related studies, one of which specified an assumed leakage rate of 1% CH_4, while the other two did not specify leakage rate assumptions. The cradle-to-gate carbon intensity for SMR of landfill gas was estimated to be 3.57 kg CO_2e/kg H_2.[141] The value presented in this section may not appropriately represent SMR utilizing renewable natural gas as feedstock since the renewable natural gas is typically derived from dairy farms rather than landfills. The average carbon intensity for manure dairy farms is considerably lower than landfill gas estimates found in the study, 3.57 kg CO2e/kg H_2. The CI for manure dairy farms on average is several orders of magnitude lower at approximately –322 kg CO2e/kg H_2.[142]

Production efficiency is a highly impactful variable when determining lifecycle carbon intensity from any SMR process. Cho et al. (2022) found that direct carbon intensity from SMR (using natural gas as feedstock) decreased by 6% when the efficiency was increased by 5% and

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[138] Argonne National Laboratory, 2022b, Hydrogen Life-Cycle Analysis, Ibid
[139] Cho, H.H. et al. 2022, Environmental impact assessments, Ibid
[140] Cho, H.H. et al. 2022, Environmental impact assessments, Ibid
[141] Cho, H.H. et al. 2022, Environmental impact assessments, Ibid
[142] CARB, 2024, LCFS Pathway Certified Carbon Intensities, https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities

decreased by 11% when the efficiency was increased by 10%.[143] A study by Nikolaidis and Poullikkas published in 2017 noted that the average production efficiency for existing SMR facilities ranges from 74% to 85%. Increasing the production efficiency of an SMR process reduces the carbon intensity.[144]

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[143] Cho, H.H. et al. 2022, Environmental impact assessments, Ibid

[144] Nikolaidis, P. and A. Poullikkas, 2017, A comparative overview of hydrogen production processes, Renewable and Sustainable Energy Reviews 67: 597-611, https://doi.org/10.1016/j.rser.2016.09.044

Appendix C: GHG Emission Calculations Spreadsheets

Please refer to the excel spreadsheets provided in the Appendix C folder in the Living Library.

ANGELES LINK PHASE 1

Nitrogen Oxides (NOx) and other Air Emissions Assessment

DRAFT – JULY 2024

SoCalGas commissioned this NOx and other Air Emissions Assessment from Stantec Consulting Services Inc. The analysis was conducted, and this report was prepared, collaboratively.

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1.0 EXECUTIVE SUMMARY

Southern California Gas Company (SoCalGas) is proposing to develop a clean renewable hydrogen[1] pipeline system to facilitate transportation of clean renewable hydrogen from multiple regional third-party production sources and storage sites to various delivery points and end users in Central and Southern California, including in the Los Angeles Basin. The CPUC's Phase 1 Decision, approving the Memorandum Account for SoCalGas's proposed Angeles Link project (Angeles Link) requires SoCalGas to track costs for conducting the feasibility studies. In the Decision, clean renewable hydrogen refers to hydrogen that does not exceed 4 kilograms of carbon dioxide equivalent (CO2e) on a lifecycle basis per kilogram of hydrogen produced and does not use fossil fuel[2] in the hydrogen production process. The Decision (OP 6 (h)) requires SoCalGas to assess potential NOx emissions associated with Angeles Link including appropriate controls to minimize and mitigate such emissions.

The purpose of this study is to assess the potential for both NOx emissions increases and reductions associated with Angeles Link, which accounts for emissions from not just transmission of hydrogen, but also from third-party production and third-party storage, as well as end users. Specifically, this NOx assessment evaluates potential NOx and other air emissions associated with new hydrogen infrastructure (i.e., third-party production,[3] third-party storage, and transmission),[4] as well as potential NOx emissions associated with end users in the mobility, power generation, and hard-to-electrify industrial sectors.[5] Although emission calculations include those conducted for hydrogen-natural gas fuel blends, the assumption is that blending would happen by the customer behind the meter. The study also identified minimization opportunities to reduce potential NOx emissions.

Although NOx is the primary focus of this emissions assessment, the study also includes a high-level assessment of other potential emissions, with a focus on volatile organic compounds (VOC) which is a precursor to ozone, and diesel particulate matter (DPM), which is the primary pollutant associated with diesel combustion. The NOx, VOC, and DPM emissions are a result of combustion of fuels and vary based on the type of fuel and equipment.

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[1] In the California Public Utilities Commission (CPUC)'s Angeles Link Phase 1 Decision (D.)22-12-055 (Phase 1 Decision), clean renewable hydrogen refers to hydrogen that does not exceed 4 kilograms of carbon dioxide equivalent (CO2e) produced on a lifecycle basis per kilogram of hydrogen produced and does not use fossil fuels in the hydrogen production process.

[2] Fossil fuel is defined as a mixture of hydrocarbons including coal, petroleum, or natural gas, occurring in and extracted from underground deposits.

[3] The potential NOx emissions associated with water conveyance or transport of biomass for production of hydrogen were not included in the scope of this study.

[4] The terms "new infrastructure" and "hydrogen infrastructure" refer to general hydrogen infrastructure comprised of third-party production, third-party storage, and transmission. The term "Angeles Link infrastructure" refers to transmission via pipelines including compression.

[5] Mobility, power generation, and hard-to-electrify industrial sectors as defined in the parallel Demand Study.

Projected quantities of displacement of diesel and gasoline by hydrogen fuel cells in the mobility sector, and anticipated replacement of natural gas with hydrogen in the power generation and hard-to-electrify industrial sectors were based on estimated demand values provided by the parallel Phase 1 Demand Study. The Demand Study projected potential economy-wide demand in Central and Southern California using three scenarios: conservative, moderate, and ambitious demand.

In comparison to the overall potential market demand projected in the Demand Study, the projected throughput of Angeles Link to help meet a portion of that total demand, is estimated to range from 0.5 to 1.5 million metric tonnes per year (MMT/yr). The three throughput scenarios for the Angeles Link buildout of low, moderate, and high (0.5 MMT/yr, 1.0 MMT/yr, and 1.5 MMT/yr) align with the conservative, moderate and ambitious Demand Scenarios (1.9 MMT/yr, 3.2 MMT/yr, and 5.9 MMT/yr). To estimate the potential NOx emissions associated with the project, including those from not just transmission of hydrogen, but also from third-party production and third-party storage as well as end users, emissions were calculated using the Demand Study data. The ratio of anticipated hydrogen throughput values for Angeles Link to projected values in the Demand Study were then calculated for each of the conservative (26.85%), moderate (31.12%), and ambitious (25.36%) scenarios. These ratios were then applied to the NOx and other pollutants estimated emissions using the Demand Study scenarios to determine NOx and other pollutants estimates associated with Angeles Link Throughput Scenarios. This analysis is shown in Table 1 below.

Table 1
NOx Reduction Estimates for Demand Study Scenarios Applied to Projected Angeles Link Throughput Scenarios

Demand Scenario	Total Projected Hydrogen Demand (MMT/yr)	Overall NOx Reductions for Demand in 2045 (tpy)	Angeles Link Projected Hydrogen Throughput (MMT/yr)	Overall NOx Reductions Based on Angeles Link Throughput in 2045 (tpy)
Low	1.9	13,847	0.5	3,793
Moderate	3.2	17,179	1	5,347
High	5.9	20,529	1.5	5,206

Key Findings

- In 2030, the Ambitious Demand Scenario estimates approximately 5,240 ton/year NOx reductions as shown in Table 6, associated with the displacement of fossil fuels by hydrogen for end-users minus emissions from infrastructure associated with third-party production, third-party storage, and transmission of hydrogen. Based on throughput values for Angeles

Link, the High Throughput Scenario estimates that Angeles Link could supply 25.36% of the overall hydrogen demand project by the Demand Study. Therefore, overall NO_x emissions reductions associated with the Angeles Link High Throughput Scenario in 2030 are estimated at 1,329 tons per year as shown in Table 14. This value of 1,329 tons of NOx per year is the same as 23% of the NOx reductions South Coast Air Quality Management District (South Coast AQMD) has proposed to be achieved by 2037 for total stationary commercial and large combustion source NOx control measures in their 2022 Air Quality Management Plan (AQMP).[6]

- In 2045, the Ambitious Demand Scenario estimates NOx emissions reductions of 20,529 tons/year (as shown in Table 6) associated with the displacement of fossil fuels by hydrogen for end-users minus emissions from new infrastructure associated with the third-party production, third-party storage, and transmission of hydrogen demand. Based on throughput values for Angeles Link, the High Throughput Scenario estimates that Angeles Link could supply 25.36% of the overall hydrogen demand. Therefore, overall NO_x emissions reductions associated with the Angeles Link High Throughput Scenario in 2045 are estimated at 5,206 tons per year. This value of 5,206 tons of NOx per year is the same as 90% of the NOx reductions South Coast AQMD has proposed to be achieved by 2037 for total stationary commercial and large combustion source NOx control measures in their 2022 AQMP.[7]
- Of the three end-user sectors, the mobility sector makes up the bulk of the NO_x emissions reductions (over 99% in the ambitious Demand Scenario). This parallels the 2018 emissions inventory used by South Coast AQMD in their 2022 AQMP which shows that 85% of emissions in the South Coast AQMD are from mobile sources and 15% are from stationary sources. Mobility NOx emissions (e.g., primarily heavy-duty transportation) is expected to be reduced with the conversion to zero emission vehicles (ZEVs). Options for ZEVs include hydrogen fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEVs). The Demand Study projected the anticipated fossil fuel displacement associated with FCEVs only. The associated NOx reductions were estimated only for conversion to FCEVs; this study does not project emission reductions related to fossil fuel displacement that will be associated with BEVs.
    - The study assumes that hydrogen is utilized in fuel cells in the mobility sector, and in combustion units for stationary applications within power generation and hard to electrify Industrial sectors. The use of hydrogen in fuel cells produces zero NO_x emissions, while the combustion of hydrogen does have the potential to form NO_x emissions.
- A relatively small reduction in NO_x emissions is expected from combusting hydrogen as compared to pure natural gas. The difference in NO_x emissions from the combustion of hydrogen fuel compared to fossil fuels is attributable to differences between NOx emission

[6] South Coast AQMD, 2022a, 2022 Air Quality Management Plan, Appendix IV-A, Stationary and Mobile Source Control Measures, https://www.aqmd.gov/docs/default-source/clean-air-plans/air-quality-management-plans/2022-air-quality-management-plan/final-2022-aqmp/appendix

[7] South Coast AQMD, 2022a, 2022 Air Quality Management Plan, Appendix IV-A, Stationary and Mobile Source Control Measures, https://www.aqmd.gov/docs/default-source/clean-air-plans/air-quality-management-plans/2022-air-quality-management-plan/final-2022-aqmp/appendix

factors for hydrogen fuel as compared to NOx emission factors for natural gas. Current research into the scientific literature supports the potential for a reduction in NO_x emissions when transitioning from the combustion of fossil fuels to hydrogen fuels as 1) hydrogen has the potential to combust at a wider range of air to fuel ratios and lower temperatures than fossil fuels, 2) there are potentially favorable differences in the thermodynamic efficiency of hydrogen in turbines as compared to natural gas, and 3) certain burner technologies have proven experimentally to emit lower NO_x emissions from hydrogen combustion as compared to natural gas combustion. Since current data and scientific research is still evolving, the Study takes a conservative approach to estimating NOx and other air emissions.

- In the power generation sector, the estimated NO_x reductions associated with market adoption of hydrogen are approximately 0.7 ton/year in 2030 and up to approximately 72 ton/year in 2045 based on the Ambitious Demand Scenario. The bulk of the expected reductions from Power Generation (e.g. over 80%) are attributed to the peaker and baseload sub-sector for all years. Expected emissions reductions associated with Angeles Link in the power generation sector in 2030 are roughly 0.2 tons per year, and in 2045 are roughly 18.2 tons per year based on the Angeles Link High Throughput Scenario.

- In hard to electrify industrial sectors, the estimated NO_x reductions associated with market adoption of hydrogen are 7 ton/year in 2030 and 19 ton/year in 2045 using the Ambitious Demand Scenario. In the Ambitious Demand and High Throughput Scenarios, refineries account for the largest reductions (e.g. 52.2% Ambitious, 2030), followed by Stone, Glass, Cement (18.4% Ambitious, 2030), Food and Beverage (17.4% Ambitious, 2030), and Metals (8.1% Ambitious, 2030). These percentages are not expected to change much between 2030 and 2045. Expected emissions reductions associated with the Hard to Electrify Industrial sector in 2030 are roughly 1.9 tons per year, and in 2045 are roughly 4.9 tons per year using the Angeles Link High Throughput Scenario.

- In the Mobility sector, the estimated NO_x reductions associated with market adoption of hydrogen are roughly 5,600 ton/year in 2030 and 22,000 ton/year in 2045 using the Ambitious Demand Scenario. The largest percentage of overall NO_x reductions associated with market adoption of hydrogen in the Mobility sector in the Ambitious Demand and High Throughput Scenarios are attributable to heavy-duty vehicles (e.g. 69.1% in 2030 and 77.4% in 2045), followed by buses (exceeded by construction and mining by 2045) (14.2% in 2030 and 5.6% in 2045), construction and mining vehicles(6.8% in 2030 and 6.7% in 2045), and then medium-duty vehicles (6.4% in 2030 and 4.4% in 2045). Three of the top four sub-sectors contributing the greatest magnitude of NO_x emissions reductions are the three on-road sub-sectors. The magnitude of reductions from the collective on-road sub-sectors is much greater than the magnitude of reductions from the collective off-road sub-sectors. The largest variable impacting the magnitude of emissions reductions from on-road versus off-road vehicles is the estimated volume of fossil fuels displaced as projected by the Demand Study. Expected emission reductions associated with the Mobility sector in 2030 are roughly 1,400 tons per year, and in 2045 are roughly 5,660 tons per year, using the Angeles Link High Throughput Scenario.

- Based on currently available information, new infrastructure potential emissions account for a relatively small percentage when compared with end-user emissions reductions. In 2030 the infrastructure NO_x emissions associated with the market adoption of hydrogen are estimated to be approximately 360 tons/year, which accounts for 6% of the total estimated NO_x reductions from end-users associated with the Ambitious hydrogen demand projections (2030) from the Demand Study. In the same scenario for the year 2045, infrastructure NO_x emissions are approximately 1,900 tons/year, which accounts for about 8% of total NO_x reductions from end-users associated with the Ambitious Demand Scenario projections (2045) from the Demand Study. Based on the High Throughput Scenario for Angeles Link, new infrastructure emissions in the maximum emissions scenario for 2030 are estimated at 91 tons per year of NO_x, and for 2045 are estimated at 481 tons per year of NO_x.

- The estimated annual reductions in $PM_{2.5}$ and PM_{10} emissions associated with end-users displacing fossil fuels with hydrogen fuel are estimated at approximately 2,339 and 3,539 tons, respectively, for 2045 in the Ambitious Demand Scenario. The South Coast Air Quality Management District (South Coast AQMD) projects annual $PM_{2.5}$ emissions in 2037 to be approximately 60.08 tons/day, PM_{10} to be 173.63 tons/day, and total PM to be 298.51 tons/day. This yields $PM_{2.5}$ emissions of 21,929 tons and PM_{10} emissions of 63,375 tons for the year 2037. Therefore, the estimated annual average reductions in $PM_{2.5}$ and PM_{10} emissions in the South Coast AQMD for the market adoption of hydrogen are potentially up to 11% and 6%, respectively. The total reductions in $PM_{2.5}$ and PM_{10} emissions associated with the Angeles Link High Throughput Scenario in 2045 are about 593 and 898 tons per year, respectively. These values are about 3% and 1% of projected 2037 $PM_{2.5}$ and PM_{10} emissions in the South Coast AQMD, respectively.

- Hydrogen is a non-carbon containing fuel that eliminates diesel particular matter (DPM) when replacing diesel fuel. Studies indicate that hydrogen fuel substitution of non-diesel fossil fuels almost entirely reduces PM emissions in spark-ignited engines and turbines. DPM reductions from the displacement of diesel fuel with hydrogen fuel in the Ambitious Demand Scenario are estimated to be approximately 656.37 tons per year by 2045.

- Hydrogen usage is not known to produce direct VOC emissions and VOC may be eliminated by replacing fossil fuels with hydrogen fuel. A reduction in VOC emissions associated with end-users displacing fossil fuels with hydrogen fuel as projected by the Demand Study was estimated at approximately 4,595 tons by 2045 in the Ambitious Demand Scenario. The South Coast AQMD projects their annual VOC emissions in 2037 to be 120,335 tons.[8] Therefore, the annual average reductions in VOC emissions estimated by the market adoption of hydrogen are about 3.8% of the VOC emissions in the South Coast AQMD region. The estimated reductions in VOC emissions associated with the Angeles Link High Throughput Scenario are about 1,165 tons per year in 2045.

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[8] South Coast AQMD, 2022b, 2022 Air Quality Management Plan Appendix III Base and Future Year Emission Inventory, Adopted December 2, https://www.aqmd.gov/docs/default-source/clean-air-plans/air-quality-management-plans/2022-air-quality-management-plan/final-2022-aqmp/appendix-iii.pdf?sfvrsn=6

Emissions Minimization Opportunities: Opportunities to minimize NOx emissions or measures to reduce NOx emissions can be implemented to reduce NOx emissions, including with equipment design, control of combustion temperature, and application of existing and emerging aftertreatment technologies. Existing technologies include selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), and non-selective catalytic reduction (NSCR), while emerging technologies include electron beam irradiation and electrochemical reduction.

Stakeholder Input

The input and feedback from stakeholders including the Planning Advisory Group (PAG) and Community Based Organization Stakeholder Group (CBOSG) has been helpful to the development of this draft NOx and other Air Emissions Assessment Study Report. For example, in response to stakeholder comments, maps have been prepared that depict the anticipated NOx emissions reductions geographically. Additionally, as another example, the study includes a review of relevant literature provided by stakeholders, as applicable. The feedback that has been received to-date related to this Study and how those comments are addressed is summarized in more detail in Section 12.

NOX AND OTHER AIR EMISSIONS
DRAFT STUDY – ANGELES LINK

About the Research

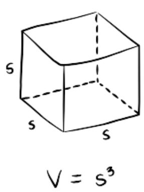
Understanding the Draft Study

Study Purpose

- Estimate NOx emissions associated with Angeles Link infrastructure, as well as third-party production and third-party storage. Assess projected NOx emission reductions from displacing fossil fuels with hydrogen in various end user sectors.

Scope

- Focus on NOx emissions from hydrogen infrastructure and reductions from fossil fuel displacement.
- Includes examination of opportunities to mitigate and minimize NOx emissions.



Key Assumptions

- Use of renewable electricity for hydrogen production to minimize NOx emissions from the energy supply side.
- Anticipation of technological efficiencies and market adoption rates to project air quality benefits.

Limitations

- Acknowledges the feasibility study nature, indicating the potential for ongoing refinement of data and conclusions.

Informed by Research

- Research from academic institutions (UCI, Georgia Tech) and private organizations (EPRI, EDF).
- Regulatory frameworks from federal (US EPA, US DOE), state (CARB, CEC), and local agencies (e.g., South Coast AQMD).
- Developments in hydrogen technology from manufacturers and technical data from government entities (US DOE, NREL).

Understanding the Impact of Angeles Link

Identifying End-Users for Angeles Link

Mobility Sector

- Heavy-Duty Trucks, Medium-Duty Vehicles, Buses, Agriculture, Construction & Mining Equipment, Cargo Handling Equipment, Ground Support Equipment, Commercial Harbor Craft.

Power Generation Sector

- Turbines and Co-generation.

Hard-to-Electrify Industries

- Chemical Manufacturing, Metal Refining and Treatment, Stone/Glass/Cement, Food & Beverage, Paper & Pulp, Aerospace, Refineries.

Methodology

Clean Renewable Hydrogen refers to hydrogen that does not exceed 4 kilograms of CO2 produced on a lifecycle basis per kilogram of hydrogen produced and does not use fossil fuel in the hydrogen production process where fossil fuel is defined as extracted from underground deposits.

Evaluated Emissions Change for Demand Scenarios and Angeles Link Throughput Scenarios (Low, Mid, High)

Fuel Throughput x Emissions Factor = Emissions

Emission Reductions = Fossil Fuel Emissions – Hydrogen Emissions

Third-Party Production
- Electrolysis
- Biomass gasification
- RNG Steam methane reforming

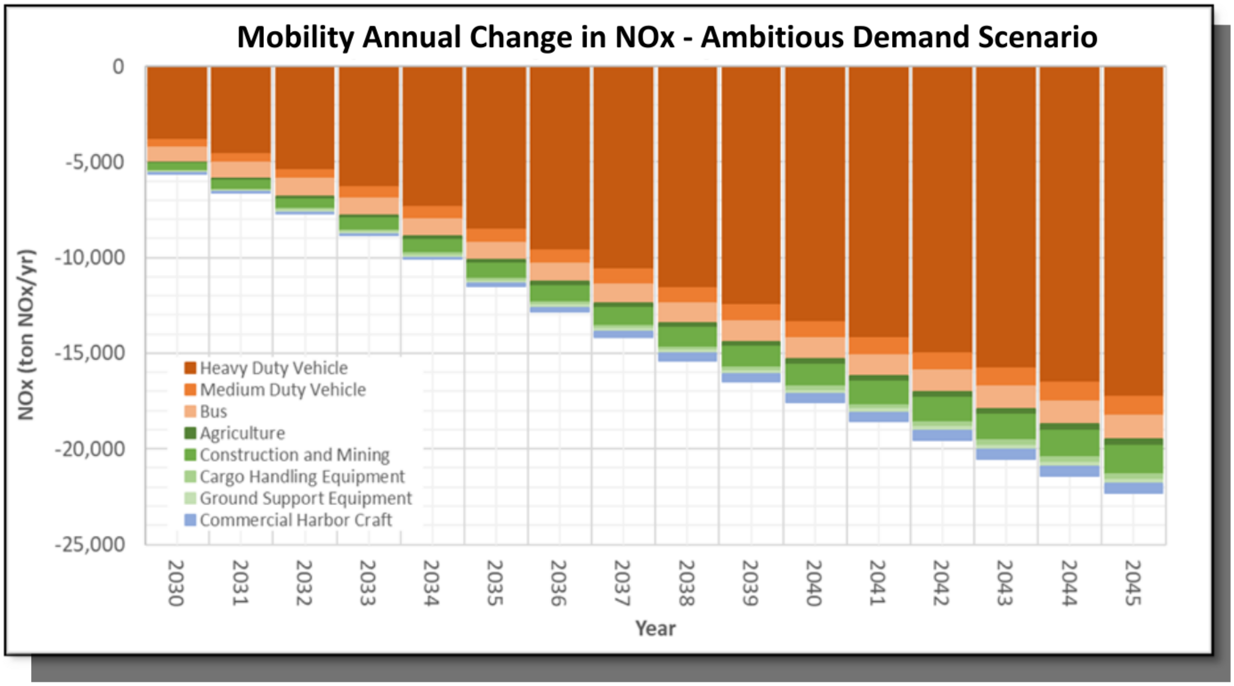
Third-Party Storage and Transmission
- Electric driven compressors
- Hydrogen fueled compressors

Industrial and Power
- Natural gas displacement

Mobility
- Diesel and gasoline displacement

NOx Results for Demand Scenarios by End-Use Sectors

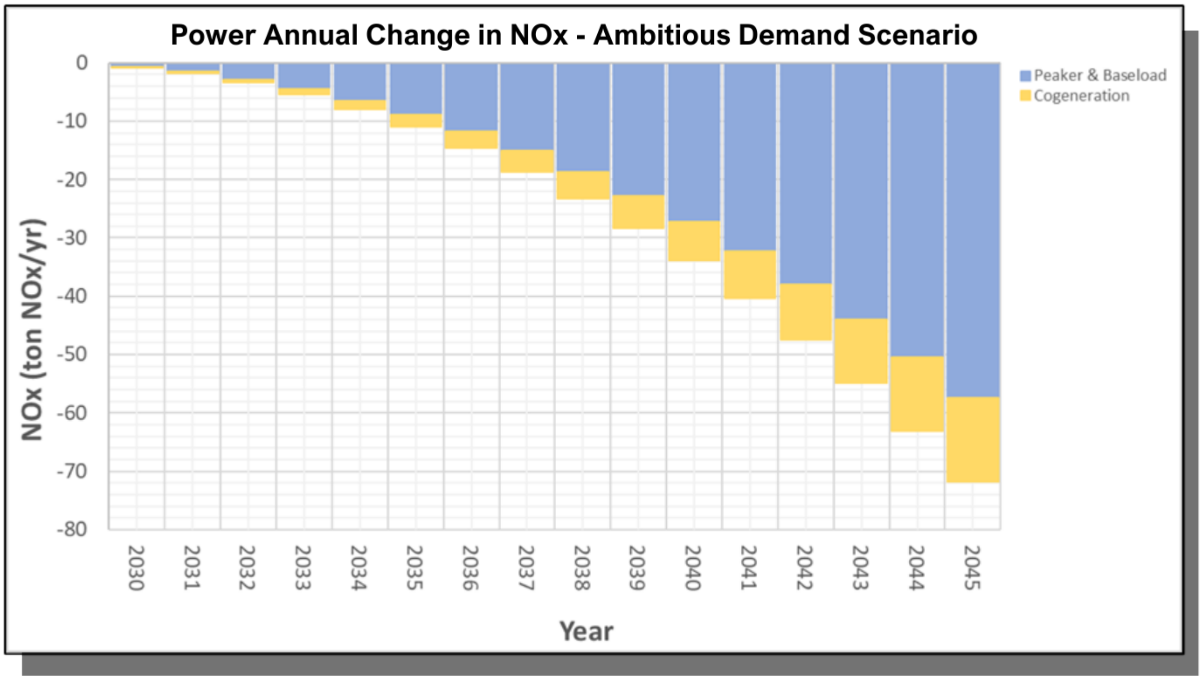
End User Annual Reductions in NOx Emissions, based on High Demand Scenario, 2030-2045 (ton NOx/year)



Mobility Sector

- **2030: 5,589 tons/year reductions**
- **2045: 22,333 tons/year reductions**

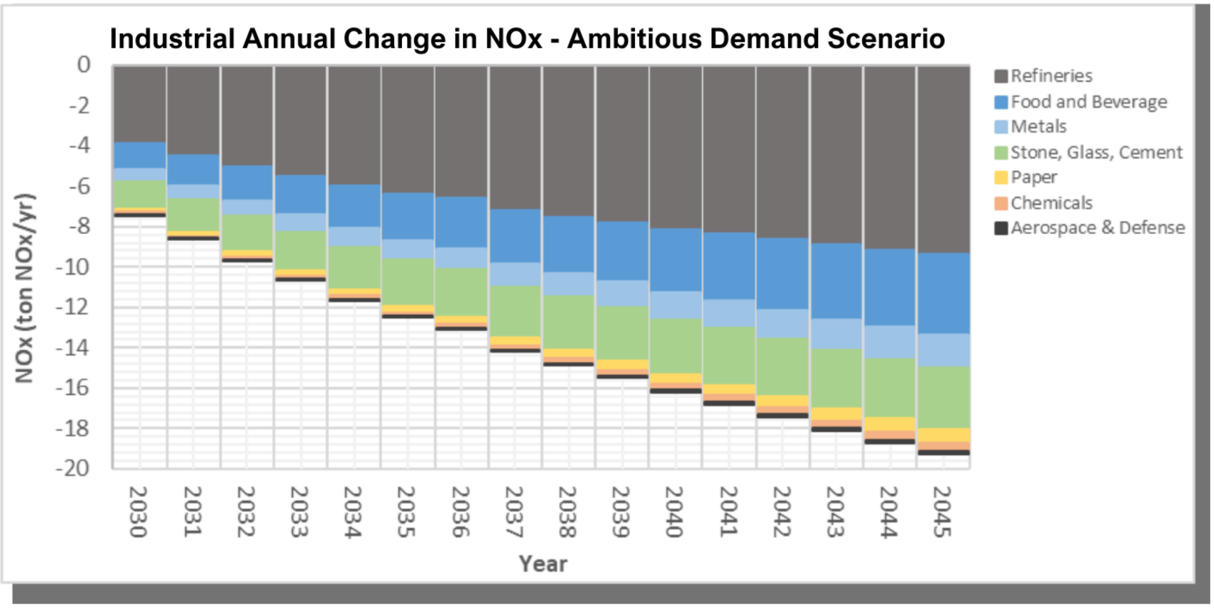
The Mobility sector comprises over 99% of end-user reductions.



Power Generation Sector

- **2030: 0.7 ton/year reductions**
- **2045: 71.7 tons/year reductions**

Suggests efficiency improvements in peaker and baseload power sub-sectors.



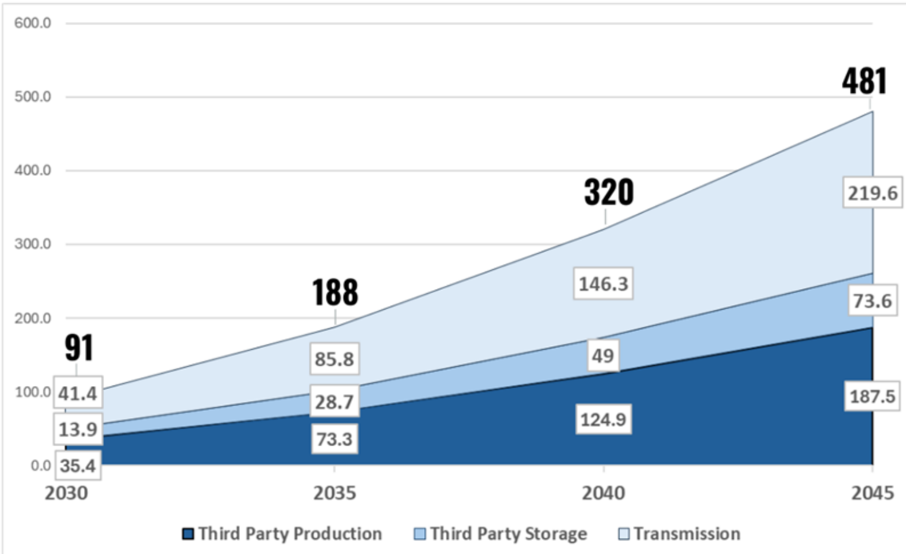
Hard to Electrify Industrial Sector

- **2030: 7.4 tons/year reductions**
- **2045: 19.3 tons/year reductions**

Main contributions from refineries, food & beverage, and stone/glass/cement sectors.

Evaluating the Air Quality Impact of Angeles Link

NOx Results for Angeles Link Infrastructure, as well as Third-Party Production, Third-Party Storage and Transmission (tons per year)



NOx Emissions from Transmission

The NOx emissions are based on an assumed transmission distance of 450 miles using hydrogen. For compressors using renewable electricity, the NOx emissions are zero. For compressors using hydrogen, there are some NOx emissions.

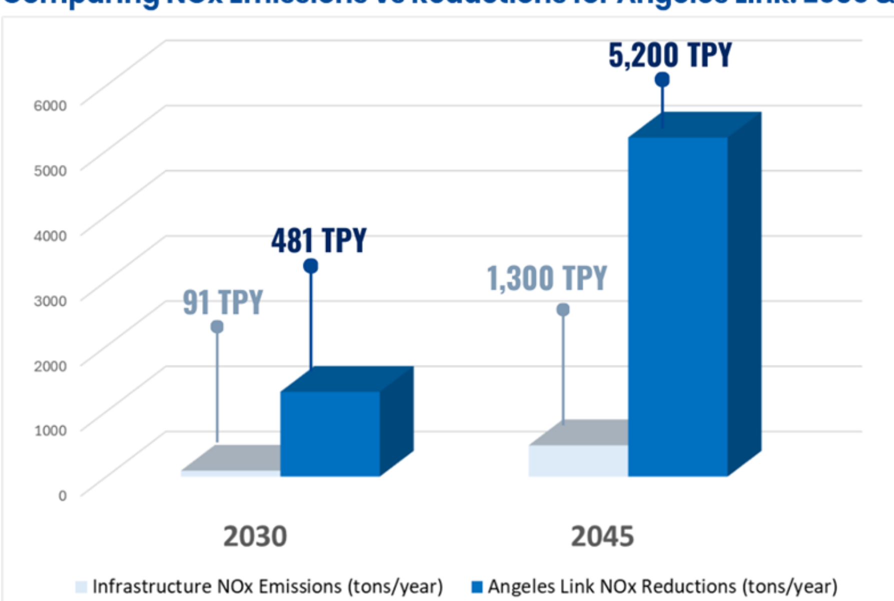
NOx Emissions from Third-Party Production

The values for NOx emissions represent 100% RNG SMR. In contrast, the emissions for 100% Electrolysis or Biomass Gasification are zero.

NOx Emissions from Third-Party Storage

The NOx emissions values represent third-party storage at 2,900 psi using an H2 reciprocating engine. For compressors using renewable electricity, the NOx emissions are zero. For compressors using hydrogen, there are some NOx emissions.

Comparing NOx Emissions vs Reductions for Angeles Link: 2030 & 2045



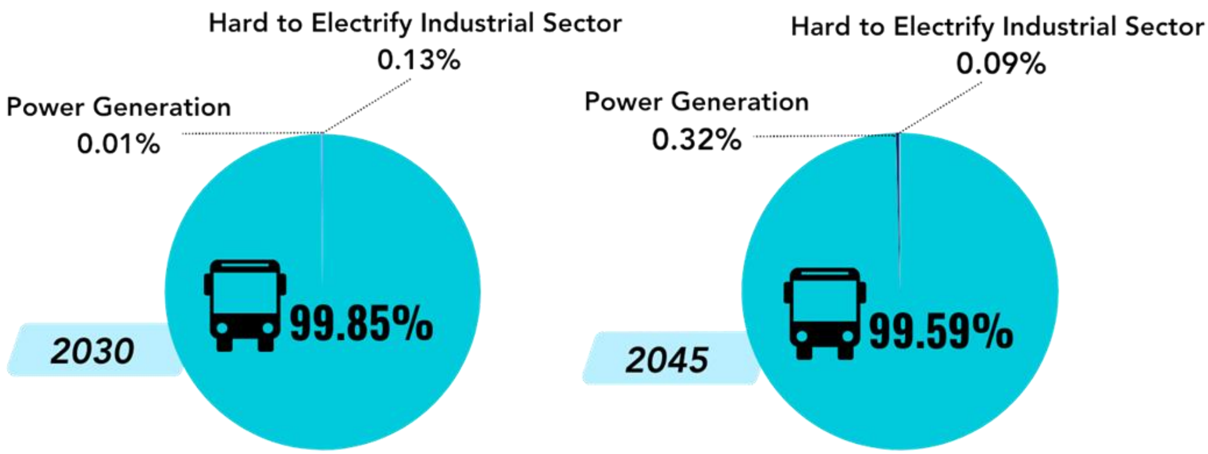
Estimated NOx Infrastructure Emissions vs. Expected NOx End User Reductions for Angeles Link (2030 & 2045)

The chart emphasizes that the NOx reductions achieved by the Angeles Link project far exceed the emissions generated by the infrastructure itself, particularly by 2045.

Note: The depicted values include estimated NOx from third-party production and third-party storage.

NOx Emissions and Reductions for Angeles Link: 2030 & 2045

End User Sectors' NOx Reductions in High Throughput Scenario



Notes: Assumptions for the Mobility sector are based on the projected hydrogen demand that would displace diesel and gasoline fuel for vehicles that are projected to convert FCEVs with zero NOx emissions. *Emission factors for NOx from displaced diesel and gasoline fuel were developed using EMFAC data.*

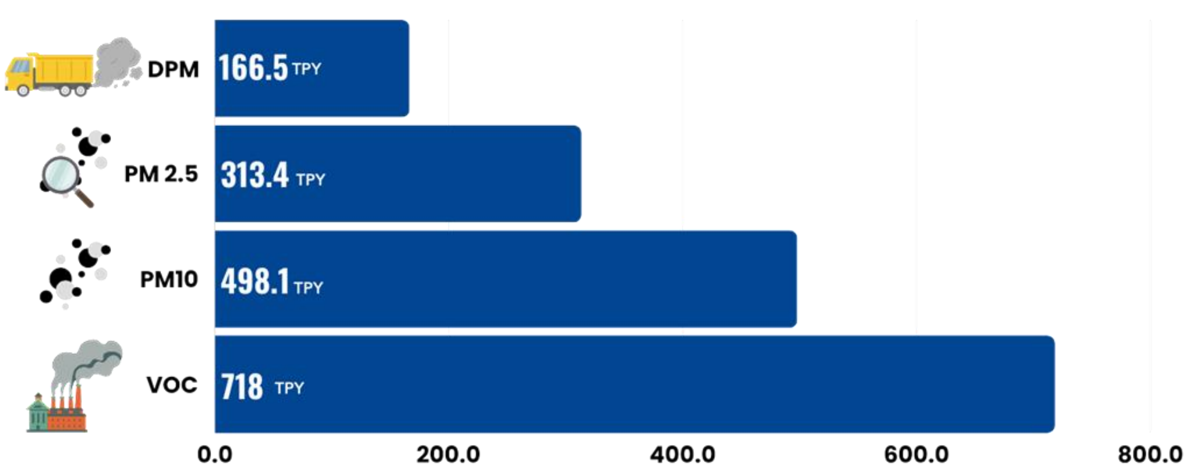
Mobility Sector
- **2030: 1,400/year**
- **2045: 5,660 tons/year**

Power Generation Sector
- **2030: 0.2 tons/year**
- **2045: 18.2 tons/year**

Hard to Electrify Industrial Sector
- **2030: 1.9 tons/year**
- **2045: 4.9 tons/year**

Emission Reductions for Other Emissions: 2045

Angeles Link Specific Emissions Reductions in High Throughput Scenario, 2045 (tons/year)



NOx Minimization Opportunities

Equipment Design

- Use low swirl burners suitable for various equipment, such as boilers and furnaces, to handle hydrogen's high flame speed and adiabatic flame temperature.
- Consider lean or ultra-lean burn technology to reduce NOx emissions effectively.
- Consider thermal efficiency and minimize residence time in combustion reactions to reduce NOx formation.

Air to Fuel Ratio and Flame Temperature

- Increase the air-to-fuel ratio (lean operation) to lower combustion temperatures and reduce thermal NOx emissions.
- Employ strategies like exhaust gas recirculation (EGR), pre-mixing, and using high-emissivity porous materials to mitigate NOx emissions.
- Adjust equivalence ratios and hydrogen mole fraction in the fuel to achieve lower NOx emissions through optimized combustion properties.

Flame Type

- Distinguish between premixed and non-premixed flames; manage fuel and air mixing to control peak temperatures and NOx levels.
- Use technologies like micromixers in gas turbines and adjust combustion system settings to reduce NOx emissions effectively.

Exhaust Gas Recirculation

- Inject exhaust gas back into the engine to displace air and lower oxygen levels in the combustion chamber, thus reducing maximum combustion temperatures.
- Optimize EGR effectiveness through careful management of combustion properties and fuel composition.

Thermal Efficiency

- Increase compression ratio and utilize strategies like stratified charge to improve thermal efficiency and reduce the potential for NOx formation during combustion.

Post-Combustion Treatments

- Use SCR, NSCR, or SNCR methods for NOx control in exhaust systems.
- Emerging technologies such as electron beam irradiation for NOx management.

Abbreviations

AB	Assembly Bill
AL	Angeles Link
APCD	Air Pollution Control District
AQMD	Air Quality Management District of California
BEV	Battery Electric Vehicle
CAAP	Clean Air Action Plan
CARB	California Air Resources Board
CEC	California Energy Commission
CFR	Code of Federal Regulations
CPUC	California Public Utilities Commission
DRI	Direct Reduced Iron
EF	Emission Factor
EGU	Electricity Generating Unit
EO	Executive Order
EPRI	Electric Power Research Institute
FARMER	Funding Agricultural Replacement Measures for Emission Reductions
FCEV	Hydrogen Fuel Cell Vehicle
FERC	Federal Energy Regulatory Commission
ICE	Internal Combustion Engine
IRA	Inflation Reduction Act
NREL	National Renewable Energy Lab
NSPS	New Source Performance Standards
PEM	Proton Exchange Membrane
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PNNL	Pacific Northwest National Laboratory
SMR	Steam Methane Reforming
UC	University of California
UCI	University of California Irvine
US DOE	United States Department of Energy

US EPA	United States Environmental Protection Agency
ZEAT	Zero Emissions Advanced Technology
ZECAP	Zero Emissions for California Ports
ZEV	Zero Emission Vehicle

Glossary

Adiabatic flame temperature - The adiabatic flame temperature is the temperature reached by a flame under ideal conditions during the study of combustion. It is a higher temperature that is reached during actual processes. There are two types of adiabatic flame temperature: constant volume and constant pressure. The constant volume adiabatic flame temperature is the temperature that results from a complete combustion process that occurs without any work, heat transfer or changes in kinetic or potential energy. Its temperature is higher than in the constant pressure process because no energy is used to change the volume of the system.

Air toxics – Air toxics are toxic**,** or hazardous**,** air pollutants that cause or are suspected of causing cancer, birth defects, or other serious harms.

Air to Fuel Ratio – the air to fuel ratio equals the actual air to fuel ratio divided by the stoichiometric air to fuel ratio for the fuel. A value greater than 1 refers to lean mixtures and a value less than 1 refers to rich mixtures.

Ambient air – Ambient air refers to atmospheric air in its natural state. Ambient air typically consists of 78% nitrogen and 21% oxygen. The remaining 1% is a combination of carbon, helium, methane, argon, and hydrogen.

Autoignition (Ignition) Temperature – The minimum temperature that a substance mixed with air will ignite and burn without an ignition source.

Best Available Control Technology (BACT) – A pollution control standard mandated by the Clean Air Act and administered by the Environmental Protection Agency (EPA) and through delegation to local California Air Pollution Control districts. The BACT standard determines which air pollution control technology must be used to control the emission levels of a specific pollutant to its specified limit. The determination of what constitutes the "best available technology" for a particular pollutant and piece of equipment is decided within a system of defined criteria that considers energy consumption, total facility emissions, regional environmental impact, and the economic costs that would result from the use of the various emissions control solutions available. The BACT standard is the current standard applied to new or modified affected equipment.

Blended fuels – Blended fuels are mixtures of traditional and alternative fuels in varying percentages. Blends can be thought of as transitional fuels**.** The lowest-percentage blends are being marketed and introduced to work with current technologies while paving the way for future integration, in this case, eventual usage of 100% hydrogen fuel.

Calorific value – The amount of heat released during combustion of a fuel. Also referred to as the heating value. Lower heating value (LHV) is typically used in engine and turbine manufacturers' information whereas higher heating value (HHV) is used by air quality regulators and external combustion vendors. HHV is approximately 10% higher than LHV.

Clean renewable hydrogen - Clean renewable hydrogen is defined as hydrogen that does not exceed 4 kilograms of CO_2e produced on a lifecycle basis per kilogram of hydrogen produced and does not use fossil fuel in the hydrogen production process where fossil fuel is defined as a mixture of hydrocarbons including coal, petroleum, or natural gas, occurring in and extracted from underground deposits per D.22-12-055 dated December 15, 2022.

Cogeneration or **combined heat and power** (**CHP**) – CHP is the use of a heat engine or power station to generate electricity and useful heat at the same time. Cogeneration is a more efficient use of fuel or heat, because otherwise-wasted heat from electricity generation is put to some productive use. CHP plants recover otherwise wasted thermal energy for heating, which is also referred to as CHP district heating.

Compressors - A compressor is a mechanical device that increases the pressure of a gas by reducing its volume. An air compressor is a specific type of gas compressor. Compressors are similar to pumps: both increase the pressure on a fluid and both can transport the fluid through a pipe. The main distinction is that the focus of a compressor is to change the density or volume of the fluid, which is mostly only achievable on gases. Gases are compressible, while liquids are relatively incompressible, so compressors are rarely used for liquids. The main action of a pump is to pressurize and transport liquids.

Continuous Emission Monitoring System (CEMS) – A CEMS involves equipment necessary to analyze a gas or particulate matter concentration or emission rate using pollutant analyzer measurements and a conversion equation, graph, or computer program to show results of the applicable emission limitation or standard. CEMS are required under some of the EPA regulations for either calculating mass emissions (40 CFR 60 Part 70) or determination of exceedances of the standards (40 CFR 60 Part 60). Performance Specifications are used for evaluating the acceptability of the CEMS at the time of or soon after installation of equipment and whenever specified in the regulations.

Density – the mass per unit volume of a substance.

Diffusivity – Diffusivity is a measure of the capability of a substance or energy to be diffused or to allow something to pass by diffusion. Diffusivity refers to the spreading of something or making it less concentrated.

Drayage trucks - Drayage trucking involves shipping goods a short distance using ground freight. You see drayage loads commonly in intermodal shipping, such as moving large containers from a ship to rail for delivery.

Electrolyzer – An electrolyzer uses electrolysis as a method for carbon-free hydrogen production using renewable electricity. Electrolysis is the process of using electricity to split water into hydrogen and oxygen.

Emission source types – Emission source types are sources of emissions from activities or processes that release greenhouse gases and/or pollutants into the atmosphere.

End-users – An end-user uses hydrogen delivered by the new infrastructure.

Engine – a machine that converts thermal energy into useful work (e.g., electricity of shaft power) to produce force and motion.

Equivalence Ratio – equivalence ratio refers to the fuel to air ratio. Defined as the ratio of the fuel-to-oxidizer ratio to the stoichiometric fuel-to-oxidizer ratio.

Exhaust gas aftertreatment – a device that reduces exhaust emissions from combustion equipment such as turbines and engines. It cleans exhaust gases to ensure the engines meet emission regulations. The main function of an aftertreatment system is to reduce emissions post combustion.

External combustion – The process of combining heat, fuel, and oxygen for the combustion process without direct contact with the working fluid. For example, in a boiler, heat is transferred to water (working fluid) across a boundary. The water does not come into direct contact with the combustion gases.

Feasibility study – A feasibility study is an assessment of the practicality of a proposed project plan or method. For example, asking "Is this feasible?" by analyzing technical and operational feasibility factors.

Feedstock – Feedstock is the material that is used in some hydrogen production equipment and such as renewable natural gas and biomass.

Flammability range – The range of air-to-fuel ratios for which a substance will burn when exposed to an ignition source. The low end of this range is "rich" combustion where excess fuel inhibits combustion. The high end of this range is "lean" combustion where excess air inhibits combustion.

Flame speed – The rate of expansion of a flame front in a premixed combustion reaction. This is the speed that unburned gas reactant gases (e.g., fuel and air) must move relative to an unmoving flame to supply it with fuel.

Fossil fuel – Hydrocarbon materials of biological origin. Fossil fuel includes decomposing plants and other organisms, buried beneath layers of sediment and rock. These fuels include coal, oil, and natural gas.

Global Warming Potential (GWP) - Global warming potential (GWP) is a measure of how much infrared thermal radiation a greenhouse gas added to the atmosphere would absorb over a given time frame, as a multiple of the radiation that would be absorbed by the same mass of added carbon dioxide (CO_2). GWP is 1 for CO_2. For other gases it depends on how strongly the gas absorbs infrared thermal radiation, how quickly the gas leaves the atmosphere, and the time frame being considered.

Green hydrogen - Green hydrogen is produced through water electrolysis process by employing renewable electricity. The reason it is called green is that there is no CO_2 emission during the production process. Water electrolysis is a process which uses electricity to decompose water into hydrogen gas and oxygen.

Heavy-duty transportation – Heavy-duty transportation includes flatbed trailers, wide load hauling, large trucks, and freight trucks.

Hydrogen – Hydrogen is a colorless, odorless, tasteless, flammable gaseous substance that is the simplest member of the family of chemical elements.

Hydrogen fuel cell - A hydrogen fuel cell is an electrochemical cell that produces a current that can work using a spontaneous redox reaction**.** The combination of the two half-cell potentials for the electrochemical reaction creates a positive potential for cells. In general, fuel cells are different from most batteries in that they require a continuous source of fuel and oxygen (usually from air) to sustain the chemical reaction, whereas in a battery the chemical energy usually comes from substances that are already present in the battery. Fuel cells can produce electricity continuously for as long as fuel and oxygen are supplied. The byproduct of a hydrogen fuel cell is water vapor.

Ignition energy – The minimum energy required to initiate the self-sustained combustion of a substance.

Infrastructure – Infrastructure are the resources such as pipelines and compressors required for an activity such as transmission of hydrogen.

Internal combustion – The process of combining heat, fuel, and oxygen within a combustion chamber where the combustion gases themselves are the working fluid.

Lowest achievable emission rate (LAER) - Under the Clean Air Act, LAER is the rate of emissions that reflects the most stringent emission limitation in the implementation plan of any state for a source or sources unless the owner or operator demonstrates such limitations are not achievable; or the most stringent emissions limitation achieved in practice, whichever is more stringent.

Methane – Methane is a chemical compound with the chemical formula CH_4 (one carbon atom bonded to four hydrogen atoms). It is the main component of natural gas.

Methodology – Methodology is the general research strategy that outlines the way in which research is to be undertaken and, among other things, identifies the methods to be used in it. These methods, described in the methodology, define the means or modes of data collection or, sometimes, how a specific result is to be calculated.

Minimal platinum loading - Minimal platinum loading is a term used in the context of PEM electrolysis. In a PEM electrolyzer, platinum is used as a catalyst for the electrodes. The cathodes are commonly made of platinum black or of platinum layers on a carbon core.

NOx – NOx is shorthand for nitrogen oxides (comprised of NO and NO_2) which is an air pollutant subject to air quality regulations formed during combustion of fossil fuels and a precursor to ozone.

Non-selective catalytic reduction – Non-selective catalytic reduction (NSCR) is a method of aftertreatment that can be utilized for exhaust streams with low oxygen content. NSCR uses a catalyst reaction to simultaneously reduce NOx, CO, and VOC to water, CO2, and nitrogen. The catalyst is typically a noble metal.

Polymer Electrolyte Membrane (PEM) is one of the water electrolysis technologies to split water molecules into hydrogen and oxygen. Its name comes from the use of a gas-tight solid polymer-based membrane as electrolyte, the ion transport material between electrodes.

Polymer electrolyte membrane fuel cell – Polymer electrolyte membrane fuel cells (PEMFC) convert the chemical energy stored in hydrogen fuel directly and efficiently to electrical energy with water as the only byproduct.

Pipeline Transmission System – a system of pipelines, compressor stations, and metering stations used to move gases.

Project Scenario - A project scenario is a description of what a project proposal will look like when it is completed. This allows companies to identify potential problems that may occur along the way so they can be addressed in project planning for a smooth and productive outcome. Scenario planning, sometimes called scenario thinking or scenario analysis, is used by organizations as part of their strategic planning process.

Reciprocating compressors - A reciprocating compressor uses a linear drive to move a piston or a diaphragm back and forth to compress a gas. This motion compresses the gas by reducing the volume it occupies. Reciprocating compressors are the most used compressors for applications that require a very high compression ratio (compression ratio is the ratio of the pressure at the outlet of the compressor over the pressure at the inlet of the compressor).

Refining – Refining is removing impurities or unwanted elements from a substance, typically as part of an industrial process.

Residence time - Residence time is the exposure to peak combustion temperature, which also impacts the formation of NO_x emissions. The longer the residence time, the greater the formation of NO_x. Therefore, it is important for manufacturers to design to minimize the residence time.

Selective catalytic reduction - Selective catalytic reduction (SCR) converts nitrogen oxides, also referred to as NO_x, with the aid of a catalyst into diatomic nitrogen (N_2), and water (H_2O). SCR catalysts are made from various porous ceramic materials used as a support, such as titanium oxide, and active catalytic components are usually either oxides of base metals (such as vanadium, molybdenum and tungsten), zeolites, or various precious metals. Ammonia or urea is used as a reagent to reduce the NOx. Another catalyst based on activated carbon was also developed which is applicable for the removal of NOx at low temperatures.

Selective non-catalytic reduction – Selective non-catalytic reduction (SNCR) is a post combustion emission control technology for reducing NOx. The process involves injecting ammonia or urea at a location where the flue gas is between 1,400^{o}F and 2,000^{o}F to react with NOx formed in the combustion process.

Stack testing - A stack test, also referred to in EPA regulations as a performance or source test, measures the amount of a specific regulated pollutant, pollutants, or surrogates being emitted; demonstrates the capture efficiency of a capture system; or determines the destruction or removal efficiency of a control device used to reduce emissions at facilities subject to the requirements of the Clean Air Act (CAA or Act).

Stationary source – A stationary source refers to a qualitative term used to describe any fixed emitter of air pollutants, such as power plants, oil refineries, and heavy industrial facilities.

Steam generating units – Industrial/commercial/institutional steam generating units are boilers that are capable of combusting over 10 million international British thermal units per hour (MMBtu/hr) of fuel. A boiler or steam generator is a device used to create steam by applying heat energy to water.

Stoichiometric ratios/calculations - Stoichiometric ratios/calculations are used to analyze the relationship between the weights of reactants and products before, during, and following chemical reactions. Stoichiometry is founded on the law of conservation of mass where the total mass of the reactants equals the total mass of the products, leading to the insight that the relations among quantities of reactants and products typically form a ratio of positive integers. This means that if the amounts of the separate reactants are known, then the amount of the product can be calculated. Conversely, if one reactant has a known quantity and the quantity of the products can be empirically determined, then the amount of the other reactants can also be calculated.

Throughput – Throughput is the amount of a product or substance that is provided within a specified period of time.

Turbines – A turbine is a rotary mechanical device that extracts energy from a fluid flow and converts it into useful work. The work produced can be used for generating electrical power when combined with a generator. A turbine is a turbomachine with at least one moving part called a rotor assembly, which is a shaft or drum with blades attached. Moving fluid acts on the blades so that they move and impart rotational energy to the rotor. In a gas turbine, the turbine is driven by expansion of hot gases. In a steam turbine, expanding steam drives the turbine. The turbine can do mechanical work or be used to generate electricity.

2.0 STUDY APPROACH

The study estimates NOx emissions associated with anticipated third -party production, third-party storage, and transmission of hydrogen and estimates NOx emission reductions from end users of hydrogen in the mobility, power generation, and hard to electrify industrial sectors, to determine anticipated overall NOx reductions. Additionally, potential NOx emissions minimization opportunities are identified to further reduce NOx emissions. The parallel Angeles Link Phase 1 Demand Study provides details and scenario options needed to complete this study. Evaluation of NOx emissions for the estimated ranges of Angeles Link throughput of 0.5 to 1.5 MMT per year of hydrogen was also conducted.

Where applicable, the study relies on specific technical information available from regulatory agencies, transportation agencies, and equipment manufacturers. Research conducted by entities, such as academic institutions was evaluated to determine best available methods for quantifying emissions of NOx from combustion of hydrogen. EPA calculation methodologies were also used to estimate NOx emission factors for hydrogen. Relevant local air district requirements regarding NOx emission limitations for combustion units were considered. When specific information was not available, estimates were made based on availability of related data and assumptions, which are explained within the relevant section of the study. The study also includes a high-level assessment of other potential emissions with a focus on PM and VOC.

2.1 TECHNICAL RESEARCH

The study collected, reviewed, and analyzed technical research studies and information related to NOx emissions associated with hydrogen combustion. This analysis included:

- Available literature and studies from research-based academic institutions such as University of California Irvine (UCI) Combustion Laboratory and Georgia Institute of Technology and private organizations such as Electric Power Research Institute (EPRI).
- Existing, proposed, and potential future regulatory requirements from federal agencies including United States Environmental Protection Agency (US EPA), United States Department of Energy (US DOE), state agencies such as California Air Resources Board (CARB) and California Energy Commission (CEC), and local agencies including the nine local air districts located within the geographic scope of this study such as South Coast AQMD and San Joaquin Valley Air Pollution Control District (APCD).
- Technological developments and timelines from manufacturers working on hydrogen technology.
- Technical literature and data releases from government agencies and laboratories including the US DOE and the National Renewable Energy Lab (NREL).
- Potential NOx emissions minimization opportunities from technological advancements.

The study researched available literature and studies to evaluate:

- How NOx is formed from hydrogen combustion.
- How NOx might be controlled when combusting hydrogen.
- How to quantify the formation of NOx from hydrogen combustion.

Preliminary information reviewed regarding the formation of NOx indicated:

- NOx may be formed via three pathways during combustion: thermal NOx, fuel NOx, and prompt NOx.
- Information regarding the formation of NOx was reviewed from publications by US EPA and other regulatory agencies, academia, and research institutions.
- Control of NOx emissions from hydrogen combustion begins with designing equipment to account for unique properties of hydrogen, as outlined in available studies and reports, including government publications by US EPA and US DOE.
- Aftertreatment such as selective catalytic reduction provide demonstrated NOx minimization opportunities.

3.0 TECHNICAL APPROACH

The following assessment process (Figure 1) was used for this study's technical approach. The approach was based on review of technical research studies, research of anticipated technological advancements, and review of expected evolution of regulatory frameworks.

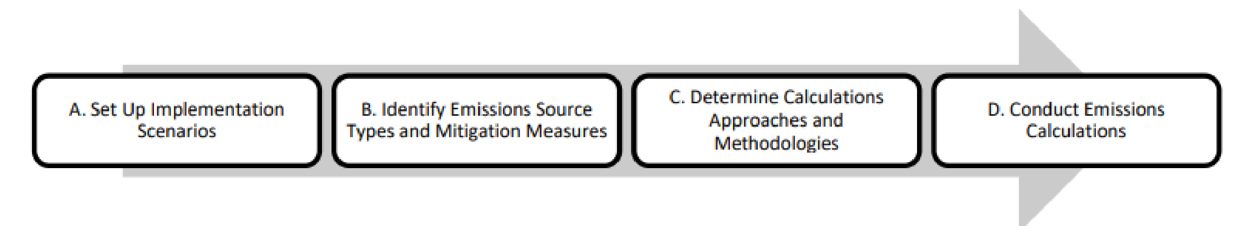


Figure 1: NOx Emissions Assessment Process for Angeles Link

3.1 SET UP IMPLEMENTATION SCENARIOS

Scenarios were set up to evaluate potential NOx emissions from new hydrogen infrastructure and NOx reductions from end users in the 2030 to 2045 timeframe. End use sectors are anticipated to achieve the ability to accommodate 100% hydrogen fuel use at various times due to availability of technology and feasibility of transitioning existing equipment to hydrogen use and building of new hydrogen infrastructure. Use of clean renewable hydrogen as fuel for each end-use sector was evaluated beginning with 2030. Potential NOx emissions were calculated using approaches described herein.

3.2 IDENTIFY EMISSIONS SOURCE TYPES

The study evaluated NOx and other emissions by developing emission calculation approaches and methodologies associated with the following:

- Infrastructure (third-party production, third-party storage, and transmission)
- End Users (mobility, power generation, and hard to electrify industrial sectors)

NOx emissions are a result of combustion of fuel. NOx is created from the conversion of nitrogen in fuel and ambient air at elevated temperatures. Evaluation of NOx emissions minimization opportunities focused on technologies that minimize combustion temperatures and post-combustion NOx emission control technology, such as catalytic reduction.

The pie chart figure below demonstrates the sources of NOx emissions in the state of California, and the percentages arising for various industries, as developed by CARB.

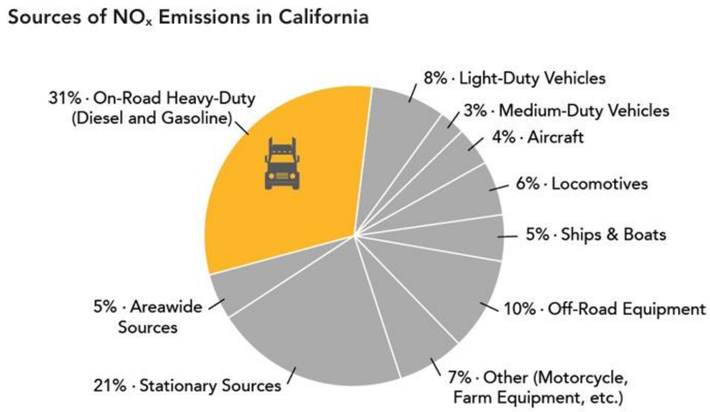


Figure 2: Existing Sources of NOx Emissions in California[9]

3.2.1 Hydrogen Production (Third-party)

Three potential clean renewable hydrogen production options were evaluated. Each of these three options qualifies as producing clean renewable hydrogen (i.e. less than 4 kilograms of CO_2e produced on a lifecycle basis per kilogram of hydrogen produced and excluding fossil fuels)[10].

1) Electrolyzers[11] powered by renewable electricity to split water molecules into oxygen and hydrogen. This process does not use combustion so there is no potential for NOx emissions associated with electrolyzers.

2) Biomass gasification[12] is a process that involves heat, steam, and oxygen to convert biomass to hydrogen without combustion. Since this process does not use combustion, there is no potential for NOx emissions associated with biomass gasification.

3) Renewable natural gas (RNG)[13] fueled steam methane reformers (SMR). Steam methane reforming is a process in which biogas (RNG) reacts with steam in the presence of a catalyst to produce hydrogen and carbon dioxide. This option has NOx emissions and those potential emissions were evaluated.

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[9] CARB, 2020, Facts about the Low NOx Heavy-Duty Omnibus Regulation, Ibid
[10] Fossil fuels defined as a mixture of hydrocarbons including coal, petroleum, or natural gas, occurring in and extracted from underground deposits.
[11] Hydrogen Production: Electrolysis | Department of Energy
[12] Hydrogen Production: Biomass Gasification | Department of Energy
[13] Renewable Natural Gas | US EPA

3.2.2 Hydrogen Storage (Third-Party) and Transmission

For the purpose of this study, third-party hydrogen storage may occur above ground or below ground, and hydrogen is delivered to end users via pipelines. Storage and transmission of hydrogen requires the use of compressors. It was assumed that compressors will be driven by renewable electricity powered electric motors or compressors driven by engines or turbines. For compressors driven by electric motors, there will be no NOx emissions. If compressor drivers are engines or turbines, it was assumed that they will be fueled by 100% clean renewable hydrogen. As a result, reciprocating engines and turbines have the potential to produce NOx.

For the purposes of this study, it was determined that the potential range of storage pressures for compressed gaseous hydrogen is 290 psi to 2,900 psi. A variety of storage options exist both for aboveground storage vessels and suitable geologic formations for belowground storage.

The transport of gases and liquids in pipeline is driven by a pressure gradient along the direction of flow that compensates for the frictional resistance at the pipe wall. When transporting gas through a pipeline, there will be pressure drop over a distance due to the work needed to compensate for frictional losses. This pressure gradient along a length of pipeline causes the gas to flow in a particular direction. Compression is required to maintain adequate pressure. Hydrogen has a higher compressibility factor than natural gas. Therefore, the pressure drop over a distance is lower for hydrogen than it is for natural gas. The reduced pressure drop over a distance may impact compression needs for hydrogen pipeline transportation. Hydrogen pipeline transportation compression needs may also be impacted by the lower heating value of hydrogen.[14] For this study, it was assumed that 100% of hydrogen demand would be transported via pipeline.

For compressors driven by electric motors, there will be no NOx emissions. However, reciprocating engines and turbines have the potential to produce NOx.

3.2.3 Hydrogen Industrial End Users

Potential NOx emissions source types from end users in three key sectors were evaluated: mobility, power generation, and hard to electrify industrial sectors. Information obtained from the parallel Demand Study informed the analysis of end uses in each of these three sectors, as well as their respective subsectors.

- **Mobility Sector:** includes heavy-duty trucks, medium-duty vehicles, buses, agriculture, construction & mining, cargo handling equipment, ground support equipment, and commercial harbor craft.
- **Power generation:** turbines are the primary source for potential NOx emissions in power generation.

[14] Yang, M., R. Hunger, S. Berrettoni, B. Sprecher, B. Wang, 2023, A review of hydrogen storage and transport technologies, Clean Energy 7(1): 190–216, https://doi.org/10.1093/ce/zkad021

- **Hard to electrify industrial:** subsectors include energy intensive industries such as refining, food and beverage manufacturing, primary and fabricated metals, stone, glass, and cement, paper, chemical manufacturing, and aerospace & defense.

Source types with the potential for NOx emissions in the power generation and industrial sectors include hot water boilers, steam generating units, process heaters, furnaces/kilns, internal combustion engines, turbines, and miscellaneous combustion equipment.

The period of this study evaluation is from 2030 when Angeles Link would be initiated through 2045 when it would be fully implemented.

3.3 FORMATION OF NO_X

To achieve the goal of quantifying NO_x emissions from the combustion of hydrogen in third-party production, third-party storage, and transmission associated with Angeles Link, and the displacement of fossil fuels by hydrogen usage for end-users, it was important to understand how NO_x is formed.

NOx may be formed through several pathways during combustion, including thermal NO_x, fuel NO_x, and prompt NO_x. Thermal NO_x is formed in the high temperature flame zone near the burner and occurs from the reaction with nitrogen present in ambient air.[15] It is generally assumed that ambient air is 79.1% molecular nitrogen and 20.9% molecular oxygen. The higher the temperature of combustion, the more thermal NO_x emissions will form during combustion when molecular nitrogen is present in the air. Thermal NO_x will start to form rapidly when combustion temperatures exceed 1,850 degrees Kelvin. For a given fuel to air ratio, the temperature of the resulting hydrogen/air flame is higher than that of a natural gas/air flame. This fact is often raised in comments indicating that NO_x levels are higher for hydrogen compared to natural gas. However, by adjusting the fuel to air ratio (lambda or equivalence ratio), thermal NO_x levels will change according to the fuel to air ratio for a particular fuel and may increase or decrease accordingly. As a result, mitigation of thermal NO_x can be achieved by altering the combusting fuel to air ratio.[16]

Fuel NO_x is formed from the oxidation of the already-ionized nitrogen that may be contained in the fuel. Fuel NO_x will vary based on the nitrogen content of a given fuel and is not relevant when combusting pure hydrogen as no nitrogen is present in the fuel. Prompt NO_x is formed when molecular nitrogen from the air reacts with hydrocarbons in the fuel. This group is then combusted

[15] NREL, 2022, A Literature Review of Hydrogen and Natural Gas Turbines: Current State of the Art with Regard to Performance and NOx Control, DOE/NETL-2022/3812, August 12, https://netl.doe.gov/sites/default/files/publication/A-Literature-Review-of-Hydrogen-and-Natural-Gas-Turbines-081222.pdf

[16] McDonell, V, 2023, personal communication, December 11

with oxygen from the air to form NOx. Prompt NO_x is not relevant when combusting pure hydrogen fuel as there are no hydrocarbons present in the fuel.[17]

3.4 NOX EMISSION FACTORS

3.4.1 Combustion of Displaced Fossil Fuels

Pollutant emissions factors from the combustion of carbon-based fuels for various types of combustion equipment have been published by numerous sources. The US EPA developed and continues to maintain their AP-42: Compilation of Air Emissions Factors from Stationary Sources.[18]

3.4.2 Combustion of Hydrogen

The scientific literature was reviewed to determine if and how NOx emissions are formed when combusting hydrogen, and if any details were available to quantify these NOx emissions. The research completed for this study did not reveal any published hydrogen-specific combustion emission factors. Studies evaluating the formation of NOx from the combustion of hydrogen typically fall into two categories: (1) modeling or (2) direct measurement. It was noted that direct measurements of NOx emissions from practical combustion systems using pure hydrogen are scarce at the present time. Modeling studies have mostly demonstrated that equipment can be designed to minimize the formation of NOx emissions from the combustion of hydrogen, typically by reducing combustion temperature or residence time. Results from direct measurement studies are variable, and most were completed on equipment that was not originally designed for the unique combustive properties of hydrogen.

Research conducted under this study searched for direct measurement NOx emissions data for pure hydrogen combustion, but very little test data is available, as few types of combustion units can effectively operate on pure 100% hydrogen fuel at this time. The direct measurement NOx emissions data from hydrogen combustion is available for various percentages of hydrogen within various equipment types and operated at a range of conditions and equivalence ratios. It was determined that there were not enough existing direct measurements of NOx emissions from combustion units at various hydrogen percentages and for each of the different equipment and burner types to utilize as representative of hydrogen combustion technology to quantify NOx emissions within this study. Direct measurement is an avenue for improving the estimates of this study, given the potential for this approach to be more accurate, as technology improves, and more consistent test data is available.

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[17] NREL, 2022, A Literature Review, Ibid

[18] EPA, AP-42 Compilation of Air Emissions Factors from Stationary Sources, https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors-stationary-sources

True hydrogen emissions factors, which correlate hydrogen fuel combustion to NOx emissions, would likely be the next most accurate NOx calculation method after direct measurement. True hydrogen emissions factors could be published by a government authority such as the US EPA or by vendors of hydrogen combustion equipment. True hydrogen emissions factors for NOx were not utilized as the calculation method in this study because published, reputable factors are not yet available.

The method used to quantify NOx emissions from hydrogen combustion in this study were proxy emissions factors. Proxy emissions factors are compatible with the Demand Study, were sufficient to estimate end-user emissions, available for combustion units, and applicable across the entire project geography. Emissions calculations differed between mobility and stationary sources (power generation, hard to electrify industrial, and infrastructure). Mobility using hydrogen fuel cells does not have NOx emissions. Proxy emissions factors for NOx from stationary sources were developed based on regulatory emission limits as described below.

Proxy emissions factors for stationary sources were developed based on the understanding that Southern California is largely an ozone non-attainment area. As a result, regulatory emission limits and BACT/LAER will be the upper bound for future NOx emissions within the project geography. Proxy emissions factors were identified and selected by reviewing emission limits from local air district regulations and formally assessing them based on 1) their ability to encompass a variety of equipment types and sizes 2) their ability to encompass a variety of fuels and 3) their level of "restrictiveness." More restrictive emissions limits were considered more representative of future requirements anticipated from the local air Districts (i.e., requirements for lowering emission limits would get stricter over time). These proxy emissions factors could then be converted to representative hydrogen emissions factors using the correction factor approach. The benefit of this proxy emissions factor approach based on regulatory emission limits is that these factors can be applied to individual equipment to represent the appropriate equipment mix within a given sector. Moreover, the correction factor approach enables these emissions factors to be applied across a full spectrum of fuels ranging from pure hydrogen, hydrogen-natural gas blends (if blended by the end user), and pure natural gas.

3.5 CALCULATION METHODOLOGY

For each type of combustion equipment, potential NOx emissions were estimated for combustion of the displaced fossil fuel (diesel, gasoline, natural gas) and for combustion of clean renewable hydrogen, as applicable. Calculations to estimate emissions were prepared using the following two equations.

Fuel Throughput x Emissions Factor = Emissions (equation 1)

Emission Reductions = Fossil Fuel Emissions – Hydrogen Emissions (equation 2)

The first equation (equation 1) multiplies the fuel throughput of the fossil fuel or of the hydrogen by the respective emission factor to calculate the NOx emissions. The second equation (equation 2) calculates the estimated NOx emission reductions by subtracting the NOx for hydrogen combustion from the NOx for the displaced fossil fuel combustion.

Potential NOx emissions were calculated at the unit level and scaled based on conservative, moderate, and ambitious scenarios in the Demand Study for each year from 2030 to 2045. The study evaluated potential for NOx emissions based on the type of equipment and specific source categories.

Local air district rules were reviewed to determine NOx emission factors for natural gas combustion to estimate emissions associated with the new hydrogen infrastructure, as well as with stationary end user sectors (i.e., power generation and hard to electrify industrial). Then a correction factor was applied to estimate NOx from hydrogen combustion. Volumetric (ppmv) correction factors can be utilized to convert natural gas emissions factors to equivalent values for pure hydrogen and blended hydrogen-natural gas fuels. After applying this correction factor, NOx in ppmv can be converted to a mass emissions rate using the EPA Method 19 equation.[19] This conversion uses the oxygen correction factor, F-factor, and stoichiometric/unit conversions. Through this approach, a representative emissions factor for natural gas can be converted to an approximate hydrogen or hydrogen-blend emissions factor. These generated emissions factors were compared against manufacturers test data and specification sheets to verify that they fell within an expected range. This methodology was utilized to develop emissions factors for hydrogen fueled internal and external combustion units for stationary sources. The detailed process to estimate NOx emissions from hydrogen combustion is provided in Appendix A.

Inherent in preparation of the NOx emissions estimates was the assumption that permitted NOx emission limits would stay the same or decrease given the requirements to make progress towards achieving ozone attainment.[20]

The Study assumes that power generation and hard to electrify industrial end users will continue to comply with applicable Clean Air Act and air districts' permit requirements when transitioning to hydrogen fuel because it has been assumed that the California regulatory environment will not allow for an increase in permitted NOx emissions at stationary sources. It has been observed that innovations in NOx technology has often been catalyzed and driven by the adoption of stringent air quality regulations, and such adoptions, coupled with other factors such as market competition

[19] EPA Method 19 Determination of Sulfur Dioxide Removal Efficiency and Particulate Matter, Sulfur Dioxide, and Nitrogen Oxide Emission Rates, 2023, https://www.epa.gov/sites/default/files/2017-08/documents/method_19.pdf

[20] Jack Brouwer, UCI, Angeles Link Planning Advisory Group meeting, December 15, 2023.

and economies of scale, stimulate advancements and reduce the costs of emission controls as these adoptions becomes more widespread.[21]

For the purposes of this study, it was assumed that adjustments to the hydrogen combustion process such as lowering of combustion temperature[22] and modifying air/fuel ratios,[23] and technological advancements[24] would be in place so permitted NOx emissions would stay the same or decrease with the combustion of hydrogen in equipment in the power generation and hard to electrify industrial sectors. Based upon review of existing technical literature, while there is uncertainty regarding actual measurements of NOx for pure hydrogen combustion applications, actual NOx emissions, which can differ from permitted NOx, may also stay the same or decrease for most end user applications depending on combustion conditions such as temperature and residence time. Advancements in hydrogen combustion technology and post-combustion treatment are anticipated to close the gap between actual NOx emissions associated with natural gas combustion and hydrogen combustion once hydrogen specific design considerations are more broadly applied.

3.5.1 Infrastructure

Hydrogen may be produced by electrolysis using renewable electricity, biomass gasification (non-combustion process), or SMR using external combustion sources fueled by pure hydrogen and renewable natural gas as feedstock. New compressors will be needed for the storage and transportation of pure hydrogen. These compressors may be driven by electric motors; by reciprocating internal combustion engines, or turbines operating on pure hydrogen.

3.5.1.1 Hydrogen Third-Party Production

Three equipment options were evaluated for production to meet the definition of clean renewable hydrogen.

1. Electrolyzers powered by renewable electricity (zero NOx)
2. Biomass gasification (zero NOx)
3. RNG SMR (some NOx)

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[21] Sonia Yeh, et. al., Technology Innovations and Experience Curves for Nitrogen Oxides Control Technologies, 2005, Technology innovations and experience curves for nitrogen oxides control technologies (Journal Article) | OSTI.GOV
[22] S.K., Alavandi, et. al., 2007, https://www.sciencedirect.com/science/article/abs/pii/S0360319907007276
[23] L. Wang, et. al., 2004 Interactions among soot, thermal radiation, and NOx emissions in oxygen-enriched turbulent nonpremixed flames: a computational fluid dynamics modeling study - ScienceDirect
[24] K. Kammer Hansen, Electrochemical Removal of NOx Using Oxide-Based Electrodes – A Review, 2018, (electrochemsci.org)

Multiple scenarios were evaluated to estimate the range of low to high NOx emissions. Three different possibilities were calculated: 1) 100% production was completed by electrolysis using renewable electricity or biomass gasification, which would yield zero NOx emissions; 2) One-third of the production was completed by each electrolysis, biomass gasification, and SMR; and 3) 100% of the hydrogen was produced by SMR. The range extends from zero NOx associated with the 100% electrolysis and the 100% biomass gasification scenarios to the highest potential NOx emissions for the 100% RNG SMR scenario. Equation 1 was used to conduct the NOx emissions calculations.

Fuel Throughput x Emissions Factor = Emissions (equation 1)

The first equation (equation 1) multiplies the fuel throughput of the fossil fuel or of the hydrogen by the respective emission factor to calculate the NOx emissions. The NOx emission estimates can be refined once assumptions regarding anticipated third-party hydrogen production processes have been developed and/or proportions of hydrogen intended to be produced from different methods have been identified.

3.5.1.1.1.1 Biomass Gasification

Within the biomass gasification process, biomass is thermochemically converted at high temperatures (700-1,400 Celsius) to a synthesis gas (syngas) through the process of gasification. Gasification is "the partial combustion of biomass by controlling the amount of air to transform hydrocarbons into carbon monoxide, carbon dioxide, and hydrogen." [25]

Direct emissions measurement data for biomass gasification was not discovered. In addition, no calculation methodologies for NOx and other air pollutants were identified for the biomass gasification process. As biomass gasification is not a true combustion process, there is no known potential pathway for the formation of NOx emissions. Gasification also typically occurs in a low oxygen environment at equivalence ratios around 0.25 to 0.50, which minimizes the potential for NOx formation. Studies have noted that in gasification systems where the formation for NOx emissions is possible, De-NOx technologies can be utilized for removal.[26] Another study noted that N_2 is typically the primary nitrogen component in the produced syngas, and that ammonia may also occur, particularly when using biomass such as animal waste that is high in protein. This study notes that standard catalytic reduction methods typically used for NOx reduction can be used to reduce any nitrogen compound in the produced syngas.[27] One study completed by

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[25] Dai, B., W. Zhu, L. Mu, X. Guo, H. Qian, X. Liang, and G.M. Kontogeorgis, 2019, Effect of the Composition of Biomass on the Quality of Syngas Produced from Thermochemical Conversion Based on Thermochemical Data Prediction, Energy & Fuels 33(6): 5253–5262, https://doi.org/10.1021/acs.energyfuels.9b00106

[26] Safavi, S.M., C. Richter, and R. Unnthorsson, 2021, Dioxins and Furan Emissions from Gasification, in Gassification, V. Silva and C.E. Tuna, editors, https://www.intechopen.com/chapters/74698

[27] Balas, M., M. Lisy, J. Kubick, Jiri Pospisil, 2014, Syngas Cleaning by Wet Scrubber, WSEAS Transactions on Heat and Mass Transfer 9: 195-204, https://www.wseas.org/multimedia/journals/heat/2014/a025712-169.pdf

Sikarwar et al (2016) notes that there is the potential for nitrogen contamination in the outlet of the biomass gasification system if fuel nitrogen is present.[28] For the purposes of this study, it is assumed that no nitrogen is contained in the biomass or any other fuel source for use in hydrogen production. Therefore, it is assumed that there are no NOx emissions from biomass gasification.

The biomass gasification process requires dry biomass for utilization. It is possible to obtain biomass containing moisture that would require drying on-site. However, this is dependent on the biomass available in the area and the supply chain and procurement for the specific facility. Due to the level of uncertainty around whether on-site drying would be required for each specific biomass gasification facility, this study assumed that biomass would be procured ready to utilize and would not require moisture removal on-site.

The syngas formed through biomass gasification can then be utilized in steam reforming to obtain additional hydrogen from the remaining hydrocarbons. Biomass gasification using steam as the oxidizing agent can achieve efficiencies of up to 44%.[29] Running the syngas through the steam reforming process improves the overall efficiency and converts any remaining hydrocarbons, primarily methane (CH_4), to hydrogen.

3.5.1.1.1.2 Steam Methane Reforming

This study assumed that third party production using SMR would have RNG as the feedstock and external combustion technology fueled by hydrogen for heating. Therefore, there is the potential for NOx formation.

SMR utilizing natural gas as feedstock is commonly used for hydrogen production. A study published in 2022 evaluated the air pollutant emissions from 33 SMR facilities across the United States, excluding any co-refineries. The researchers evaluated emissions data for these facilities as reported under the US EPA Greenhouse Gas Reporting Program (GHGRP), the National Emissions Inventory (NEI), and the Toxics Release Inventory (TRI). They determined production capacities for each of the 33 facilities using data from the Pacific Northwest National Laboratory (PNNL). By taking a direct average of the emissions data from each of these facilities, they found that natural gas SMR direct emissions 0.00168 kg NOx/kg H_2 produced.[30]

The most important variable impacting the estimated NOx emissions from the SMR process is the external combustion heat rating required to produce the desired volume of hydrogen. Two potential cases for the required heat rating of the external combustion units were developed:

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[28] Sikarwar, V.S., M. Zhao, P. Clough, J. Yao, X. Zhong, M. Zaki Memon, N. Shah, E.J. Anthony and P.S. Fennell, 2016, An overview of advances in biomass gasification, Energy and Environmental Science 9(10): 2927-3304, https://pubs.rsc.org/en/content/articlepdf/2016/ee/c6ee00935b

[29] Rödl, A., et. al., 2018, Chapter 3, Ibid

[30] Cho, Hannah Hyunah, Vladimir Strezov, and Tim J. Evans, 2022, Environmental impact assessment of hydrogen production via steam methane reforming based on emissions data, Energy Reports 8: 13585-13595, https://doi.org/10.1016/j.egyr.2022.10.053

maximum and minimum. These cases were developed based on the ratio of heat rating (MMBtu/hr) to facility production capacity (MMscf/day hydrogen produced) for facilities with specifications that were assumed to be representative of potential third-party production. The assumption was made that hydrogen would not be produced at a facility co-located with a refinery and therefore, design specifications for SMR facilities co-located at refineries were excluded from consideration within this study. To estimate an appropriate heat rating for the steam reforming process, air permits for existing steam methane reforming plants were reviewed. Only standalone SMR production facilities, external combustion units with a given heat rating rather than a "not-to-exceed", and facilities with no more than 2 external combustion units were considered.

The external combustion unit heat rating was compared against the plant hydrogen production capacity to develop a ratio of (MMBtu/hr) / (MMscf/day hydrogen production). For facilities where the plant hydrogen production capacity was not identified in the air permit, the facility hydrogen production capacity was gathered from the Pacific Northwest National Laboratory (PNNL) Hydrogen Analysis Resource Center North American Merchant Hydrogen Plant Production Capacity list.[31] Of these facilities considered, the average ratio was 2.97 MMBtu/hr per MMscf/day of hydrogen production. Three calculation cases were established, the maximum case using the average plus standard deviation for the ratio value (3.62), the average ratio value (2.97), and the minimum case using the average minus the standard deviation for the ratio value (2.32).

For the purposes of this study, it was assumed that the external combustion unit would operate using hydrogen as fuel. It was assumed that some of the hydrogen produced by SMR would be siphoned off to use as fuel. As such, the volume of hydrogen produced was increased based on the amount of hydrogen that would be needed as fuel. To calculate the amount of hydrogen that would be required for use as fuel to generate the necessary total volume of hydrogen to meet end-user demand, the end-user demand was converted to an MMscf/day value and the maximum MMBtu/hr case of 3.62 MMBtu/hr per MMscf/day of hydrogen production was utilized to determine an appropriate MMBtu/hr rating to meet the demand. The MMBtu/hr values were multiplied by 8,760 (hours/year) to calculate the maximum annual MMBtu value for the hydrogen fuel. This annual MMBtu value was added to the end-user MMBtu demand values for each Demand Scenario to determine the total estimated annual production volumes.

A thermal efficiency was then applied to account for the fact that energy conversion is generally less than 100%. Research was completed to determine an appropriate thermal efficiency for a hydrogen fueled external combustion unit. No single value was discovered that would be representative for all hydrogen fueled external combustion units. Therefore, an average of multiple values was utilized. Values were obtained from US DOE, a study completed by Gupalo

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[31] Pacific Northwest National Laboratory (PNNL), 2016, North American Merchant Hydrogen Plant Production Capacities, data available on the Hydrogen Tools website, https://h2tools.org/hyarc/hydrogen-data/merchant-hydrogen-plant-capacities-north-america

et al. (2023), and an article by Gerardo Lara in Power Engineering.[32,33,34] Based on this information, an efficiency of 73% was applied for the hydrogen production calculations within this study.

Based on this methodology, roughly 38% of the hydrogen produced would be utilized as fuel for heat generation. As a note, this is likely a high estimate due to the use of only the maximum MMBtu/hr per MMscf/day hydrogen production ratio to determine fuel requirements. Utilizing the average case ratio yields a hydrogen use percent of total production of 31%, where the minimum case ratio yields 24%. A higher efficiency value would decrease these percentages.

For natural gas external combustion, an emission factor of 0.0062 lb/MMBtu or 5 ppm from South Coast AQMD Rule 1146 for boilers, steam generators, and process heaters greater than or equal to 5 MMBtu/hr (typically used in industrial, institutional, and commercial operations) was utilized. The correlation factor methodology was used to convert this emission factor to a NOx emission factor for pure hydrogen combustion.

3.5.1.2 Hydrogen Third-Party Storage and Transmission

Compressors will be needed for storage and transmission of hydrogen. Three options for types of compressors were evaluated.

1. Electric motor driven compressors (zero NOx)
2. Clean renewable hydrogen fueled reciprocating engine driven compressors (some NOx)
3. Clean renewable hydrogen fueled centrifugal turbine driven compressors (some NOx)

Potential emissions of NOx from hydrogen fueled reciprocating engine driven compressors and turbine driven compressors were calculated using equation 1.

Fuel Throughput x Emissions Factor = Emissions (equation 1)

The first equation (equation 1) multiplies the fuel throughput of the fossil fuel or of the hydrogen by the respective emission factor to calculate the NOx emissions. Hydrogen can be stored as a

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[32] US DOE, Purchasing Energy-Efficient Large Commercial Boilers, https://www.energy.gov/femp/purchasing-energy-efficient-large-commercial-boilers

[33] Gupalo, O., 2023, Study of the efficiency of using renewable hydrogen in heating equipment to reduce carbon dioxide emissions, from IOP Conference Series: Earth and Environmental Science, doi:10.1088/1755-1315/1156/1/012035, https://iopscience.iop.org/article/10.1088/1755-1315/1156/1/012035/pdf

[34] Lara, G., 2022, Boilers running on hydrogen: What you need to know, from Power Engineering, https://www.power-eng.com/hydrogen/boilers-running-on-hydrogen-what-you-need-to-know/

pure gas, pure liquid, or chemically when bonded with other substances (ex. metal hydrides).[35] In this study, hydrogen was only evaluated for storage as a compressed pure gas. Compressed gaseous hydrogen can be stored in aboveground pressure vessels or underground. Hydrogen transmission was evaluated with respect to pipeline transport with a total of 450 miles based on information provided by the Pipeline Sizing and Routing Study.

The third-party storage and pipeline transmission of gaseous hydrogen requires compressors to pressurize hydrogen which will likely be powered by electric motors, reciprocating engines, or turbines.[36,37,38,39] Compressors driven by electric motors do not have emissions. For reciprocating engines or turbines as the driver of compressors, these will be powered by pure hydrogen combustion, and will have the potential to produce NOx emissions.

A two-step calculation approach was utilized to determine NOx emissions from compression associated with third-party storage and transmission:

1. Estimate the total energy requirements to power compressors.
2. Calculate emissions from reciprocating engines and turbines associated with this energy.

Based on data from Bossel and Eliasson (2003),[40] the following information was required to determine expected NOx emissions from third-party storage and transmission:

- Hydrogen storage pressure
- Hydrogen storage quantity
- Hydrogen transmission distance
- NOx emissions factor for compressor power source

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[35] Elberry, A.M., J. Thakur, A. Santasalo-Aarnio, and M. Larmi, 2021, Large-scale compressed hydrogen storage as part of renewable electricity storage systems, International Journal of Hydrogen Energy 46(29): 15671-15690, https://doi.org/10.1016/j.ijhydene.2021.02.080

[36] Solar Turbines Incorporated, 2021, Hydrogen Pipelines & Storage, presentation, https://netl.doe.gov/sites/default/files/netl-file/21TMCES_Kurz.pdf

[37] Tahan, M., 2022, Recent advances, Ibid

[38] Witkowski, A., A. Rusin, M. Majkut, and K. Stolecka, 2017, Comprehensive analysis of hydrogen compression and pipeline transportation from thermodynamics and safety aspects, Energy 141: 2508-2518, https://doi.org/10.1016/j.energy.2017.05.141

[39] Di Bella, F.A., 2015, Development Of A Centrifugal Hydrogen Pipeline Gas Compressor, Technical Memorandum No. 1785 Concepts NREC Project No. 10195 Prepared for the US DOE, https://www.osti.gov/servlets/purl/1227195/

[40] Bossel, U., and B. Eliasson, 2003, Energy and the Hydrogen Economy, https://afdc.energy.gov/files/pdfs/hyd_economy_bossel_eliasson.pdf

Storage pressure scenarios were developed based on storage pressures from Tahan (2022).[41] This publication presented a variety of hydrogen storage options at a high-level and their corresponding pressures. The highest and lowest pressures from this publication were utilized to represent the full range of potential storage pressures, and therefore third-party storage energy demands, from this project. These high and low storage pressure scenarios were 2,900 and 290 psi respectively, corresponding to storage underground and in spherical pressure vessels, respectively.

It was assumed that storage requirements would be similar between hydrogen and natural gas to accommodate fluctuations in fuel supply and demand. Data from the “2023 California Gas Report Supplement”[42] was used to estimate a California-specific value for the fraction of annual hydrogen demand that would be stored (2022 data). From this source, it was determined that the average quantity of supplied natural gas in California during 2022 was 6,023 MMcf/day, which equates to approximately 2,198 Bcf/yr. This source also indicated that in 2022 California had a natural gas storage capacity of approximately 304 Bcf. Dividing these two values yielded a maximum (conservative) fraction of annual natural gas demand that would be stored: 13.8%. This value was applied to hydrogen; therefore, it was assumed that annually 13.8% of hydrogen produced would be stored by third parties.

The total energy requirement to power compressors for storage and transmission were developed from Bossel and Eliasson (2003),[43] a widely cited scientific paper. Figure 3 below is a chart from this publication of compression energy (MJ/kg) needed to compress hydrogen at various pressures. Using this figure, the amount of energy required to store hydrogen can be calculated given a particular quantity of hydrogen (kg) and storage pressure (bar). From Figure 3, the following values were derived.

- Pressure of 290 psi → 4 MJ/kg
- Pressure of 2,900 psi → 14 MJ/kg

The energy required to drive the compression storage was derived by converting the MJ/kg value to MMBtu using 1,055 J/BTU (conversion factor) and 51.9 MMBtu/100 MMBtu for efficiency and then multiplying the MMBtu value by the lb/MMBtu NOx emissions factor.

The transmission distance scenario was based on a preliminary pipeline length estimate of 450 miles based on information provided by the Pipeline Sizing and Routing Study. Rather than using a specific pressure for the transmission system, estimated gas consumption per kilometer (km) of pipeline to energize compressors was used to calculate the required MMBtu of hydrogen for the transmission of the volume of hydrogen provided in the Demand Scenarios and Throughput

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41 Tahan, M., 2022, Recent advances, Ibid

42 CPUC, 2023, 2023 California Gas Report Supplement prepared per Decision D.95-01-039, https://www.socalgas.com/sites/default/files/Joint_Biennial_California_Gas_Report_2023_Supplement.pdf

43 Bossel, U., and B. Eliasson, 2003, Ibid.

Scenarios. Specifically, Figure 4 below, is a chart of the percentage of hydrogen that would be consumed to power compressors to transport hydrogen over a particular distance of pipeline. This figure can be used to calculate the amount of hydrogen (and therefore energy) required to transport hydrogen a distance via pipeline.

The article indicated that 1.4% of the hydrogen flow would be required every 150 km to power or energize the compressors along the transmission system. This percentage of the projected hydrogen demand was used to calculate the MMBtu of hydrogen that would be combusted for the purposes of energizing the transmission compressors. The total energy required to power compressors used for third-party storage and transmission was estimated using this methodology from Bossel and Eliasson (2003).

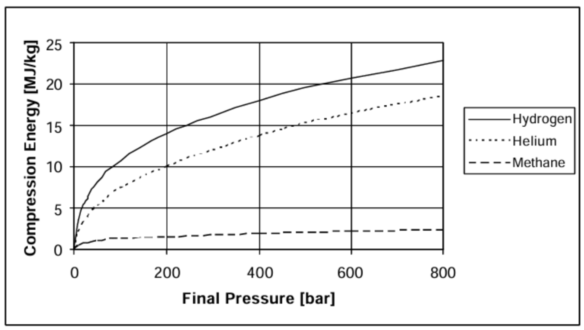

Figure 3: Adiabatic Compression Work for Hydrogen, Helium, and Methane

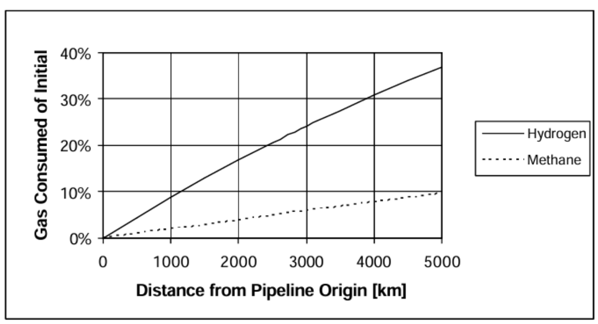

Figure 4: Fraction of Gas Consumed to Transport Hydrogen and Methane

Since compressors will potentially be powered by reciprocating engines or turbines, NOx emissions factors were sourced that corresponded to each of these. Emissions factors were developed similarly to the stationary source emission factors based on the most restrictive emissions factors from the air district prohibitory rules. For reciprocating engines and turbines, these emissions factors came from South Coast AQMD Rules 1110.2[44] and 1134[45], respectively. Efficiency values for each of these power source types were sourced from scientific literature to convert fuel energy (MMBtu) to energy supplied by power sources for compression (MJ). These efficiency values for hydrogen reciprocating engines and turbines were sourced from scientific literature as 60.3% and 51.9% respectively.[46] [47]

Based on Figures 3 and 4 above and information from the literature as summarized above, the compression needs for storage were determined to be 4 MJ/kg for storage pressure at 290 psi and 14 MJ/kg for storage pressure at 2,900 psi. Additionally, for transmission, the hydrogen that would be consumed by the reciprocating or centrifugal compressors, was determined to be 0.0093% of the volume in the pipelines per kilometer of transmission via pipelines.

NOx emissions were calculated by multiplying overall compressor energy demand by NOx emissions factor. NOx emissions were estimated for a total of 12 scenarios corresponding to four storage and transmission scenarios for each of the three Demand Scenarios. These four transmission and storage scenarios were based on each combination of two storage pressure scenarios, two pressure source scenarios, and one transmission distance scenarios. This was repeated for a total of 12 scenarios for each of the three Throughput Scenarios. These emissions scenarios are listed in the table below. In combination, these scenarios represent the range of possible transmission and storage characteristics and the corresponding NOx emissions.

Storage Scenario:

- Underground Storage Pressure: 2,900 psi
- Aboveground Storage Pressure: 290 psi

Transmission Scenario:

- Compressors driven by electric motors running on renewable electricity
- Engine driving reciprocating compressor: emissions factor for natural gas combustion of 11 ppmvd from South Coast AQMD Rule 1110.2 converted to pure hydrogen representative factor using correction factor methodology and 60.3% efficiency

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[44] South Coast AQMD, 2023a, Rule 1110.2 "Emissions from Gaseous and Liquid Fueled Engines" https://www.aqmd.gov/docs/default-source/rule-book/reg-xi/r1110_2.pdf?sfvrsn=8

[45] South Coast AQMD, 2022c, Rule 1134 "Emissions from Oxides of Nitrogen from Stationary Gas Turbines" https://www.aqmd.gov/docs/default-source/rule-book/reg-xi/rule-1134.pdf?sfvrsn=4

[46] Babayev, R., H.G. Im, A. Andersson, and B. Johansson, 2022, Hydrogen double compression-expansion engine (H2DCEE): A sustainable internal combustion engine with 60%+ brake thermal efficiency potential at 45 bar BMEP, Energy Conversion and Management 264: 115698, https://doi.org/10.1016/j.enconman.2022.115698

[47] Salam, Md A., Md. A. Ali Shaikh, and K. Ahmed, 2023, Green hydrogen based Power Generation prospect for sustainable development of Bangladesh using PEMFC and hydrogen gas turbine, Energy Reports 9: 3406-3416, https://doi.org/10.1016/j.egyr.2023.02.024

- Turbine driving centrifugal compressor: emissions factor for natural gas combustion of 2.5 ppmvd from South Coast AQMD Rule 1134 converted to pure hydrogen representative factor using correction factor methodology and 51.9% efficiency.

Table 2
Storage and Transmission Calculation Scenarios Evaluated

Scenario	Storage Pressure	Transmission Distance	Compressor Driver	Demand
1	High (2,900 psi)	450 miles	Reciprocating Engine	Low
2	Low (290 psi)	450 miles	Reciprocating Engine	Low
3	High (2,900 psi)	450 miles	Turbine	Low
4	Low (290 psi)	450 miles	Turbine	Low
5	High (2,900 psi)	450 miles	Reciprocating Engine	Moderate
6	Low (290 psi)	450 miles	Reciprocating Engine	Moderate
7	High (2,900 psi)	450 miles	Turbine	Moderate
8	Low (290 psi)	450 miles	Turbine	Moderate
9	High (2,900 psi)	450 miles	Reciprocating Engine	High
10	Low (290 psi)	450 miles	Reciprocating Engine	High
11	High (2,900 psi)	450 miles	Turbine	High
12	Low (290 psi)	450 miles	Turbine	High

The table below illustrates the percentage reduction in NOx emissions when changing input variables between the transmission scenarios and storage scenarios, changing from underground (2,900 psi) to aboveground (290 psi) storage pressures, changing from engines driving reciprocating compressor to turbines driving centrifugal compressor, and changing from these combustion power source types to electricity.

In the transmission compression scenarios evaluated the largest potential for reduction in emissions would be realized by using electric motors rather than reciprocating engines or centrifugal turbines with electric motors. A reduction in emissions can also be achieved by switching reciprocating engines for turbines, resulting in an approximate 76% reduction in emissions regardless of storage pressure scenario. Where combustion sources are used to power compressors, switching from high to low pressure reduces emissions by 18% and 20% for reciprocating engines and turbines, respectively. These results clearly indicate that compression power source has the greatest impact on emissions with reciprocating engines resulting in the most emissions, followed by turbines, and finally with zero emissions attributed to electric motors powered by renewable electricity.

Table 3 Impact of Power & Storage Scenarios on Emissions Reductions		
Power Scenario	**Storage Scenario**	**Percent Emissions Reduction (%)**
Reciprocating	Change High to Low Pressure	18%
Turbine	Change High to Low Pressure	20%
Electricity	Change High to Low Pressure	NA
Change Recip to Turbine	2,900 psi	76%
Change Recip to Electricity	2,900 psi	100%
Change Turbine to Electricity	2,900 psi	100%
Change Recip to Turbine	290 psi	77%
Change Recip to Electricity	290 psi	100%
Change Turbine to Electricity	290 psi	100%

3.5.2 End Users

Each of the end use sectors are anticipated to have varying levels of hydrogen adoption over time and may begin by using a hydrogen-natural gas blend that would be blended behind the customer's meter.

3.5.2.1 Mobility Sector

The Mobility sector is anticipated to use hydrogen fuel cells beginning in 2030. Research conducted under the parallel Demand Study Mobility model informed the analysis of potential hydrogen demand and the displacement of fossil fuels by hydrogen usage in this sector. Source types with NO_x emissions in this sector include on-road vehicles such as heavy-duty vehicles (HDV), medium-duty vehicles (MDV), and buses. With hydrogen fuel cells, the NOx and other air pollutant emissions from these on-road mobile sub-sectors using hydrogen within this study will be zero.

The Mobility sector also includes off-road vehicles within Agriculture, Commercial Habor Craft (CHC), Cargo Handling Equipment (CHE) at ports, Construction and Mining, and Ground Support Equipment at airports (GSE). With hydrogen fuel cells, the NOx and other air pollutant emissions from these off-road mobile sub-sectors using hydrogen within this study will be zero.

For off-road sources, data from the EMFAC model includes the NOx and other air pollutant emissions, fuel consumption, hours of operation per year, total population of vehicles, and horsepower hours per year. For on-road sources, the same data is available and additional data available includes vehicle miles traveled, trips per year, and emissions factors used to calculate emissions based on activity data. The data is provided for each vehicle category within each region/air district by year and fuel type, gasoline, diesel, and natural gas.

Fossil fuel emissions factors for mobile sources were developed utilizing the emissions and fuel consumption data provided by the CARB EMFAC model. These emissions factors were developed in units of tons of pollutants per gallon of fuel consumed for each sub-sector by year and fuel type. This was completed by utilizing the EMFAC projected mass emissions (short ton/year) for each pollutant for each vehicle category by year, region, and fuel type and dividing the emissions by the gallons of fuel consumed for the category. Once this factor of tons per gallon was developed for each vehicle category by year, region, and fuel type, they were weighted by the amount of fuel consumed by each vehicle category by year, region, and fuel type and the weighted factors were used to compile an overall emissions factor in tons of pollutant per gallon of fuel used for each sub-sector (encompassing each region and vehicle category) by year and fuel type. EMFAC does account for improvements in fuel efficiency and emissions control over the years. Therefore, NOx emissions factors calculated from EMFAC data for most sub-sectors decreases over time throughout the length of this study.

Table 4 below shows the average over the 15 year study period NOx emissions factors, as developed from EMFAC emissions and fuel consumption data, for the 15 years by fuel type for on-road versus off-road sub-sectors. For on-road sub-sectors, diesel has the largest NOx emissions factor whereas off-road sub-sectors, gasoline does.

Table 4
NOx Compiled Emissions Factors

Type	Fuel	NOx (ton/gal)
On-Road	Diesel	1.62E-05
On-Road	Gasoline	7.26E-06
Off-Road	Diesel	3.06E-05
Off-Road	Gasoline	3.17E-05

For the mobility sector it was assumed that hydrogen demand would be utilized in hydrogen fuel cells. Therefore, emissions of NOx and other air pollutants from mobile sources utilizing hydrogen within this study were assumed to be zero.

3.5.2.2 Power Generation Sector

Power Generation in California is primarily generated by internal and external combustion sources powered by liquid and gaseous fuels. Hydrogen usage in the Power Generation sector is anticipated to begin with hydrogen-natural gas blends and transition to pure hydrogen as the technology becomes available. The transition from blended to pure hydrogen fuels was evaluated by the Demand Study Power Generation model and based on technological and economic feasibility and air permitting BACT requirements. Research conducted under the parallel Demand Study informed the analysis of end uses in this sector.

All stationary source fossil fuel consumption in this study was represented as natural gas. The two sub-categories evaluated were: (1) peaker & baseload and (2) cogeneration. The fuel types considered for stationary calculations were pure hydrogen, pure natural gas, and hydrogen-natural gas blends (of various percentages).

Table 5 below shows the proportion of fuel assumed to be combusted within each of the four combustion equipment categories as developed from information in the CARB Standard Emission Tool (CEPAM2019v1.03),[48] and emissions factors for each category developed from regulatory mandated emissions limitations within the geographic region of this study. It is assumed that the proportion of fuel throughput within each equipment category does not change over time. Based on the data from the CARB Standard Emission Tool (CEPAM2019v1.03), 99.0% of total fuel throughput in the cogeneration sub-sector is utilized in internal combustion turbines which have the lowest emissions factor of all the equipment categories evaluated within the Power Generation sector. In Peaker and Baseload, 94.2% of equipment is assumed to be turbines. This higher proportion of turbines in cogeneration may contribute, in part, to the lower contribution of total NOx mass emissions from cogeneration as compared to power generation. While equipment proportions contribute a small amount, the largest contributor to the difference in NOx mass emissions between cogeneration and peaker and baseload is the overall energy demand between the sub-sectors.

[48] CARB, 2024b, Standard Emission Tool CEPAM2019v1.03, CARB webpage, https://ww2.arb.ca.gov/applications/statewide-emissions

Table 5
Proportion of Equipment Categories within Power Generation Sub-sectors

Angeles Link Study Sub-Sector	Equipment Category	Throughput Fraction	NOx 100% NG EF Value (lb/MMBtu)	NOx EF Air District	NOx EF Rules	Note	NOx 100% Hydrogen EF (lb/MMBtu)
Baseload and Peaker	General External Combustion	5.7%	0.0145	South Coast	1146, 1146.1, 1146.2	Average of Multiple	0.0136
	Reciprocating Engine	0.1%	0.0405	South Coast	1110.2	Single Factor	0.0381
	Turbine	94.2%	0.0083	South Coast	1135	Average of Multiple	0.0078
Cogeneration	General External Combustion	0.8%	0.0145	South Coast	1146, 1146.1, 1146.2	Average of Multiple	0.0136
	Reciprocating Engine	0.2%	0.0405	South Coast	1110.2	Single Factor	0.0381
	Turbine	99.0%	0.0074	South Coast	1134	Single Factor	0.0069

3.5.2.3 Hard to Electrify Industrial Sector

Hard to electrify industrial sectors include energy intensive industries such as refining, food and beverage manufacturing, primary and fabricated metals, stone, glass, and cement, paper, chemical manufacturing, and aerospace & defense. Equipment types with the potential for NO_x emissions in these sectors include hot water boilers, steam generating units, process heaters, furnaces/kilns, reciprocating internal combustion engines, turbines, and miscellaneous combustion equipment. The Demand Study did not specify the quantities of industrial hydrogen demand that would be blended.

Emission calculations were developed given the following assumptions:

- A percentage of the total hydrogen demand would be used as a blended fuel with natural gas; blending would happen by the customer behind the meter.
- Manufacturer data, air permitting NOx emission limits, and equipment retirement rates were used as a basis.

- The hydrogen-natural gas percentage of blended fuels was estimated based on manufacturers specification sheets and direct measurement study data for reciprocating engines, turbines, general external combustion units, and ovens.

It was assumed that the hydrogen-natural gas percentage for blended hydrogen would vary by equipment-type. The values in Table 6 are based on an assumption of steady incremental increases with a goal of complete transition by 2050. The values in Table 7 were estimated based on manufacturer specification sheets and direct measurement studies. A dataset consisting of 22 data points, across 14 manufacturers, from manufacturer's data and scientific literature were used to estimate equipment-level hydrogen-natural gas blending percentages by taking a direct average. The estimated emissions are based on these assumptions.

Table 6
Equipment-level Hydrogen-Natural Gas Blending Percentages

Equipment Type	Percent of Total Hydrogen Demand as 100% Hydrogen					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**
Engine	0	20	40	60	80	100
Turbine	0	20	40	60	80	100
External Combustion	0	20	40	60	80	100
Oven	0	20	40	60	80	100

Table 7
Equipment Level Hydrogen Blending Ratios by Volume for Industrial End-Users

Equipment Type	Hydrogen to Natural Gas Ratio
Engine	25%
Turbine	57%
External Combustion	22%
Oven	22%

Table 8 below shows the percentage of sub-sector fuel throughput and emissions factors for each of the four equipment categories in the hard to electrify industrial sub-sectors. The study assumed that refineries use 21.2% of their fuel in external combustion and 78.6% of their fuel in turbines, which have the lowest emissions factor. Due to the similarities in the proportions of fuel used by each equipment type within all of the hard to electrify industrial sub-sectors, it is not likely that the variations in fuel usage proportions between equipment types makes a noticeable impact on emissions reductions between sub-sectors. The largest variable contributing to the difference in emissions reductions between sub-sectors comes from the projected hydrogen demand.

Table 8 Equipment Categories in Hard to Electrify Industrial Sub-sectors and Percent of Fuel and Emissions Factors

CARB Inventory Sector	Study Sub-Sector	Equipment Category	Through-put Fraction	NOx 100% NG EF Value (lb/ MMBTU)	Air District Source of NOx EF	NOx EF Rules	Note	NOx 100% Hydrogen EF (lb/MMBTU)
Food and Beverage	Food and Beverage	General External Combustion	98.6%	0.0145	South Coast	1146, 1146.1, 1146.2	Average of Multiple	0.0136
		Oven	0.1%	0.0492	SJV	4309	Single Factor	0.0462
		Reciprocating Engine	1.1%	0.0405	South Coast	1110.2	Single Factor	0.0381
		Turbine	0.3%	0.0092	South Coast	1134	Single Factor	0.0087
Manufacturing and Industrial	Metals, Stone/ Glass/ Cement, Paper, Chemicals, Aerospace and Defense	General External Combustion	81.2%	0.0145	South Coast	1146, 1146.1, 1146.2	Average of Multiple	0.0136
		Oven	0.2%	0.0492	SJV	4309	Single Factor	0.0462
		Reciprocating Engine	12.8%	0.0405	South Coast	1110.2	Single Factor	0.0381
		Turbine	5.8%	0.0092	South Coast	1134	Single Factor	0.0087
Refining	Refineries	General External Combustion	21.2%	0.0145	South Coast	1146, 1146.1, 1146.2	Average of Multiple	0.0136
		Reciprocating Engine	0.2%	0.0405	South Coast	4309	Single Factor	0.0381
		Turbine	78.6%	0.0074	South Coast	1134	Single Factor	0.0069

3.5.3 Conduct Emission Calculations

The study prepared emission calculations using emission factors and activity data compiled for each of the topic areas.

- The tool was designed to conduct calculations at the unit level (per unit equipment count, unit distance, unit throughput, or other unit parameters, as applicable).
- The emissions calculation tool was scaled from unit level information to estimate impacts across the geographic region that Angeles Link would potentially span.
- Emission calculations utilized information from evaluated research, the Demand Study, and other Phase 1 feasibility studies.

There are several modeling studies and direct measurement studies related to NOx emissions from hydrogen combustion. Research completed for this study did not reveal published hydrogen-specific combustion emission factors for NOx. Multiple modeling studies have demonstrated that equipment can be designed to minimize the formation of NOx emissions from hydrogen combustion, typically by reducing combustion temperature or residence time. Direct measurement includes continuous emissions monitoring systems (CEMS) and stack testing. Results from direct measurement studies are variable, and most were completed on equipment originally designed to combust natural gas rather than hydrogen.

Few manufacturers have published NOx emissions data from hydrogen combustion in their units. With the bulk of hydrogen combustion technology still in development, the availability of actual NOx emissions data specific to hydrogen combustion is low at this time of this evaluation.

Emissions minimization methodologies can be implemented to reduce NOx emissions including equipment design, pre-mixing of air and fuel, management of air to fuel ratio to control combustion temperature, and emerging aftertreatment technologies. NOx control equipment options also include existing technologies such as selective catalytic reduction (SCR) and non-selective catalytic reduction (NSCR).

4.0 BACKGROUND INFORMATION

4.1 PROPERTIES OF HYDROGEN

To quantify NOx emissions from the combustion of hydrogen, it is important to understand the combustive properties of hydrogen and the potential pathways for the formation of NOx. Hydrogen has unique combustive properties that impact NOx formation when combusted. Hydrogen's wide range of flammability allows it to operate, depending on equipment type, on a variety of air-to-fuel ratios. Additionally, hydrogen's high autoignition temperature permits higher compression ratios in reciprocating compressors, while its high flame speed at stoichiometric ratios increases thermal NOx emissions in turbine.[49] Hydrogen's lower heat content than natural gas results in a lower power output per volume compared to natural gas, gasoline, or diesel fuels. Consequently, three times more hydrogen (by volume) is required to achieve the same thermal output as natural gas.[50]

4.2 REGULATORY INFORMATION

Air quality regulation can provide limits to the allowable air pollutant emissions and can also help incentivize research and development into new technologies. Regulatory incentives have the potential to increase demand for a product. Regulatory pressures have the potential to dictate why one product will be developed as compared to another. The breadth of existing and proposed regulations at the local, state, and federal levels related to hydrogen was considered in this study.

4.2.1 Federal Regulatory Landscape

Inflation Reduction Act (IRA) of 2022[51]: The IRA provides a ten-year Production Tax Credit for clean hydrogen produced after December 31, 2022. The IRA added Section 45V to the Internal Revenue code to define tax credit tiers for "qualified clean hydrogen" with a well-to-gate GHG emissions rate of less than 4.0 kilograms of CO_2e per kilogram of hydrogen. Providing that prevailing wage and apprenticeship requirements are satisfied, Section 45V designates four tax credit tiers based on the carbon intensity of hydrogen produced, with credits starting at $0.60 per kg for hydrogen emitting between 2.5 kg and 4 kg of CO_2e per kg produced, rising to $3.00 per kg for hydrogen emitting less than 0.45 kg of CO_2e per kg of hydrogen produced.[52]

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[49] Onorati, A., et al., 2022, The role of hydrogen, Ibid

[50] US EPA, 2023a, Hydrogen in Combustion Turbine Electric Generating Units, Ibid

[51] US Congress, 2022, Inflation Reduction Act, Public Law 117-169, August 16, https://www.congress.gov/117/plaws/publ169/PLAW-117publ169.pdf

[52] Id. As of this writing, the Internal Revenue Service (IRS) is still finalizing regulations to implement the Section 45V Credit for Production of Clean Hydrogen. In December 2023, IRS published a notice of proposed rulemaking. *See 88 Federal Register 89220*, "Section 45V Credit for Production of Clean

As directed by the Clean Air Act, US EPA sets **New Source Performance Standards** (NSPS) to regulate pollution emitted by new and modified equipment. Current standards for existing natural gas combustion units do not apply to units that combust 100% hydrogen fuels.

The Clean Air Act requires the US EPA to establish and enforce National Ambient Air Quality Standards (NAAQS) for criteria pollutants including ozone (O_3), carbon monoxide (CO), lead (Pb), particulate matter (PM), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2). The California Air Resources Board (CARB) has also established and enforces the California Ambient Air Quality Standards (CAAQS). If a local air district does not meet the NAAQS or CAAQS, it is deemed to be "nonattainment." Areas that are designated as nonattainment are required to develop implementation plans outlining steps and processes that will help the area reduce its emissions and achieve attainment. Eight of the nine air districts within the geographic scope of this study are designated as non-attainment for ozone: Eastern Kern County APCD, Imperial County APCD, San Joaquin Valley APCD, Santa Barbara County APCD, South Coast AQMD, Ventura County APCD, Antelope Valley AQMD, and Mojave Desert AQMD.[53] San Luis Obispo County is the only county located within the geographic scope of this study that is currently in attainment for all criteria pollutants.

Air permitting of new or modified equipment includes implementation of New Source Review (NSR) requirements. Application of Best Available Control Technology (BACT) or Lowest Achievable Emissions Rate (LAER) emission limits is required. Each district implements BACT and LAER requirements using their own rules.[54] This includes hydrogen technology and equipment.

The US EPA signed the final rule for the **Clean Trucks Plan** on December 20, 2022 which focuses on reducing emissions from heavy-duty engines and vehicles beginning in model year 2027.[55]

4.2.2 California State Regulatory Landscape

On the state level, California has a unique regulatory structure around hydrogen, renewable fuels and minimization of NO_x emissions.

Hydrogen; Section 48(a)(15) Election To Treat Clean Hydrogen Production Facilities as Energy Property," 12/26/2023, https://www.federalregister.gov/documents/2023/12/26/2023-28359/section-45v-credit-for-production-of-clean-hydrogen-section-48a15-election-to-treat-clean-hydrogen.

53 CARB, 2023a, Nonattainment Area Plans, CARB webpage, https://ww2.arb.ca.gov/our-work/programs/california-state-implementation-plans/nonattainment-area-plans

54 CARB, 2023b, Best Available Control Technology Definitions, CARB webpage, https://ww2.arb.ca.gov/our-work/programs/stationary/stationary-source-permitting/bact-program/bact-definitions

55 US EPA, 2024a, Clean Trucks Plan, https://www.epa.gov/regulations-emissions-vehicles-and-engines/clean-trucks-plan

The **California Clean Air Act (CCAA)** establishes California ambient air quality standards (CAAQS) specific to California. Local air district rules and regulations are built around these standards similar to how other states build their rules and regulations around the NAAQS.

Senate Bill 350 (SB 350) Clean Energy and Pollution Reduction Act was issued in 2015. The objectives outlined in SB 350 included procuring 50% of the state's electricity from renewable sources by 2030 and doubling statewide energy efficiency savings in electricity and natural gas to retail customers by January 1, 2030.[56]

Senate Bill 100 (SB 100) 100 Percent Clean Energy Act of 2019 set a goal of powering all retail electricity sold in California, as well as state agency electricity needs, with renewable and zero-carbon resources by 2045. By 2030, at least 60% of California's electricity would need to be renewable.[57] SB 100 requires California Energy Commission (CEC), California Public Utilities Commission (CPUC), and CARB to issue joint policy reports every four years beginning in 2021.[58] Senate Bill 1075 (SB 1075) requires CARB, CPUC, and the California Workforce Development Board to conduct an evaluation on hydrogen that includes policy recommendations to assist in implementing the production and use of hydrogen in California. The assessment was required by legislation to be published by June 1, 2024, however a draft has not yet been released.[59] Senate Bill 1389 (SB 1389) Energy: planning and forecasting of 2002 requires the California Energy Commission to prepare an integrated energy policy report (IEPR) every two years.[60] The most recent report was published in 2024.[61]

California Governor's Executive Order (EO) N-79-20 Zero-Emission by 2035 was issued in 2020 pertaining to on-road and off-road mobile sources of emissions. This EO outlines a state goal that 100% of in-state sales of passenger vehicles be zero-emission by 2035. Also, 100% of medium and heavy-duty State government vehicles must be zero-emission by 2045 for all operations where feasible, and 2035 for drayage trucks. The EO also outlined a goal that State government should transition to 100% zero-emission off-road vehicles and equipment by 2035, where feasible. "Zero-emission vehicle" or "ZEV" means a vehicle that produces no emissions

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[56] State of California, 2015, SB350, Clean Energy and Pollution Reduction Act of 2015, filed October 7, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB350

[57] State of California, 2018, SB100 California Renewables Portfolio Standard Program: emissions of greenhouse gases, filed September 10, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB100

[58] California Energy Commission, 2023, SB 100 Joint Agency Report, agency website, https://www.energy.ca.gov/sb100

[59] State of California, 2022a, SB1075 green hydrogen: emissions of greenhouse gases, September 16, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220SB1075

[60] State of California, 2002, SB1389 Energy: planning and forecasting, September 14, https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=200120020SB1389

[61]Adopted 2023 Integrated Energy Policy Report,
2023 Integrated Energy Policy Report (ca.gov)

from the onboard source of power, as defined by CARB in their glossary of terms.[62] Per DriveClean.org, developed by CARB, only battery-electric vehicles and hydrogen fuel cell electric vehicles currently meet this definition.[63]

Regulation established by CARB to meet the goals outlined in this EO include the **Advanced Clean Trucks regulation** for on-road vehicles weighing more than 8,500 pounds,[64] the **Advanced Clean Cars II** for passenger cars, light-duty trucks, and medium-duty vehicles,[65] and the **Advanced Clean Fleet regulation** for drayage operations at seaports and railyards, fleets owned by State, local, and federal government agencies, and high priority fleets.[66]

The state has also issued the **Innovative Clean Transit regulation** requiring that 100% of new bus sales must emit zero emissions by 2029, and 100% of on-road transit buses must emit zero emissions by 2045.[67] Additionally, the Alameda-Contra Costa Transit District which is the largest public bus-only transit agency in California is a recognized leader is zero emission buses both nationally and internationally with both hydrogen fuel cell and battery electric buses in their fleet.[68]

CARB 2022 State Implementation Plan: California Air Resources Board adopted the 2022 State SIP Strategy on September 22, 2022.[69] The SIP Strategy outlines many of the regulations discussed in this report, along with estimated emissions reductions and implementation plans.

Within CARB's 2022 State Implementation Plan (SIP), they requested that the US EPA require zero-emissions from on-ground operations at California airports. CARB stated that zero emissions from on-ground operations would be required in order for South Coast AQMD to meet their required NO_x emissions reductions due to their non-attainment status for ozone by 2037.[70] In

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[62] CARB, 2023c, Glossary, https://ww2.arb.ca.gov/glossary
[63] DriveClean, 2023, Glossary, https://driveclean.ca.gov/glossary
[64] CARB, 2021a, Advanced Clean Trucks Regulation, filed March 15, https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks
[65] CARB, 2022a, Advanced Clean Cars II, filed November 30, CARB regulation webpage https://ww2.arb.ca.gov/our-work/programs/advanced-clean-cars-program/advanced-clean-cars-ii.
[66] CARB, 2022b, Advanced Clean Fleets Regulation, Appendix A-2: High Priority and Federal Fleets Requirements, Public Hearing Notice and Material Posted August 30, 2022, https://ww2.arb.ca.gov/rulemaking/2022/acf2022
[67] California Code of Regulations, 2019, Article 4.3 Innovative Clean Transit of Title 13. Motor Vehicles, August 13, unofficial electronic version, https://ww2.arb.ca.gov/sites/default/files/2019-10/ictfro-Clean-Final_0.pdf
[68] AC Transit, Zero Emission Bus Transition Plan, 2022, 0162-22 ZEB Transition Plan_052022_FNL.pdf (actransit.org)
[69] CARB, 2022c, 2022 State Strategy for the State Implementation Plan, Adopted September 22, https://ww2.arb.ca.gov/sites/default/files/2022-08/2022_State_SIP_Strategy.pdf
[70] CARB, 2022c, 2022 State Strategy for the State Implementation Plan, Ibid

2018 through 2020, CARB considered a **Zero-Emission Airport Ground Support Equipment program** but has not finalized any requirements under such a program.[71]

The **Zero Emission Airport Shuttle Rule** outlines that 100% of on-road airport vehicles and equipment must be zero emissions by 2035 where feasible.[72]

CARB is considering expanding its **Clean Off-Road Equipment Voucher Incentive Project (CORE)** program, which provides vouchers to purchasers of zero-emission offroad freight equipment, to include agriculture.[73]

CARB is investing cap-and-trade dollars into a program called **Funding Agricultural Replacement Measures for Emission Reductions (FARMER)**. The FARMER program was established per Assembly Bill (AB) 134 and AB 109. The program aims to develop ZEV technology for the off-road agricultural Mobility sources.[74]

CARB adopted a **Zero Emission Forklift** rule in June 2024which phases out the operation of large spark-ignited (LSI) forklifts in California and spurs the use of zero-emissions alternatives. Manufacturers will no longer be allowed to produce or sell, for use in California, Class IV and Class V LSI forklifts, categories that largely operate on propane, gasoline and natural gas, beginning in 2026. The rule also phases out the use of spark-ignited forklifts by large fleets, defined as 26 units or more, starting in 2028. Smaller fleets will phase out use of spark-ignited forklifts starting in 2029.[75]

CARB has funded a project with GTI Energy called **Zero Emission for California Ports (ZECAP)** to develop and demonstrate zero-emission hydrogen fueled yard trucks at the Port of Los Angeles (POLA). Capacity Trucks built two hydrogen-fueled yard trucks, powered by Ballard fuel cell engines, which were then tested at the TraPac Terminal at the POLA for one year. They found that these hydrogen-fueled yard trucks operated successfully and with 2.5 to 3 times the efficiency of conventional diesel powertrains.[76]

The goal of zero-emissions from off-road mobility vehicles by 2035 outlined in EO N-79-20 applies to commercial harbor crafts. CARB published amendments to the Commercial Harbor Craft Regulation which includes requirements for short-run ferries and excursion vessels to meet **Zero-**

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[71] CARB, 2023i, Zero-Emission Airport Ground Support Equipment, CARB webpage, https://ww2.arb.ca.gov/our-work/programs/zero-emission-airport-ground-support-equipment

[72] CARB, 2019, Zero-Emission Airport Shuttle Regulation Factsheet, October, https://ww2.arb.ca.gov/sites/default/files/2019-10/asb_reg_factsheet.pdf

[73] CARB, 2022c, 2022 State Strategy for the State Implementation Plan, Ibid

[74] CARB, 2023d, FARMER Program, Ibid

[75] CARB, 2024c, Zero Emission Forklifts, https://ww2.arb.ca.gov/news/californias-forklifts-become-cleaner-and-less-polluting

[76] Sowa, B., 2023, Zero and Near Zero Emission Freight Facilities Project: Zero Emissions for California Ports (ZECAP), GTI Energy, May

Emission and Advanced Technologies (ZEAT) for new and newly acquired vehicles, and in-use short run ferries, after January 1, 2023.[77]

2021 Senate Bill 643 requires the California Energy Commission (CEC), CARB, and CPUC to assess the hydrogen infrastructure and fuel production required for the transition to ZEVs.[78] They are hoping that their equipment can ultimately qualify as a "Zero Emission Vehicle" under CARB's Advanced Vehicle regulations. However, at this time, the only vehicle types that qualify as ZEVs are electric vehicles and hydrogen fuel cell vehicles. There are multiple California Assembly and Senate bills related to renewable energy and a hydrogen economy that have been introduced, but not yet implemented.

Assembly Bill 324 (AB 324) Utilities and Energy – Gas Corporations, Renewable Gas Procurement was introduced in 2023. This bill would require the CPUC to establish procurement goals for renewable hydrogen and consider requiring each gas corporation and core transport agent to meet these goals.[79]

Senate Bill 746 (SB 746) Energy Conservation Contracts would add hydrogen to the list of primary fuel sources under the definition of "alternate energy equipment." Current law states that "a public agency, as defined, may enter into specified energy conservation contracts, including contracts for the sale of electricity, electrical generating capacity, or thermal energy produced by the energy conservation facility at such rates and on such terms as are approved by its governing body." "Energy conservation facility" is defined as alternate energy equipment, and SB 746 would add hydrogen to this definition.[80]

CARB has also issued the **Low NO_x Heavy-Duty Omnibus Regulation**, requiring a warranty from the manufacturer for emissions for 12 years or 800,000 miles. The rule was approved for adoption by CARB on August 27, 2020. Amendments to this regulation were proposed in 2023 to provide more flexibility for engine manufacturers.[81] The purpose of this regulation is to add additional controls to heavy-duty trucks, particularly during low load conditions. Within this rule, NO_x standards are reduced by 75% in 2024, increasing to 90% reductions by 2027. The rule also revamps the in-use testing program, adjusts warranty requirements, increases the durability

[77] State of California, 2022b, Final Regulation Order Commercial Harbor Craft Regulation, Final Regulation Order: title 13, section 2299.5 and title 17, section 93118.5, Filed December 30, https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2021/chc2021/chcfro.pdf

[78] State of California, 2021, SB643 Fuel cell electric vehicle fueling infrastructure and fuel production: statewide assessment, October 8, https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220SB643

[79] State of California, 2023a, AB324 Gas Corporations: renewable gas procurement, March 27, https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202320240AB324

[80] State of California, 2023b, SB746 Energy conservation contracts: alternate energy equipment: green hydrogen: Tri-Valley-San Joaquin Valley Regional Rail Authority, October 7, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202320240SB746

[81] CARB, 2023e Proposed Amendments to the Heavy-Duty Engine and Vehicle Omnibus Regulation, CARB webpage last updated December 6, https://ww2.arb.ca.gov/rulemaking/2023/hdomnibus2023

demonstration program, amends the emissions averaging, banking, and trading program, and provides test procedures for powertrain certification of heavy-duty hybrid vehicles.[82]

CARB has implemented a **Community Air Protection Program** (CAPP), per AB617,[83] to improve local air quality with the support of residents. Blueprint 2.0, their first five-year update to the strategy, was approved by the board in October 2023. Three new tools were added to the program, including community air grants, flexible use of incentive funds to meet community goals, and community-focused enforcement. The program pulls together members of disadvantaged communities with the local air districts in decision making and planning for reducing air pollution within their communities.[84]

4.2.3 Local Air Districts Landscape

California has thirty-five local Air Districts throughout the state. These districts are responsible for managing air pollutant emissions within their geographic region. They do this through planning, monitoring, and air permitting of equipment. Each district has its own set of regulations, permitting requirements, and emissions limitations for equipment.[85]

The US EPA defines a State Implementation Plan (SIP) as "a collection of regulations and documents used by a state, territory, or local air district to implement, maintain, and enforce the National Ambient Air Quality Standards, or NAAQS, and to fulfill other requirements of the Clean Air Act."[86] SIPs outline plans for how a state will maintain or obtain compliance with the NAAQS. SIPs must be approved by the US EPA, and examples of what may be included in the SIP include maintenance plans, emissions inventories, monitoring networks, permitting programs, attainment demonstrations, transportation control measures, and contingency measures.

Local air districts in non-attainment areas are also required to develop implementation plans, or air quality management plans outlining how they will achieve attainment status. The South Coast AQMD published their most recent AQMP on December 2, 2022, which outlines their projected emissions, emissions reductions, and plans for meeting attainment status.[87] The San Joaquin Valley APCD published their most recent air quality plan, the 2022 Ozone Plan, in 2022. The plan

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[82] CARB, 2020, Facts about the Low NOx Heavy-Duty Omnibus Regulation, https://ww2.arb.ca.gov/our-work/programs/heavy-duty-low-nox/hd-low-nox-omnibus-regulation-fact-sheet

[83] CARB, 2023g, AB 617 Implementation, CARB website, https://ww2.arb.ca.gov/our-work/programs/resource-center/ab-617-implementation

[84] CARB, 2023h, Community Air Protection Blueprint, CARB webpage, https://ww2.arb.ca.gov/capp-blueprint

[85] CARB, 2023f, California Air Districts, CARB webpage, https://ww2.arb.ca.gov/california-air-districts

[86] US EPA, 2023b, Basic Information about Air Quality SIPs, US EPA webpage accessed 2023 at https://www.epa.gov/air-quality-implementation-plans/basic-information-about-air-quality-sips

[87] South Coast Air Quality Management District (South Coast AQMD), 2022, 2022 Air Quality Management Plan (AQMP), https://www.aqmd.gov/home/air-quality/air-quality-management-plans/air-quality-mgt-plan

outlines their attainment strategy and demonstration, emissions inventory, and incremental progress, among other topics. [88] Both the South Coast AQMD and San Joaquin Valley APCD 2022 plans were approved by CARB on January 26, 2023 and are awaiting EPA's approval for inclusion into the SIP.

Air permitting of new or modified equipment includes implementation of New Source Review (NSR) requirements. Application of Best Available Control Technology (BACT) or Lowest Achievable Emissions Rate (LAER) emission limits is required. Each district implements BACT and LAER requirements using their own rules .[89] These LAER and BACT requirements mean that new and modified equipment will need to meet the lowest emissions limits technologically feasible. It is assumed that the California regulatory environment would not allow for an increase in permitted equipment NO_x emission limits at stationary sources. As such, it was assumed that technological advancements for combustion and emission controls would be in place so that the permitted NO_x emission limits would stay the same or decrease with the combustion of hydrogen in equipment in the power generation and hard to electrify industrial sectors.

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[88] San Joaquin Valley Air Pollution Control District, 2023, 2022 Ozone Plan For the San Joaquin Valley, webpage, https://ww2.valleyair.org/rules-and-planning/air-quality-plans/ozone-plans/2022-ozone-plan-for-the-san-joaquin-valley/

[89] CARB, 2023b, Best Available Control Technology Definitions, CARB webpage, https://ww2.arb.ca.gov/our-work/programs/stationary/stationary-source-permitting/bact-program/bact-definitions

5.0 TECHNOLOGY DEVELOPMENTS

This study collected, reviewed, and analyzed technical research studies and information related to NO_x emissions associated with the combustion of hydrogen. This effort included studies from research-based academic institutions such as the University of California Irvine (UCI) Combustion Laboratory and the Georgia Institute of Technology; private organizations such as the Electric Power Research Institute; existing, proposed, and potential future requirements from federal agencies including the US EPA, the United States Department of Energy (US DOE) and the National Renewable Energy Lab (NREL); state agencies such as the California Air Resources Board (CARB) and the California Energy Commission (CEC); and local agencies including each of the nine local air districts located within the geographic scope of this study; technological developments and timelines from manufacturers working on hydrogen technology such as Siemens, Mitsubishi, General Electric, and Cummins; hydrogen demand from the Demand Study; and other Phase 1 studies.

5.1 HYDROGEN CONVERSION TECHNOLOGIES

To develop and quantify emissions estimates, it was important to understand the current technology landscape. It is important to evaluate the types of hydrogen conversion technology (technologies that convert the energy in hydrogen to power or heat) that are currently in production and commercially available, what types of technologies are being researched, tested in the prototype phase, and those that are still conceptual. It is also important to evaluate manufacturers goals and stated timeframes for when hydrogen technology is expected to become commercially available as well as the development timelines outlined by the US DOE.

Manufacturers are developing and commercializing combustion technology capable of operating on 100% hydrogen fuel for applications in power generation, industrial heating, mobility, and other sectors. For example, there are existing turbine units capable of combusting 100% hydrogen fuels. However, these are typically smaller industrial or aeroderivative units such as the 30-40 MW Siemens Aeroderivative SGT-A35 or the 10-15 MW Siemens SGT-400. Manufacturers are still largely developing combustion technology for large-frame turbines capable of combusting 100% hydrogen fuel while minimizing air pollutant emissions.[90]

[90] US EPA, 2023a, Hydrogen in Combustion Turbine Electric Generating Units, Ibid

Studies indicate that many existing natural gas combustion units can operate effectively on blended hydrogen fuels of up to 30% without design modifications.[91,92,93,94]

Some existing burner equipment can effectively operate on hydrogen fuel blends upwards of 70% without modification, such as the ultralow NO_x residential water heaters tested by the UCI Combustion Laboratory. The same study found that conventional water heaters could only typically operate on hydrogen blends of up to 40-50% by volume.[95] The percentage of hydrogen by volume that an existing combustion unit can utilize without modification depends on a wide range of variables.

Current and developing hydrogen conversion technology can be grouped into three primary categories: hydrogen fuel cells, hydrogen combustion engines, and hydrogen turbines.

5.1.1 Fuel Cells

Fuel cell hydrogen vehicles (FCEVs) generate electricity from hydrogen in the fuel cell and use that electricity to power an electric motor much like an electric vehicle and their efficiency can be as high as 60-80%.[96] Polymer electrolyte membrane fuel cell (PEMFC) or proton exchange membrane (PEM) is the most common hydrogen fuel cell technology in transportation such as harbor crafts.[97] Fuel cells produce and emit water vapor and heat as emissions.

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[91] US EPA, 2023a, Hydrogen in Combustion Turbine Electric Generating Units, Ibid

[92] National Energy Technology Laboratory, 2022, A Literature Review of Hydrogen and Natural Gas Turbines: Current State of the Art with Regard to Performance and NOx Control, White Paper DOE/NETL-2022/3812, August 12, https://www.netl.doe.gov/sites/default/files/publication/A-Literature-Review-of-Hydrogen-and-Natural-Gas-Turbines-081222.pdf

[93] Glanville, P., A. Fridlyand, B. Sutherland, M. Liszka, Y. Zhao, L. Bingham and K. Jorgensen, 2022, Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance, Energies 15(5)1706, https://www.mdpi.com/1996-1073/15/5/1706

[94] Öberg, S., M. Odenberger, and F. Johnsson, 2022, Exploring the Competitiveness of Hydrogen-fueled Gas Turbines in Future Energy Systems, International Journal of Hydrogen Energy 47(1): 624-644, https://doi.org/10.1016/j.ijhydene.2021.10.035

[95] Basinger, E., B. Hickey, and V. McDonell, 2023, A compilation of operability and emissions performance of residential water heaters operated on blends of natural gas and hydrogen including consideration for reporting bases, International Journal of Hydrogen Energy 48(51):19733-19749, https://doi.org/10.1016/j.ijhydene.2023.02.018

[96] Yue, M., H. Lambert, E. Pahon, R. Roche, S. Jemei, and D. Hissel, 2021, Hydrogen energy systems: A critical review of technologies, applications, trends and challenges, Renewable and Sustainable Energy Reviews 146: 111180, https://doi.org/10.1016/j.rser.2021.111180

[97] CARB, 2021b, Public Hearing to Consider the Proposed Amendments to the Commercial Harbor Craft Regulation, Appendix E Technical Support Document and Assessment of Marine Emission Control Strategies, Zero-Emission, and Advanced Technologies for Commercial Harbor Craft, September 21, https://ww2.arb.ca.gov/rulemaking/2021/chc2021

5.1.2 Internal Combustion Engines

Hydrogen internal combustion engines (H_2ICE) for stationary use are a developing technology that operate similarly to fossil fuel internal combustion engines (ICE). Compared to fossil fuel combustion engines, hydrogen combustion engines are designed to account for the unique combustive properties of hydrogen. Hydrogen combustion engines have the potential to replace fossil fuel combustion engines in many different hard to electrify industrial sectors.

First generation H_2ICE technology includes port-injection spark-ignition where the fuel is injected during the intake stroke. This technology will likely be readily available on the market by 2025. Existing fossil fuel ICEs can be retrofitted using this technology to combust higher percentages of hydrogen fuel. Between 2025 and 2030, market introduction for second generation direct-injection spark-ignition H_2ICEs is anticipated. This technology will directly inject fuel during the early compression stroke to allow time for mixing. Also anticipated between 2025 and 2030 is the release of the second plus generation of H_2ICE technology, high pressure direct injection. This technology injects fuel near the top center of the unit at a high pressure (100-600 bar).[98]

Jenbacher is a manufacturer that currently offers hydrogen combustion technology. Jenbacher states that all their new engines are "Ready for H2", meaning that they can run on fuel blends of up to 25% hydrogen. They also offer engines able to operate on pure hydrogen, referred to as their "Type 4" engines. Their stated portfolio goals include operation of Type 2, Type 3, Type 6, and Type 9 engines by 2025 or later.[99] Caterpillar (CAT) offers gas generator sets, including the G3500H series, the CG132B, and the Cat CG170B, capable of operating on fuel blends of up to 25% hydrogen ranging from 600 kW to 2.5 MW units. The Cat G3516 gas generator set, with a maximum rating of 1250 kW, is able to utilize pure hydrogen fuels.[100] Currently, hydrogen combustion engine thermodynamic efficiency is around 20% to 25%.[101]

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[98] US DOE, 2023a, Overview of Hydrogen Internal Combustion Engine (H2ICE) Technologies, H2IQ Hour Webinar, slides available online at https://www.energy.gov/sites/default/files/2023-07/h2iqhour-02222023-2.pdf

[99] Jenbacher, 2024, Energy Solutions – Hydrogen Power Plants, industry webpage, https://www.jenbacher.com/en/energy-solutions/energy-sources/hydrogen

[100] Caterpillar, 2023, Caterpillar Expands Range of Hydrogen-Fueled Power Solutions to Include Generator Sets and Retrofit Kits from 600 kW to 2.5 MW, industry press release, October, https://www.cat.com/en_US/news/engine-press-releases/caterpillar-expands-lineup-of-hydrogen-fueled-power-solutions-with-generator-sets-and-upgrade-kits.html

[101] Yue, M., et al., 2021, Hydrogen energy systems, Ibid

5.1.3 Stationary External Combustion Sources

Boilers, heaters, and ovens are examples of external combustion units with the potential to combust hydrogen albeit sometimes with modifications.[102] External hydrogen combustion sources have the potential to produce NO_x emissions and may require burner modifications and aftertreatment to control these emissions, although several burner types show reductions in NO_x formation when burning hydrogen blends.[103] Babcock and Wilcox offers a commercially available steam boiler that can operate on 100% hydrogen fuel, called BrightGen. This unit has the ability to switch between hydrogen and natural gas combustion as needed.[104]

5.1.4 Turbines

Hydrogen-fueled gas turbines are a developing technology that have the potential to replace natural gas-fueled gas turbines in the power generation sector and hard to electrify industrial sector. The technology will likely be very similar to natural gas-fueled gas turbines, but design specifications will need to account for higher flame speeds and the wider range of flammability of hydrogen as compared to natural gas. Some existing heavy-duty equipment can combust anywhere from 5% fuel blends to 100% hydrogen. Manufacturer upgrades are available for some larger units to allow them to increase the percentage of hydrogen fuel that they are able to combust. Wet low-emission (WLE), dry low-emission (DLE), or dry low- NO_x (DLN) combustors are often utilized in heavy-duty turbines capable of combusting hydrogen fuel blends, such as Aeroderivative and industrial units to reduce the formation of some air pollutants. Wet low-emission technology utilizes water or steam to decrease the temperature of combustion. DLN and DLE technology reduces air pollutant emissions from the exhaust without the use of water or steam.[105]

Mitsubishi, Siemens, and GE are the three largest global turbine manufacturers and have each outlined plans for establishing pure hydrogen firing turbine technology for power generation. Siemens and GE have published goals to develop heavy-duty DLE and DLN turbines with the

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[102] Elavarasan, E., S. Sivaraj, M. Y. Tamilselvan, V. Vijayaragavan, P. Vignesh, 2018, Hydrogen Fired Steam Boilers, International Journal of Engineering Research and Technology Special Issue, ICITMSEE Conference Proceedings, https://www.ijert.org/research/hydrogen-fired-steam-boilers-IJERTCONV6IS10016.pdf

[103] Colorado, Andres; McDonell, Vincent. (University of California Irvine, Combustion Laboratory UCICL). 2016. Effect of Variable Fuel Composition on Emissions and Lean Blowoff Stability Limits. California Energy Commission. Publication number: CEC-500-2017- 026. Final Project Report, Effect of Variable Fuel Composition on Emissions and Lean Blowoff Stability Performance (ca.gov)

[104] Babcock & Wilcox, 2023, BrightGen™ Hydrogen Combustion Technology: Utilizing non-carbon-based fuels for steam production, Industry Brochure, https://www.babcock.com/assets/PDF-Downloads/PS-599-BrightGen-Hydrogen-Combustion-Brochure.pdf

[105] US EPA, 2023a, Hydrogen in Combustion Turbine Electric Generating Units, Ibid

ability to combust pure hydrogen by 2030, and Mitsubishi set a goal to develop DLN turbines with the ability to combust 100% hydrogen fuel by 2025.[106]

Manufacturers are advancing technology to enable combustion engines to function entirely on hydrogen, targeting applications in power generation, industrial heating, and transportation. Currently, smaller turbines such as Siemens' SGT-A35, with a capacity of 30-40 MW, and the SGT-400, rated at 10-15 MW, already operate on 100% hydrogen.[107] However, larger turbine models still require technological enhancements to sustain full hydrogen operation and maintain low air pollution levels. The leading manufacturers in this sector are Siemens, General Electric (GE), and Mitsubishi.

Both Siemens and GE are working towards developing large, advanced turbines that can achieve 100% hydrogen combustion by 2030. Mitsubishi aims to reach this capability by 2025 and has already made progress; in 2018, their proprietary burner technology in Mitsubishi Hitachi Power Systems achieved a 10% reduction in CO_2 emissions with a 30% hydrogen blend.[108,109]

GE categorizes its turbines into four groups based on their hydrogen handling capacity: Aeroderivative, B/E-Class, F-Class, and HA-Class. Per GE Vernova, gas turbines are inherently fuel flexible and can be configured to use clean renewable hydrogen as new units or units upgraded after service using natural gas. Aeroderivative, B/E-Class and F-Class can currently handle up to 100% hydrogen and the HA-Class can currently handle 50% and is expected to be able to handle 100% hydrogen in the future.[110]

Siemens has also demonstrated the adaptability of their turbines to hydrogen: the Aeroderivative SGT-A35 turbines can operate on 100% hydrogen using special burners.[111] More recently, in 2023, Siemens announced that their SGT-400 unit, with a 10-15 MW capacity, successfully ran on 100% hydrogen.[112] Siemens' HL-class turbines are engineered to manage up to 50% hydrogen

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106 US EPA, 2023a, Hydrogen in Combustion Turbine Electric Generating Units, Technical Support Document, Docket ID No.EPA-HQ-OAR-2023-0072, May 23, https://www.epa.gov/system/files/documents/2023-05/TSD%20-%20Hydrogen%20in%20Combustion%20Turbine%20EGUs.pdf

107 US EPA, 2023a, Hydrogen in Combustion Turbine Electric Generating Units Ibid

108 US EPA, 2023a, Hydrogen in Combustion Turbine Electric Generating Units Ibid

109 Mitsubishi Power, 2018, MHPS Successfully Tests Large-scale High-efficiency Gas Turbine Fueled by 30% Hydrogen Mix -- Will Contribute to Reducing CO2 Emissions during Power Generation, industry news release, January 19, https://power.mhi.com/news/20180119.html

110 General Electric Vernova, Hydrogen-Fueled Gas Turbines | GE Vernova

111 Siemens Energy, 2023a, SGT-A35 gas turbine, industry webpage, https://www.siemens-energy.com/global/en/home/products-services/product/sgt-a30-a35-rb.html#tabs-59fe95a20e-item-7c5b13e0e1-tab

112 Hydrogeninsight, 2023, Siemens Energy burns 100% hydrogen in industrial gas turbine in energy-storage pilot, online energy transition publication, October 16,https://www.hydrogeninsight.com/power/correction-siemens-energy-burns-100-hydrogen-in-industrial-gas-turbine-in-energy-storage-pilot/2-1-1535850

combustion.[113] Finally, Siemens has announced the "Zero Emission Hydrogen Turbine Center" which is a demonstration plant in Sweden to showcase a flexible and sustainable energy system connecting gas turbines with hydrogen, renewable electricity and energy storage.[114]

Few manufacturers have published data regarding NOx emissions from the combustion of hydrogen in their units. In gas turbines, largely due to the high flame speed of hydrogen, low NOx use of hydrogen in combustion units without the incorporation of water injection is a continued challenge for manufacturers. Lean pre-mixed technology is a key for dry low NOx hydrogen combustion designs.[115]

With the bulk of the hydrogen combustion technology still in development, the availability of emissions data is sparse. However, of the published manufacturer's emissions data reviewed, the potential uncontrolled NOx emissions ranged from less than 10 ppmv for the GE 7E turbine capable of combusting up to 60% hydrogen[116] (baseload condition, dry), to 25 ppmv for the Ansaldo GT36 turbine capable of combusting up to 70% hydrogen (manufacturer specification sheet indicates 25 ppmv emissions in dry gas mode with option down to 15 ppm but does not specify what the "option" is).[117] Siemens has shared that NOx emissions for their SGT-600 (up to 60% hydrogen fuel), SGT-700 (capable of combusting up to 55% hydrogen fuel), SGT-800 (capable of combusting up to 50% hydrogen fuel), and their SGT-750 (capable of combusting up to 40% hydrogen fuel) turbines are ≤ 25 ppmv.[118] Siemen's Aeroderivative SGT-A35 turbine can burn up to 100% hydrogen fuel and emits less than 15 ppmv uncontrolled.[119] Siemens has published that NOx emissions from their HL-class, including the SGT5-9000HL and the SGT6-9000HL, can be as low as 2 ppm with SCR controls.[120] These anticipated uncontrolled and controlled NOx emission values are similar to those currently permitted limits for this type of equipment.

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113 Siemens Energy, 2023b, SGT5-9000HL gas turbine, industry webpage, https://www.siemens-energy.com/global/en/offerings/power-generation/gas-turbines/sgt5-9000hl.html

114 Siemens Energy, 2024, Zero Emission Hydrogen Turbine Center, https://www.siemens-energy.com/global/en/home/products-services/solutions-usecase/hydrogen/zehtc.html

115 Webb, B.M. et al., 2023, Second Edition: Assessment of Current Capabilities, Ibid

116 McDonell, V, 2023, presentation, July 14, Ibid

117 Ansaldo | energia, 2022, The Gas Turbine: GT36 – the superior value, industry brochure, https://www.ansaldoenergia.com/fileadmin/Brochure/AnsaldoEnergia-GasTurbine-GT36-20220930.pdf

118 Siemens Energy, 2020, Hydrogen Combustion in Siemens Gas Turbines, industry presentation, http://cnr-cme.ro/wp-content/uploads/2020/08/Hydrogen-Combustion-in-Gas-Turbines-.pdf#:~:text=All%20newly%20built%20Siemens%20gas%20turbine%20types%20capable,with%20standard%20natural%20gas%20turbines%20%28new%20unit%20applications%29

119 Siemens Energy, 2023a, SGT-A35 gas turbine, Ibid

120 Siemens Energy, 2023b, SGT5-9000HL, Ibid

Table 9 Heavy Duty Gas Turbine Hydrogen Capabilities[121]				
Company	**Type**	**Notes**	**TIT °C [ºF] or Class**	**H_2 % (Vol)**
Mitsubishi Hitachi Power Systems	Diffusion	N_2 Dilution, Water/Steam Injection	1200-1400 [2192-2552]	up to 100
	Pre-Mix (DLN)	Dry	1600 [2912]	up to 30
	Multi-Cluster	Dry	1650 [3002]	up to 30
General Electric	SN	Single Nozzle (Standard)	B,E Class	up to 100
	MNQC	Multi-Nozzle Quiet Combustor w/N_2 or Steam	E,F Class	up to 100
	DLN 1	Dry	B,E Class	up to 33
	DLN 2.6+	Dry	F,H Class	up to 20
	DLN 2.6e	Dry	E Class	up to 50
Siemens	DLE	Dry	E Class	up to 30
	DLE	Dry	F Class	up to 30
	DLE	Dry	H Class	up to 30
	ACE	Dry	HL Class	up to 50
Ansaldo	Sequential	GT26	F Class	up to 30
	Sequential	GT36	H Class	up to 50
PSM	LEC-III™	DLE	B,E Class	up to 50
	Current Flamesheet™	DLE	Frame 5, 6B, 7E, 9E, 7F, 9F, 501F, 701F	up to 60
Baker Hughes	DLN	Frame 6/7/9	Frame 6/7/9	up to 32
	Diffusion	Frame 6/7/9	Frame 6/7/9	up to 100

[121] Webb, B.M., J. Harper, R. Steele, D.R. Noble, B. Emerson, D. Wu, and T. Lieuwen, 2023, Second Edition: Assessment of Current Capabilities and Near-Term Availability of Hydrogen-Fired Gas Turbines Considering a Low-Carbon Future, proceedings paper from ASME Turbo Expo 2023, https://doi.org/10.1115/GT2023-103962

5.2 HYDROGEN USE IN MOBILITY

The Mobility end-user sector is comprised of on-road and off-road commercial and industrial vehicles in various industries. This study evaluated the potential for NO_x emissions and/or reductions due to the displacement of fossil fuels by hydrogen demand in the following mobility sub-sectors: heavy-duty trucks, medium-duty vehicles, buses, agriculture, construction & mining, cargo handling equipment, ground support equipment, and commercial harbor craft.

On-Road Vehicles: Heavy-duty trucks, medium-duty vehicles, and buses are all on-road vehicles evaluated in this study. There is regulatory pressure for on-road vehicles to transition to zero-emission vehicles. Commercial availability of medium- and heavy-duty hydrogen fuel cell vehicles is still evolving. CARB has noted that heavy-duty vehicles are the largest source of NO_x within California. Heavy-duty vehicles contribute over 25% of the state's emissions of diesel particulate matter.[122] However, technological advancements are continuing on-pace with US DOE estimations.

Agriculture: The agricultural industry utilizes many off-road mobile sources in their operations, such as tractors, harvesters, and bale wagons. A 2021 presentation from the US DOE outlined some of the benefits and challenges of hydrogen fuel cells in agricultural applications. The benefits included zero emissions, 10-15 minute refueling time, lighter powertrain than batteries, and reduced noise. Challenges included the cost of the drivetrain being more expensive than a diesel powertrain, low volumetric power density, higher weight of required volume of liquid H_2 compared to diesel, cooling which would require a radiator with much larger heat rejection capacity, reduced vehicle lifetime due to higher operating temperatures, and lack of infrastructure in remote areas where farms may be located. As of 2021, the US DOE recommended more research and development into effective utilization of hydrogen fuel cells in agricultural equipment.[123]

More research has since been completed, and in February of 2023, Fendt introduced a hydrogen fuel tractor prototype that will be tested on farms later during the year.[124] Another manufacturer, Kubota, has published plans to roll out their first hydrogen fuel cell tractor in 2025.[125] Fendt

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122 CARB, 2020, Facts about the Low Nox Heavy-Duty Omnibus Regulation, Ibid

123 CNHi, 2021, Technology Challenges for Hydrogen Fuel Cells in Agricultural Applications, presentation at US DOE Hydrogen Workshop September 22-24, https://www.energy.gov/sites/default/files/2021-12/922-11-mission-innovation-CNH.pdf

124 Fendt, 2023, Fendt shows first hydrogen tractor at German Hydrogen Summit, industry press release February 27, https://www.fendt.com/int/fendt-shows-first-hydrogen-tractor-at-german-hydrogen-summit

125 Nikkei Asia, 2022, Kubota to roll out first fuel cell tractor in 2025, eyeing U.S. and Europe, June 2, https://asia.nikkei.com/Spotlight/Environment/Climate-Change/Kubota-to-roll-out-first-fuel-cell-tractor-in-2025-eyeing-U.S.-and-Europe

planned to complete their prototype in 2023 and is undergoing testing and use as of 2024.[126] [127]This study assumes that agricultural equipment will transition to hydrogen fuel cells when converting to the use of hydrogen as fuel.

Construction and Mining: The construction and mining industries utilize various off-road mobile combustion sources in their operations including, but not limited to, cranes, tractors, graders, pavers, rollers, forklifts, loaders, and backhoes. A 2020 report published by Deloitte and Ballard states that hydrogen fuel cell mining equipment is still in the "prototype" phase meaning that companies are still developing the technology and equipment has not been demonstrated or launched commercially.[128] In 2022, Cummins and Komatsu announced a partnership for the development of hydrogen fuel cell equipment for mining operations. They planned to begin by focusing their efforts on large mining truck technology. The press release shared that hydrogen fuel cell technology may be the preferred ZEV for the mining industry in remote areas where there is no available grid power. They also noted that large hydrogen fuel cell vehicles can quickly refuel, like diesel vehicles, and that they provide higher density of power.[129]

Cranes may be used in construction and mining, and a study was published in 2019 by Corral-Vega et al. evaluating fuel cell/supercapacitor powered cranes. The study found that use of a hydrogen fuel cell with a supercapacitor in a crane was technically viable. The evaluated technology was determined to be more energy-efficient and more environmentally beneficial than a standard diesel powertrain.[130] Volvo Construction Equipment has set their own goals for the development of ZEV technology. In 2022 they began testing the world's first prototype hydrogen fuel cell articulated hauler, the Volvo HX04. The HX04 re-fuels in about 7.5 minutes with 12 kg of hydrogen. This provides the equipment with enough fuel to operate for about 12 hours.[131]

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[126] Le Comptoir Des Eleveurs, 2024, Fendt hydrogen tractor in use, H2Agrar project, Lower Saxony; Germany, January 22, 2024, https://www.comptoir-des-eleveurs.com/vods/7fc6c566-27b9-ee11-bea2-000d3aaa8069/fendt-hydrogen-tractor-in-use-h2agrar-project-lower-saxony-germany

[127] FuelCellWorks, 2024, Fendt's Helios Hydrogen Tractor Undergoes Extensive Testing in Germany, March 11, 2024, https://fuelcellsworks.com/subscribers/fendts-helios-hydrogen-tractor-undergoes-extensive-testing-in-germany/

[128] Deloitte and Ballard, 2020, Fueling the Future of Mobility, white paper, https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf

[129] Electrive, 2022, Cummins & Komatsu team up on h2 fuel cell trucks for mining operations, industry media website, https://www.electrive.com/2022/07/04/cummins-komatsu-team-up-on-h2-fuel-cell-trucks-for-mining-operations/

[130] Corral-Vega, P.J., P. García-Triviño, and L.M. Fernández-Ramírez, 2019, Design, modelling, control and techno-economic evaluation of a fuel cell/supercapacitors powered container crane, Energy 186: 115863, https://doi.org/10.1016/j.energy.2019.115863

[131] Volvo Construction Equipment Global, 2022, Volvo CE starts testing of the world's first prototype hydrogen articulated hauler, industry press release, June 13, https://www.volvoce.com/global/en/news-and-events/news-and-stories/2022/volvo-ce-starts-testing-of-the-worlds-first-prototype-hydrogen-articulated-hauler/

Forklifts: Many commercial and industrial industry sectors utilize forklifts in their operations. The US DOE shared that as of November 2018 there were already more than 20,000 hydrogen fuel cell forklifts in operation across the US.[132] Toyota, a manufacturer of PEM hydrogen fuel cell forklifts, notes that hydrogen fuel cell forklifts can be refilled quickly and that they don't require as much maintenance as a lead-acid battery electric forklift.[133]

Cargo Handling Equipment: CARB has proposed to begin the transition to zero-emission vehicles for cargo handling equipment in 2026.[134] The San Pedro Bay Ports Complex issued an initial Clean Air Action Plan (CAAP) in 2017 outlining their goal of achieving 100% ZEVs for cargo handling equipment by 2030, earlier than California's goal of zero emissions from mobile sources by 2035 established in EO N-79-20.[135]The CAAP requires that a feasibility assessment for zero-emission and near zero-emission cargo-handling equipment be completed every three years. The most recent update was completed in 2021 and published in July of 2022. The assessment included an evaluation of zero emission hydrogen fuel cell electric vehicles and outlines that Toyota Motor Company, Cummins, and Hyster-Yale are both in the development stage for fuel cell yard trucks, also referred to as terminal tractors. In 2020, Hyster-Yale Group entered a partnership with Capacity Trucks to develop hydrogen yard trucks.[136] Conductix Wampfler is in the concept design stage for a hydrogen fuel cell-powered RTG crane.[137] A study completed by Li et al. in 2019 evaluated the feasibility of a fuel cell supercapacitor excavator. They found that NASTA construction equipment and Volvo construction equipment are developing prototypes for this equipment. Their economic evaluation ultimately found that fuel cell hybrid electric vehicles (FCHE) fuel economy is primarily influenced by the size of the fuel cell stack. They found that as costs decrease, the FCHEs will become commercially viable and attractive.[138]

Ground Support Equipment: Ground support equipment encompasses the off-road equipment, or equipment that was designed for on-road use but not licensed for on-road use, that supports

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132 US DOE, 2018, Fact of the Month November 2018: There Are Now More Than 20,000 Hydrogen Fuel Cell Forklifts in Use Across the United States, https://www.energy.gov/eere/fuelcells/fact-month-november-2018-there-are-now-more-20000-hydrogen-fuel-cell-forklifts-use

133 Toyota, 2023, Hydrogen Fuel Cell Forklifts: An Alternative Energy Solution, industry blog, March 28, https://www.toyotaforklift.com/resource-library/blog/energy-solutions/hydrogen-fuel-cell-forklifts-an-alternative-energy-solution

134 CARB, 2022c, 2022 State Strategy for the State Implementation Plan, Ibid

135 San Pedro Bay Ports Clean Air Action Plan, 2023, 2017 CAAP, Ibid

136 Hyster, 2020, Hyster-Yale Group and Capacity Trucks Enter Partnership to Jointly Develop Electric, Hydrogen, and Automation-Ready Terminal Tractors, Press Release, December 14 https://www.hyster.com/en-us/north-america/why-hyster/press-releases/2020/hyster-yale-group-and-capacity-trucks-enter-partnership-to-jointly-develop-electric-hydrogen-and-automation-ready-terminal-tractors/

137 Tetra Tech/Gladstein, Neandross & Associates, 2022, 2021 Update Feasibility Assessment for Cargo-Handling Equipment, report for San Pedro Bay Ports Clean Air Action Plan, https://cleanairactionplan.org/strategies/cargo-handling-equipment/

138 Li, T., L. Huang, and H. Liu, 2019, Energy management and economic analysis for a fuel cell supercapacitor excavator, Energy 172: 840-851, https://doi.org/10.1016/j.energy.2019.02.016

the operations at airports. This equipment includes, but is not limited to, cargo loaders, cargo tractors, forklifts, fuel trucks, ground power units, maintenance trucks, and service trucks.

In 2020, the US DOE developed a presentation regarding hydrogen use at airports. Their presentation outlined that the regulatory pressures, sustainability goals, the cost of regulatory compliance, the fact that airports are a standalone ecosystem, and increasing demand for air cargo are among the drivers for use of hydrogen in ground support equipment. The transition of these vehicles to hydrogen would potentially decrease the maintenance needs as compared to diesel vehicles. Hydrogen fuel cell ramp crew vans, ramp management vehicles, and crew shuttle buses were listed as, "Under Consideration," while loaders, tractors, GPU, and cargo transporters were listed as in, "Current Trials & Product Development."[139]

The US DOE along with FedEx and Charlatte completed a test of the world's first fuel cell airport ground support equipment fleet of 15 vehicles at the Memphis airport during fiscal year 2018. Results of the test at the Memphis airport demonstrated that the fuel cell-powered tugs were able to pull 50,000 pounds; they were available 90.5% of the time from February to October 2017; they achieved 304 shifts before running out of fuel and lasted 218 hours between failures on average. These statistics exceeded their target metrics in each category. Once the test project was finished in Memphis, two of the baggage tractors were relocated to Albany airport for further testing. This allowed a test of the equipment in winter weather conditions. The vehicles were re-commissioned in Albany in February of 2019. The vehicles were successfully operated in conditions ranging from 5 to 91 degrees Fahrenheit.[140]

Commercial Harbor Craft: Commercial harbor craft refers to private, commercial, government, or military marine vessels that do not otherwise meet the definition of ocean-going vessels or recreational vehicles. Commercial harbor crafts include, but are not limited to, passenger ferries, excursion vessels, tugboats, fishing vessels, research vessels, emergency response harbor craft, and barge vessels. Given the geographic region of this study, it is important to evaluate the feasibility of commercial harbor craft technology to operate on hydrogen fuel, as the region includes the San Pedro Port Complex made up of the Port of Los Angeles and the Port of Long Beach where many commercial harbor crafts operate.

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[139] Plug Power, 2020, Fuel Cells for Ground Support Equipment, US DOE H2 @ Airports 2020 workshop presentation, https://www.energy.gov/sites/default/files/2020/12/f81/hfto-h2-airports-workshop-2020-blanchard.pdf

[140] Plug Power, 2019, Plug Power to Showcase Results from Fuel Cell-Powered Ground Support Equipment program at Press Event, Highlighting Successful Collaboration with FedEx, Charlatte, Albany International Airport, and the US Department of Energy, press release August 15, https://www.globenewswire.com/news-release/2019/08/15/1902369/0/en/Plug-Power-to-Showcase-Results-from-Fuel-Cell-Powered-Ground-Support-Equipment-program-at-Press-Event-Highlighting-Successful-Collaboration-with-FedEx-Charlatte-Albany-Internationa.html

CARB funded a project called the Switch Maritime Seachange to demonstrate a hydrogen fuel cell in a ferry in Washington State. The Seachange then underwent testing in San Francisco Bay. The Switch Sea Exchange is another passenger ferry run operated by Switch Maritime that has the capability to operate on a hydrogen fuel cell. The Sandia National Laboratory conducted their own feasibility study in 2016 comparing a battery-electric propulsion system and a hydrogen fuel cell propulsion system in a high-speed, long-distance ferry. They ultimately found that the hydrogen fuel cell propulsion system provided three times the energy density of the battery electric propulsion system, at 1.71 Mega Joules per kilogram (MJ/kg).[141] A study completed by Bryan Lee with CALSTART in 2023 outlines the Hydrogen Zero Emission Tug (HyZET) project for the development of a liquid hydrogen tugboat. The study found that a tugboat powered by a hydrogen fuel cell can meet the operating requirements in the San Pedro Port Complex.[142]

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[141] CARB, 2021b, Public - Commercial Harbor Craft Regulation, Ibid

[142] Lee, B., 2023, Decarbonizing Harbor Craft: The Hydrogen Zero Emission Tug Project, publication from the 36th International Electric Vehicle Symposium and Exhibition (EVS36) Sacramento, California, USA, June 11-14, 2023, available at http://evs36.com/wp-content/uploads/finalpapers/FinalPaper_Lee_Bryan.pdf#:~:text=To%20advance%20the%20commercialization%20of%20zero%20emission%20harbor,,cell%20tugboat%20and%20to%20analyze%20its%20commercial%20viability

6.0 NO_X MINIMIZATION OPPORTUNITIES

There are several technologies that can minimize the formation of NOx emissions from the combustion of hydrogen and reduce NOx emissions that are formed. These minimization opportunities include equipment design considerations and post-combustion treatment of exhaust gases.

Emissions minimization methodologies can be implemented during equipment design including adjustment of air to fuel ratio, flame temperature, exhaust gas recirculation, thermal efficiency, and residence time. Post combustion technologies to reduce NOx once formed include existing technologies such as SCR, SNCR, and NSCR, as well as emerging technologies including electron beam irradiation and electrochemical reduction.

6.1 EQUIPMENT DESIGN

In theory, emissions of NOx may be perceived as more likely to increase as hydrogen in fuel blends increases, due to the higher flame speed (indicating higher reaction rate) and higher stoichiometric adiabatic flame temperature of hydrogen.[143] However, as noted in the scientific literature, NOx formation has the potential to increase or decrease as the percentage of hydrogen in the fuel increases depending on the burner technology utilized.[144] ETN Global describes how the higher adiabatic flame temperature of hydrogen may result in higher NOx emissions without additional design and control measures. However, literature also notes that NOx from hydrogen combustion can be controlled with selective catalytic reduction (SCR) to meet EPA levels.[145] Additional studies note that NOx emissions may remain constant or decrease while increasing the percentage of hydrogen in fuel depending on the combustion burner technology used.[146] [147] A decrease in NOx emissions when combusting hydrogen is more likely in lean or ultra lean burn technology. The table below synthesizes findings from several studies to outline the emissions characteristics and advancements in burner technology.

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143 Guarco, J, B. Langstine, M. Turner, 2021, Practical Considerations for Firing Hydrogen versus Natural Gas, Combustion Engineering Association article, https://cea.org.uk/wp-content/uploads/2021/06/Zeeco-Hydrogen-Article.pdf

144 Leicher, J., T. Nowakowski, A. Giese, and K. Görner, 2017, Power-to-gas and the consequences: impact of higher hydrogen concentrations in natural gas on industrial combustion processes, Energy Procedia 120: August, 96-103, https://doi.org/10.1016/j.egypro.2017.07.157

145 NREL, 2022, A Literature Review, Ibid

146 Breer, B., H. Priya Rajagopalan, C. Godbold, H. Johnson II, B. Emerson, V. Acharya, W. Sun, D. Noble, T. Lieuwen, 2022, Nox Production from Hydrogen-Methane Blends, Eastern States Section of the Combustion Institute, March 6

147 Colorado, Andres; McDonell, Vincent. (University of California Irvine, Combustion Laboratory UCICL), 2016, Ibid.

Comparison of Burner Technologies and Their NOx Emission Reduction Capabilities

The table synthesizes findings from several studies to outline the emissions characteristics and advancements in burner technology:

Equipment Type	Key Findings
Grouped Burners	
Low-Swirl Burner (LSB), Surface-Stabilized Combustion Burner (SSCB), Micro-Turbine Combustor (MTC) – Capstone C65, Oxygen Burner, High Speed Jet Burner (HSJ), Turbine Combustor GT333 – FlexEnergy, Radiant Tube (RT), Infrared Burner (IRB), Slot Burner (SB)	Inconsistencies in NOx production across various burner technologies were noted. Five burners exhibited increased NOx emissions with higher hydrogen content, attributed to less effective Exhaust Gas Recirculation (EGR). Conversely, four burners demonstrated a decrease in NOx emissions, potentially due to enhanced radiative heat losses facilitated by increased surface area and high emissivity materials. *Authors: California Energy Commission and UCI Combustion Laboratory, 2017*
Individual Burner Studies	
Reciprocating Internal Combustion Engine	Notable increase in NOx emissions when burning hydrogen compared to diesel. However, increasing the air-fuel (lambda) ratio led to a reduction in NOx emissions to zero. *Authors: Roiser et al., 2022*
Bunsen Burner	Significant decrease in mass-normalized NOx ppm emissions as the mole fraction of hydrogen in the fuel increased, primarily due to reduced flame temperatures from increased equivalence ratio lambda (λ). Researchers noted that there is no chemical kinetic reason for H2 flames to produce more NOx than natural gas flames. *Authors: Giacomazzi et al., 2023*
Turbine (1)	NOx volume levels remained relatively constant at hydrogen blends of 20% compared to 100% natural gas, approximately 15 ppm (15% O2). *Authors: Georgia Power McDonough-Atkinson Plant, Mitsubishi, EPRI, 2023*
Turbine (2)	A 24% increase in mass emissions of NOx as the percentage of hydrogen in the fuel rose, with co-firing ranging from 5-44% by volume. *Authors: New York Power Authority's Brentwood site, GE, EPRI, 2023*
Reciprocating Engine	Compliance with existing NOx limits maintained when co-firing up to 25% hydrogen by volume. *Authors: A.J. Mihm Power Plant in Michigan, 2022*
Gas Turbine	Single-digit NOx ppmv emissions achieved at dry, baseload conditions with co-firing 60% hydrogen on a retrofitted turbine. *Authors: Daesan Korea retrofitted GE 7E gas turbine, 2023*

6.1.1 Air to Fuel Ratio and Flame Temperature

This section explores the equipment design factors that impact the formation of NOx from hydrogen combustion and how pure hydrogen combustion equipment may be designed to minimize NOx formation. Hydrogen can combust at a wide range of air to fuel ratios. A higher air to fuel ratio means that there is more air with respect to the amount of fuel. "Lean" operation is when there is an excess of air with respect to fuel. Increasing the air to fuel ratio for hydrogen combustion will decrease the combustion temperature, and therefore, decrease the formation of thermal NOx emissions. A higher flame temperature generally contributes to higher formation of NOx emissions from combustion which is due primarily to the thermal NOx mechanism.[148] [149] Due to the higher flame temperature of hydrogen, NOx emissions have the potential to increase when combusting hydrogen fuel as compared to fossil fuels. However, the scientific literature also represents that designing equipment to operate at lean conditions and/or use EGR or pre-mixing or use porous materials with a higher emissivity have the potential to reduce NOx emissions when combusting hydrogen as compared to fossil fuels.[150,151,152] Current existing technology demonstrates variability in hydrogen flame temperature and subsequent NOx formation when combusting hydrogen. However, variability will be minimized with the continued development of technology designed to combust pure hydrogen fuels while achieving the appropriate flame temperature for minimizing NOx emissions.

Interactions between hydrogen fuel addition and combustion properties are complex, including both chemical kinetics and physical effects. Roughly three times the volume of hydrogen is required to generate the same power output as natural gas. However, hydrogen only requires 25% of the air (by volume) required by natural gas to consume a given volume of fuel. This lower air requirement may contribute to potential lowering of the flame temperature for hydrogen combustion by decreasing mass flow through the combustor, and then utilizing EGR to increase the mass flow of air which increases convective heat transfer. Decreasing the equivalence ratio by contributing excess air, while increasing the mole fraction of hydrogen in the fuel, can allow flame propagation speed to stay constant while lowering the adiabatic flame temperature at a constant power output. This process has experimentally demonstrated a decrease in NOx emissions as the hydrogen mole fraction exceeded 45% to 50% of the fuel when testing hydrogen combustion on a Bunsen burner.[153] For pre-mixed flames, this allows for leaner operation. However, for non-premixed flames where the heat input is not maintained, the BTU input may

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[148] Giacomazzi, E., et al., 2023, Hydrogen Combustion, Ibid
[149] Colorado, Andres; McDonell, Vincent. (University of California Irvine, Combustion Laboratory UCICL), 2016, Ibid.
[150] Lowe, C., et al., 2011, Technology assessment, Ibid
[151] Giacomazzi, E., et al., 2023, Hydrogen Combustion, Ibid
[152] Colorado, Andres; McDonell, Vincent. (University of California Irvine, Combustion Laboratory UCICL), 2016, Ibid.
[153] Giacomazzi, E., et al., 2023, Hydrogen Combustion, Ibid

decrease as hydrogen increases in the fuel due to the Wobbe Index. This impacts the process, power output, and flame temperature for the non-premixed combustion system.[154]

6.1.2 Flame Type

Combustion systems generally utilize two main types of "flames," premixed or non-premixed. This mixing refers to the mixing of fuel and air. The differences in these two types of flames are important when it comes to establishing local flame temperatures. As shown in the following figure, a premixed flame separates reactants from products. The local fuel to air ratio of the reactants controls the peak temperatures in the flame and therefore, can be used to control NOx formation rates. In the non-premixed case, the flame divides fuel and products from air and products. As a result, the preferential fuel to air ratio that combustion occurs at will be the stoichiometric fuel to air ratio which results in nearly the highest possible flame temperatures for the conditions at hand. By operating with excess air (high air to fuel ratio, leaner operation), premixed flames can attain low NOx emission levels. What is relevant for success in premixed flames is the ability to completely mix the fuel and air prior to combustion. Regions with stoichiometric mixtures will create a "hot spot" that can contribute to higher NOx levels. For the same local fuel to air ratio, hydrogen flames have higher temperatures than natural gas flames. However, by controlling the local fuel to air ratio, the temperature of the hydrogen flame can be set at the same temperature as natural gas. The enhanced stability of the hydrogen flame due to its unique combustive properties allows a stable reaction at a far lower fuel to air ratio than for natural gas. Therefore, hydrogen flames can operate at substantially lower combustion temperatures than natural gas.

Systems that typically use non-premixed flames include older generation gas turbine technology, diesel fueled reciprocating engines, and older boilers. These technologies were developed before an emphasis on minimizing air pollution was in place (and are still used in areas with minimal air pollutant regulations). Equipment utilizing non-premixed flames, such as these examples of generally older technology, will likely form higher NOx emissions from the combustion of hydrogen when compared to fossil fuels as they combust more closely to the stoichiometric fuel to air ratio.

Systems that utilize a pre-mixed flame may include low emission gas turbines and low NOx boilers. The pre-mixed flame in this type of equipment allows for control of the fuel to air ratio, which allows for reduction in flame temperature and reduced NOx formation. A partially pre-mixed burner may reduce NOx formation as hydrogen in the fuel increases due to their enhanced heat transfer, however, they generally have similar NOx emissions from hydrogen combustion as they would from natural gas combustion.

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[154] McDonell, V, 2023, personal communication, Ibid

For gas turbines, micromixers have demonstrated the ability to further reduce NOx formation beyond standard premixing methods.[155] Combustor flow splits and piloting are additional mechanisms with the potential to lower NOx emissions.[156]

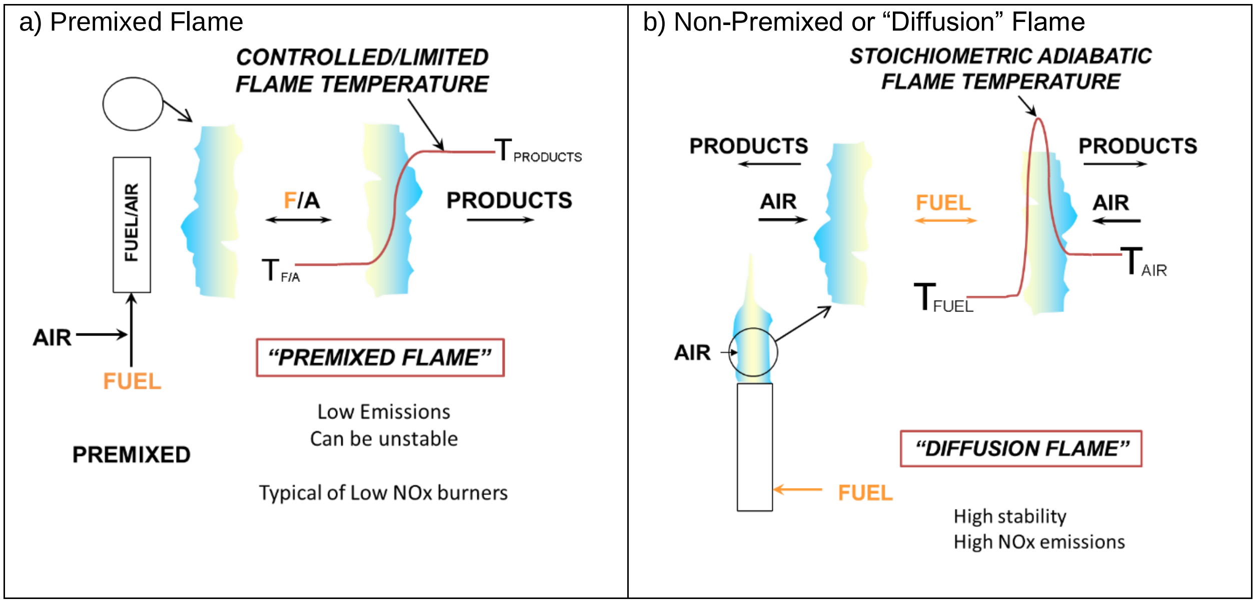

Figure 5: Flame Types

6.1.3 Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is a process utilized to reduce the temperature of combustion and subsequent NOx formation. In EGR, exhaust gas is injected back into the engine cylinders which displaces air and decreases the amount of oxygen in the combustion chamber.[157] This ultimately reduces the maximum combustion temperature. In combustion reactions considered aerodynamically stabilized, fuel composition, excess air and aerodynamics in the chamber imposed by the nozzle impact the mass flow of exhaust recirculated. The impact of EGR is highest in less reactive fuels due to slower reaction times allowing for more mixing time before combustion reactions occur. Hydrogen is generally a highly reactive fuel with a shorter flame length. At lean conditions (lower equivalence ratio), which yield lower temperatures and lower NOx formation (for all fuel types), the impact of fuel composition on reactivity is more important and decreases as

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[155] Boerner, S., H.H-W. Funke, P. Hendrick, E. Recker, R. Elsing, 2013, Development and integration of a scalable low Nox combustion chamber for a hydrogen-fueled aerogas turbine, Progress in Propulsion Physics 4: 357 – 372, https://doi.org/10.1051/eucass/201304357

[156] US DOE, 2023b, Addressing NOx Emissions from Gas Turbines Fueled with Hydrogen, H2IQ Hour Webinar, September, www.energy.gov/eere/fuelcells/h2iq-hour-addressing-nox-emissions-gas-turbines-fueled-hydrogen

[157] Wikipedia contributors, 2023, Exhaust gas recirculation. Wikipedia, The Free Encyclopedia, cited 2023 December 13, https://en.wikipedia.org/wiki/Exhaust_gas_recirculation

the equivalence ratio approaches 1. Fuel reactivity is generally lower at lean conditions (lower equivalence ratio), indicating that EGR may be more effective at reducing the formation of NOx emissions at leaner conditions.

Some burner technologies demonstrate an increase in NOx emissions as the percentage of hydrogen in the fuel is increased. Aerodynamic stabilization strategy appears to be a commonality among burner technologies that experience this increase in NOx emissions as the percentage of hydrogen in the fuel increases at a fixed equivalence ratio. As described above, the high reactivity of hydrogen increases the chemistry speed, which minimizes the mixing time, and hence, minimizes the benefits of EGR as hydrogen percentage increases in the fuel.[158] At a fixed equivalence ratio, the adiabatic flame temperature for hydrogen/air premixed flames is higher than the adiabatic flame temperature for natural gas.[159] [160]

EGR is a type of thermal dilution utilized in internal combustion engines. Water injection is another type of thermal dilution commonly used in non-premixed systems. However, water injection may decrease the thermal efficiency of an internal combustion unit. Studies have demonstrated up to 90% reduction in NOx emissions when utilizing water injection in turbines.[161] Another study on the utilization of EGR and water injection in a hydrogen fueled spark ignition internal combustion engine found that NOx emissions were reduced by 97% using water injection and reduced by 57% using EGR without a decrease in the brake thermal efficiency and overall efficiency, respectively.[162]

6.1.4 Thermal Efficiency

Thermal efficiency is the ratio of work output to heat input. The higher the thermal efficiency, the lower the potential formation of NOx during combustion, as the amount of heat input required is minimized. Increasing the compression ratio in an internal combustion unit is one way to increase the thermal efficiency of that unit. The compression ratio is a measure of how much the fuel mixture is compressed prior to ignition and the higher the compression ratio, the more fuel can be

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[158] Colorado, Andres; McDonell, Vincent. (University of California Irvine, Combustion Laboratory UCICL), 2016, Ibid.

[159] Giacomazzi, E., et al., 2023, Hydrogen Combustion, Ibid

[160] Colorado, Andres; McDonell, Vincent. (University of California Irvine, Combustion Laboratory UCICL), 2016, Ibid.

[161] Bahr, D.W., T.F. Lyon, 1984, Nox Abatement via Water Injection in Aircraft-Derivative Turbine Engines, ASME 1984 International Gas Turbine Conference and Exhibit June 4–7, 1984, Amsterdam, The Netherlands, https://doi.org/10.1115/84-GT-103

[162] Dhyani, V., K.A. Subramanian, 2019, Control of backfire and NOx emission reduction in a hydrogen fueled multi-cylinder spark ignition engine using cooled EGR and water injection strategies, International Journal of Hydrogen Energy (44) 12: 6287-6298, https://doi.org/10.1016/j.ijhydene.2019.01.129

extracted from the fuel mixture. The compression ratio for hydrogen combustion can be higher than that of natural gas due to the higher flame speed and autoignition temperature.

The higher burning velocity of hydrogen increases the cooling loss to the combustion chamber wall when combusting hydrogen in an internal combustion engine. This increased cooling loss may decrease the thermal efficiency in these units. To increase the thermal efficiency, the cooling loss to the combustion chamber wall must be reduced, but consideration also needs to be made for the potential increase in exhaust heat loss. A study by Toshio Shudo found that utilizing a stratified charge by direct injection into a lean fuel mixture could effectively improve thermal efficiency in hydrogen combustion.[163] It is important to consider the impact of heat transfer on thermal efficiency in hydrogen combustion units.

6.1.5 Combustion Residence Time

The residence time, which is the exposure to peak combustion temperature, also impacts the formation of NOx emissions. The longer the residence time, the greater the formation of NOx. Therefore, it is important for manufacturers to design to minimize the residence time of combustion reactions.[164] [165]

6.1.6 Additional Design Considerations

For gas turbines, reducing their partial load or enhancing their turn down ratio may also decrease the formation of NOx emissions.[166] Other design considerations that may minimize the formation of emissions include retarded injection timing, staged injection of fuel, preheating air, and charge air inter-cooling.

6.2 POST COMBUSTION TREATMENT OF EXHAUST GASES

Similar to current fossil fuel combustion units, exhaust gas aftertreatment is an option for hydrogen combustion units. The most commonly used methods of aftertreatment for controlling NOx emissions are SCR, SNCR, and NSCR.

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[163] Shudo, T., 2007, Improving thermal efficiency by reducing cooling losses in hydrogen combustion engines, International Journal of Hydrogen Energy 32 (17): 4285-4293, https://doi.org/10.1016/j.ijhydene.2007.06.002

[164] Onorati, A., et al., 2022, The role of hydrogen, Ibid

[165] Lewis, A.C., 2021, Optimizing air quality co-benefits in a hydrogen economy: a case for hydrogen-specific standards for NOx emissions, Environmental Science: Atmospheres 2021(1): 201-207, https://doi.org/10.1039/D1EA00037C

[166] Giacomazzi, E., et al., 2023, Hydrogen Combustion, Ibid

SCR technology employs a catalyst and reducing agents such as ammonia or urea to reduce NOx.[167] The US EPA has noted that SCR typically achieve 70% to 90% reductions in NOx emissions.[168] NOx reductions up to 100% are theoretically possible but may not currently be economical in practice.[169] [170]

SNCR is a post combustion emission control technology for reducing NOx. The process involves injecting ammonia or urea at a location where the flue gas is between 1,400ºF and 2,000ºF to react with NOx formed in the combustion process. This technology is typically used in power plants that burn biomass. SNCR may also be used to control NOx from a variety of types of equipment including industrial boilers, electric utility steam generators, cement kilns, pulp and paper power boilers, steel industry process units, and refinery process units. The control efficiency typically ranges between 25% and 90% depending on the application and equipment type.[171]

NSCR is a method of aftertreatment that can be utilized for exhaust streams with low oxygen content. NSCR uses a catalyst reaction to simultaneously reduce NOx, CO, and VOC to water, CO2, and nitrogen. The catalyst is typically a noble metal. One type of NSCR system injects a reducing agent into the exhaust gas stream prior to the catalyst reactor to reduce the NOx. Another type of NSCR system has an afterburner and two catalytic reactors (one reduction catalyst and one oxidation catalyst). NSCR control efficiencies range from 80% to 90%.[172]

There are also other technologies for NOx aftertreatment including electron beam irradiation[173] and electrochemical reduction. Electron beam irradiation technology was originally developed in Japan in the 1980's and reduction percentages are typically about 80%. Electrochemical

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[167] Elkaee, S., et al., 2024, Advancements in SCR technologies for NOx reduction: A comprehensive review of reducing agents, https://www.sciencedirect.com/science/article/abs/pii/S0957582024001770

[168] US EPA, 2003, Selective Catalytic Reduction (SCR), Air Pollution Control Technology Fact Sheet, EPA-452/F-03-032, https://www.epa.gov/catc/clean-air-technology-center-products#factsheets

[169] Sorrels, J.L., D.D. Randall, K.S. Schaffner, and C.R. Fry, 2019, Chapter 2 - Selective Catalytic Reduction, in Section 4 – Nox Control – of US EPA Air Pollution Control Cost Manual, updated June 12, https://www.epa.gov/economic-and-cost-analysis-air-pollution-regulations/cost-reports-and-guidance-air-pollution

[170] US EPA, 2003, Selective Catalytic Reduction (SCR), Ibid

[171] US EPA, 2019, Selective Noncatalytic Reduction (SNCR), https://www.epa.gov/sites/default/files/2017-12/documents/sncrcostmanualchapter7thedition20162017revisions.pdf

[172] US EPA, 2002, B.16 Nonselective Catalytic Reduction, review draft, CAM Technical Guidance Document,https://www3.epa.gov/ttnchie1/mkb/documents/B_16a.pdf#:~:text=The%20control%20efficiency%20achieved%20for%20NOx%20ranges%20from,space%20velocity%2C%20and%20the%20catalyst%20bed%20operating%20temperature

[173] Sang-He Jo, et. al., 2021, A study on additives to improve electron beam technology for NOx and SO2 reduction. https://www.sciencedirect.com/science/article/pii/S0969806X21000475

reduction technology uses ionic oxygen conductor membranes with electrodes on both sides and may be able to achieve NOx control efficiencies of about 65%.[174]

Table 10
NOx Aftertreatment Controls Summary

NOx Aftertreatment Technology	Control Efficiency	Typical Stationary Combustion Equipment
Selective Catalytic Reduction (SCR)	70% to 100%	Lean Burn Engine
Selective Non-Catalytic Reduction (SNCR)	25% to 90%	Boilers
Non-Selective Catalytic Reduction (NSCR)	80% to 90%	Rich Burn Engine
Electron Beam Irradiation	Up to 80%	Various
Electrochemical Reduction	Up to 65%	Various

174 Hansen, K.K., 2018, Electrochemical Removal of NOx Using Oxide-Based Electrodes – A Review, International Journal of Electrochemical Science 13 (10): 9273-9280, https://doi.org/10.20964/2018.10.09

7.0 DEMAND SCENARIOS EMISSION CHANGE RESULTS

This study evaluated the potential for both NOx emissions increases and reductions associated with the market transition to hydrogen in Central and Southern California, including in the Los Angeles Basin. This included accounting for emissions from infrastructure, not just transmission of hydrogen, but also from third-party production and third-party storage, as well as anticipated NOx reductions for end users in the mobility, power generation, and hard-to-electrify industrial sectors. The three Demand scenarios were used for this analysis.

7.1 DEMAND SCENARIOS OVERALL RESULTS

Overall results for NOx based on the three Demand Scenarios are provided in Table 6 below. Projected NOx reductions for end users is followed by estimated NOx emissions for infrastructure and the total overall results are shown at the bottom of the table.

Figures 6a and 6b depict the estimated annual NOx emissions associated with infrastructure as compared to the projected emission reductions for each of the mobility, power generation, and hard to electrify industrial end use sectors, for the conservative and ambitious demand scenarios, respectively. The values presented for infrastructure are the upper range of the estimates.

As shown in Table 11, as well as Figures 6a and 6b, the results of this study indicate that the anticipated NOx reductions associated with the displacement of fossil fuels by hydrogen far exceeds the potential NOx emissions related to new infrastructure. Therefore, an overall NOx emissions reduction is projected for each of the Demand Scenarios.

Table 11
Overall Annual Change in NOx Emissions for Each Demand Scenario

Category	Use Scenario	2030	2035	2040	2045
End-Users	Conservative	-1,120	-4,753	-9,446	-14,743
	Moderate	-2,870	-7,503	-12,996	-18,180
	Ambitious	-5,598	-11,532	-17,610	-22,424
Infrastructure	Max - Conservative	62	245	527	896
	Max – Moderate	91	288	596	1,001
	Max – Ambitious	358	740	1,263	1,895
	Min – Conservative	0	0	0	0

Table 11 Overall Annual Change in NOx Emissions for Each Demand Scenario					
Category	**Use Scenario**	**2030**	**2035**	**2040**	**2045**
	Min – Moderate	0	0	0	0
	Min – Ambitious	0	0	0	0
TOTAL	Conservative	-1,059	-4,507	-8,919	-13,847
	Moderate	-2,778	-7,215	-12,400	-17,179
	Ambitious	-5,240	-10,792	-16,347	-20,529

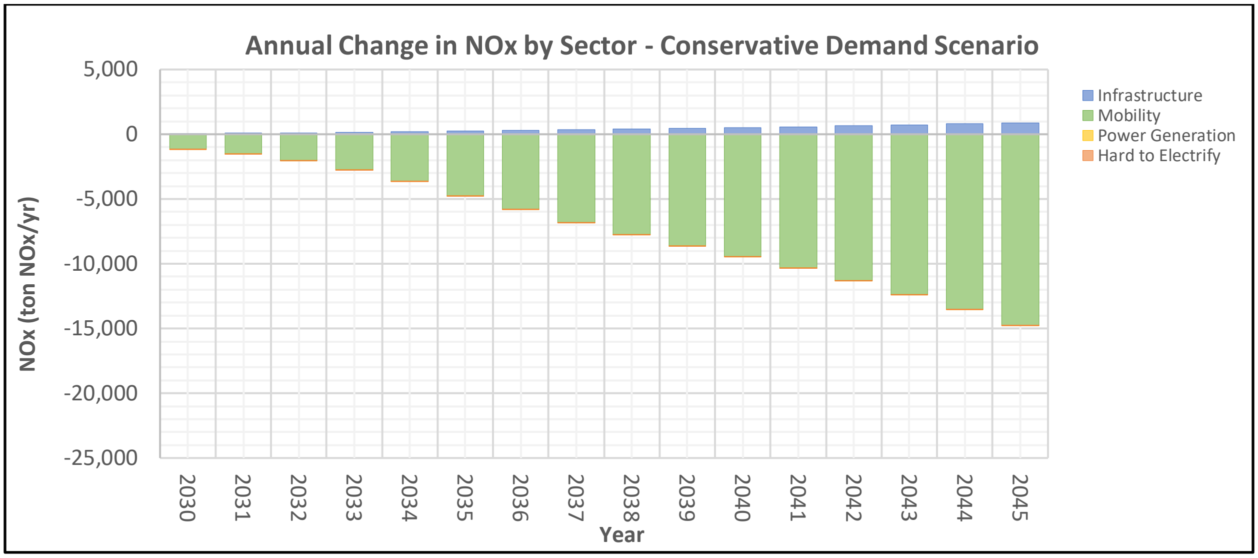

Figure 6a: Annual Change in NOx Emissions by Sector - Conservative Demand Scenario

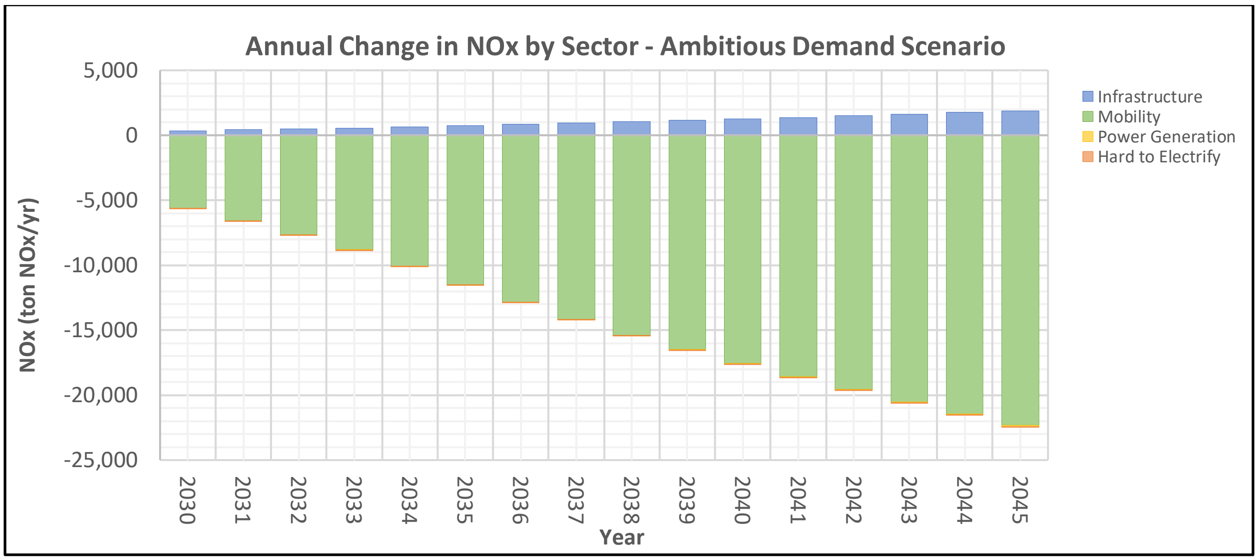

Figure 6b: Annual Change in NOx Emissions by Sector - Ambitious Demand Scenario

The largest reduction in annual end-user NOx is in the ambitious Demand Scenario in 2045 is 22,424 tons NOx/year. This is a five-fold increase in reductions for the ambitious Demand Scenario in 2045 versus the beginning of the study timeframe in 2030 when annual reductions are 5,598 tons NOx/year. For the conservative Demand Scenario, NOx reductions increase from 1,120 ton/year in 2030 to 14,743 ton/year in 2045, a ten-fold increase in NOx reductions.

The overall change in NOx emissions in the Ambitious Demand Scenario associated with new infrastructure and emission reductions associated with the displacement of fossil fuels by hydrogen in end-users as projected by the Demand Study are about 5,240 tons/year in 2030, and about 20,529 tons/year by 2045.

The specific results from each end-user and infrastructure sector will be explored in more detail throughout the next few sections.

7.2 DEMAND SCENARIOS INFRASTRUCTURE RESULTS

Within the scope of this study, potential NOx emissions from the operation of new infrastructure associated with third-party production, third-party storage, and transmission of the projected hydrogen demand within the geographic region of this study were evaluated. These new infrastructure emissions were estimated based on hypothetical scenarios developed through research. Infrastructure designs must be completed to refine emissions calculations for infrastructure.

7.2.1 Demand Scenarios Third-Party Production Results

Three hydrogen third-party production methods were identified for analysis: electrolysis, biomass gasification, and biogas (renewable natural gas) for SMR with a heater fueled by 100% hydrogen.

Electrolysis is driven by electricity, and this study assumed only renewable electricity for third-party production. Therefore, it was assumed that there is no potential for NOx emissions. Biomass gasification is a non-combustion process. As no combustion is occurring during the process, it was assumed that there was no pathway for the formation of NOx emissions. SMR does require the use of an external combustion unit. Therefore, NOx emissions were calculated from the combustion of hydrogen occurring within the external combustion unit.

Production emissions were calculated for six cases for each of the three Demand Scenarios. The minimum case is zero NOx emissions for the scenario where third-party production of hydrogen is produced by electrolysis or biomass gasification.

1. Minimum heat input rating, 0% hydrogen production from SMR (100% from electrolysis or biomass gasification)
2. Maximum heat input rating, 0% hydrogen production from SMR (100% from electrolysis or biomass gasification)
3. Minimum heat input rating, 33% of hydrogen production from SMR
4. Maximum heat input rating, 33% of hydrogen production from SMR
5. Minimum heat input rating, 100% of hydrogen production from SMR
6. Maximum heat input rating, 100% of hydrogen production from SMR

NOx emissions from the first two cases were zero, as no NOx emissions are associated with electrolysis using renewable electricity or biomass gasification. Table 12 below outlines the potential NOx emissions (ton/year) from production in the maximum emissions case for the ambitious Demand Scenario for years 2030, 2035, 2040, and 2045. NOx emissions from production increase throughout the study timeframe as hydrogen demand projections from the Demand Study increase. Minimum estimated emissions are zero NOx and maximum estimated emissions are 739 tons NOx per year for the case of 100% SMR and the maximum external combustion heat input rating for the ambitious Demand Scenario.

Table 12
NOx Emissions from Third-Party Production (ton/year)

	Emissions (tons/year)				
Demand Scenario	**2030**	**2035**	**2040**	**2045**	**Production Scenario**
Conservative Min	0	0	0	0	100% Electrolysis or Biomass Gasification
Conservative Max	17	66	141	240	100% SMR (Avg + Std. Dev)
Moderate Min	0	0	0	0	100% Electrolysis or Biomass Gasification
Moderate Max	36	112	233	391	100% SMR (Avg + Std. Dev)
Ambitious Min	0	0	0	0	100% Electrolysis or Biomass Gasification
Ambitious Max	140	289	493	739	100% SMR (Avg + Std. Dev)

7.2.2 Demand Scenarios Third-Party Storage and Transmission Results

Emissions estimates for NOx were prepared based on research and assumptions made for a range of hypothetical hydrogen third-party storage and transmission cases. Four different third-party storage and transmission cases were evaluated based on a range of input variables representative of various design options for each of the three Demand Scenarios. This led to a total of twelve different NOx emissions cases. The minimum case was the zero-emissions scenario where all compression was driven by electric motors. In this minimum case NOx emissions were zero.

Tables 13 and 14 below summarize the maximum and minimum NOx emissions from third-party storage and transmission of hydrogen, respectively, for the years 2030, 2035, 2040, and 2045 for each Demand Scenario. Estimated NOx emissions from the storage of hydrogen range from 0 ton/year to 290 ton/year, and estimated NOx emissions from the transmission of hydrogen range from 0 ton/year to 866 ton/year in 2045.

Table 13 NOx Emissions from Third-Party Storage of Hydrogen						
	Emissions (ton NOx/yr)				**Scenario**	
Scenario	**2030**	**2035**	**2040**	**2045**	**Storage Pressure**	**Power Source**
Conservative - Max	7	26	55	94	2,900 psi	Reciprocating Engine
Conservative - Min	0	0	0	0	All pressures	Renewable Electricity
Moderate - Max	14	44	91	153	2,900 psi	Reciprocating Engine
Moderate - Min	0	0	0	0	All pressures	Renewable Electricity
Ambitious - Max	55	113	193	290	2,900 psi	Reciprocating Engine
Ambitious - Min	0	0	0	0	All pressures	Renewable Electricity

Table 14 NOx Emissions from Transmission of Hydrogen						
	Emissions (ton NOx/yr)				**Scenario**	
Scenario	**2030**	**2035**	**2040**	**2045**	**Transmission Distance**	**Power Source**
Conservative - Max	19	77	165	281	450 miles	Reciprocating Engine
Conservative - Min	0	0	0	0	All distances	Renewable Electricity
Moderate - Max	42	132	272	458	450 miles	Reciprocating Engine
Moderate - Min	0	0	0	0	All distances	Renewable Electricity
Ambitious - Max	163	338	577	866	450 miles	Reciprocating Engine
Ambitious - Min	0	0	0	0	All distances	Renewable Electricity

7.3 DEMAND SCENARIOS END-USER RESULTS

Figure 7 below shows the percentage of 2030 and 2045 NOx reductions that come from each end-use sector in the ambitious Demand Scenario. As shown in the chart, 99.9% of the 2030 NOx reductions and 99.6% of 2045 NOx reductions come from the mobility sector. The Demand Study projected the anticipated fossil fuel displacement associated with FCEVs only. The associated NOx reductions were estimated only for conversion to FCEVs. This study does not project emission reductions related to fossil fuel displacement that will be associated with BEVs. This trend for most of the NOx emission reductions to come from the mobility sector is consistent throughout the study time frame within each of the Hydrogen Demand Scenarios.

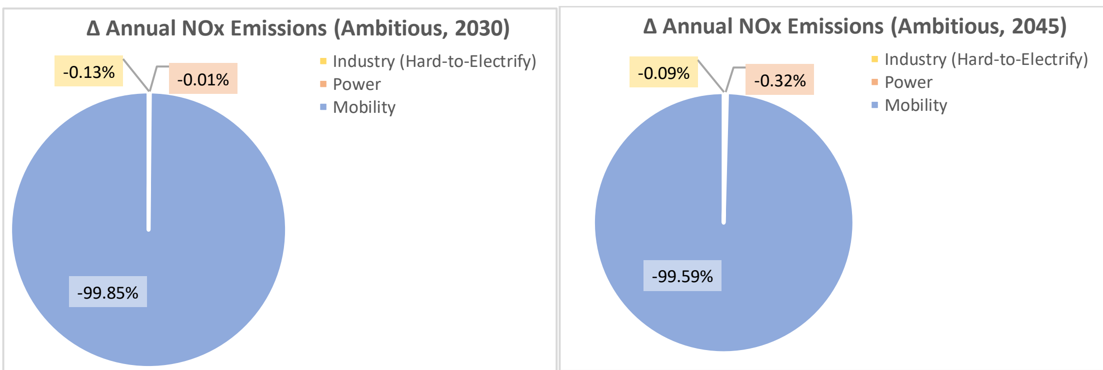

Figure 7: Percent of Reductions Attributable to Each Sector

7.3.1 Demand Scenarios Mobility Results

Hydrogen demand in the mobility sector was assumed to be utilized in hydrogen fuel cells. The only emissions from hydrogen fuel cells are water vapor and heat. Therefore, NOx emissions associated with the use of hydrogen are assumed to be zero. Fossil fuel volumes displaced by hydrogen as calculated by the Demand Study account for a 100% reduction in emissions by unit displaced. Table 15 below illustrates the NOx emissions reductions (ton/year) for the years 2030, 2035, 2040, and 2045 for each of the three Demand Scenarios. Figures 8a and 8b below illustrate the annual change in NOx emissions broken out by each sub-sector for the study timeframe in the conservative and ambitious Demand Scenario. The overall NOx reductions from mobility in 2045 in the ambitious Demand Scenario were estimated at 22,333 ton/year.

Table 15 Mobility NOx Emissions (ton/year) Reductions for Each Demand Scenario				
Scenario	**2030**	**2035**	**2040**	**2045**
Conservative	1,117	4,745	9,431	14,717
Moderate	2,866	7,490	12,967	18,126
Ambitious	5,589	11,508	17,560	22,333

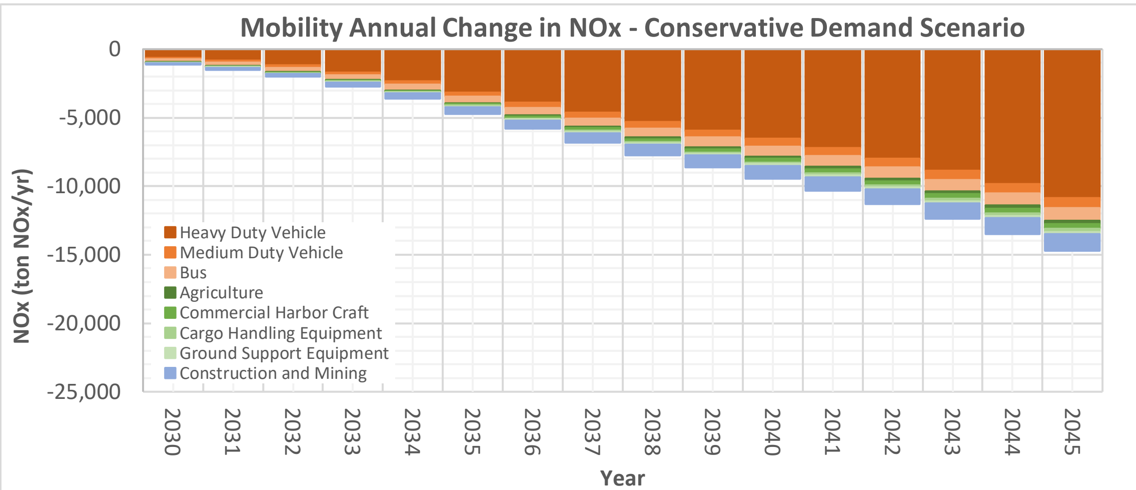

Figure 8a: Annual Change in NOx Emissions - Conservative Hydrogen Demand Scenario

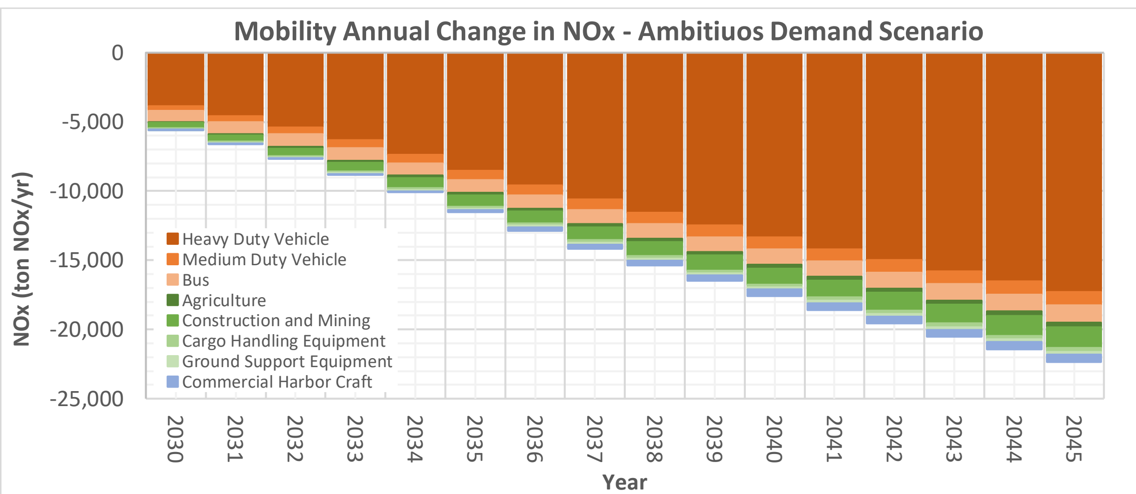

Figure 8b: Mobility Annual Change in NOx Emissions - Ambitious Hydrogen Demand Scenario

Figure 9 below shows the percentage of NOx mass emission reductions attributable to each sub-sector in the years 2030 and 2045 in the ambitious Demand Scenario. The largest percentage of reductions in NOx mass emissions are attributable to the HDV sub-sector at 69.1% of total NOx reductions in 2030 and 77.4% of total reductions in 2045. In 2030, the second largest percentage of NOx reductions is seen within the Bus sub-sector at 14.2%. In 2045, the second largest percentage of reductions is seen in the construction and mining sub-sector.

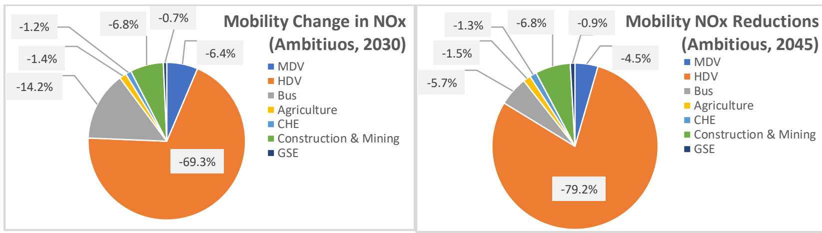

Figure 9 Percentage of NOx Emission Reductions Attributable to each Sub-Sector in the Ambitious Hydrogen Demand Scenario for Years 2030 and 2045

Tables 16 and 17 and Figures 10a and 10b below show the NOx mass emission reductions from on-road and off-road sources in the conservative and ambitious Demand Scenarios. NOx mass emission reductions from on-road sources are much larger than calculated NOx mass emission reductions attributable to off-road sources for each of the Demand Scenarios in each year within the study time frame.

Table 16
NOx Reductions from On-Road and Off-Road Mobility for Diesel and Gasoline in the Conservative Demand Scenario

Year	Diesel On-Road (ton/year)	Diesel Off-Road (ton/year)	Gasoline On-Road (ton/year)	Gasoline Off-Road (ton/year)	% On-Road	% Off-Road
2030	779	88	151	99	83%	17%
2035	3,551	343	372	479	83%	17%
2040	7,117	692	724	898	83%	17%
2045	11,565	940	961	1,252	85%	15%

Table 17 NOx Reductions from On-Road and Off-Road Mobility for Diesel and Gasoline in the Ambitious Demand Scenario						
Year	**Diesel On-Road (ton/year)**	**Diesel Off-Road (ton/year)**	**Gasoline On-Road (ton/year)**	**Gasoline Off-Road (ton/year)**	**% On-Road**	**% Off-Road**
2030	4,436	256	571	326	90%	10%
2035	9,363	613	744	789	88%	12%
2040	14,268	1,047	1,054	1,191	87%	13%
2045	18,241	1,257	1,268	1,567	87%	13%

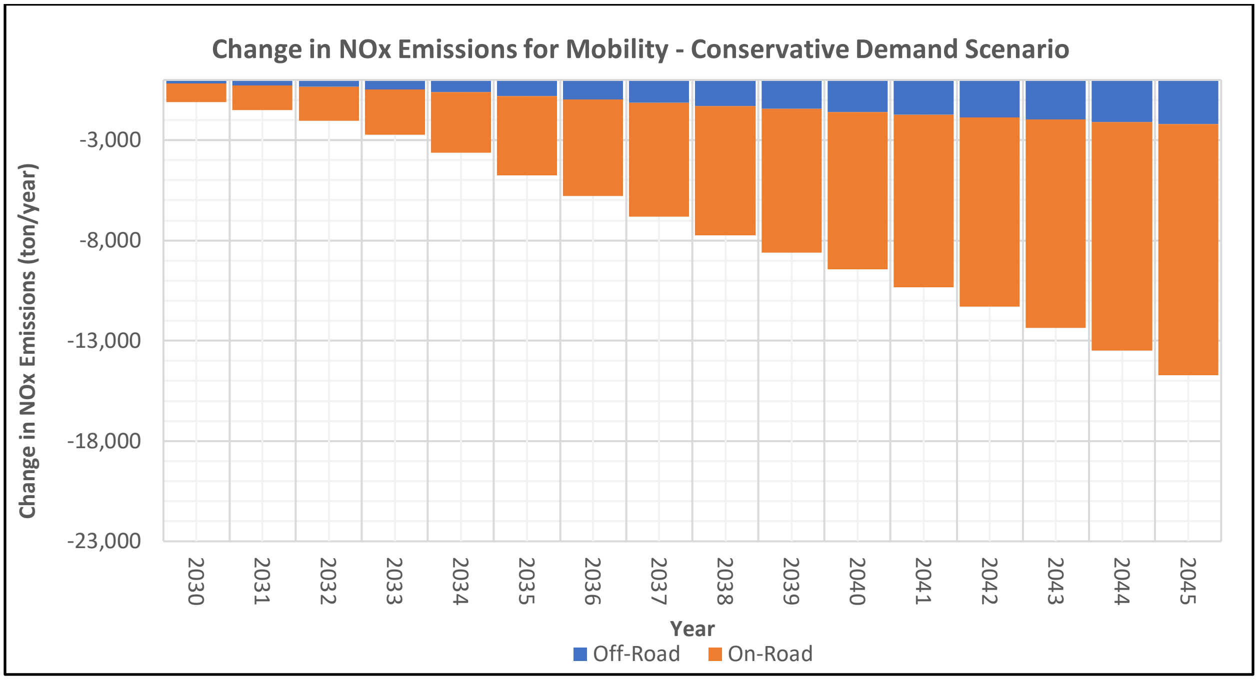

Figure 10a: Change in NOx Emissions for Mobility Sector: On-Road and Off-Road - Conservative Demand Scenario

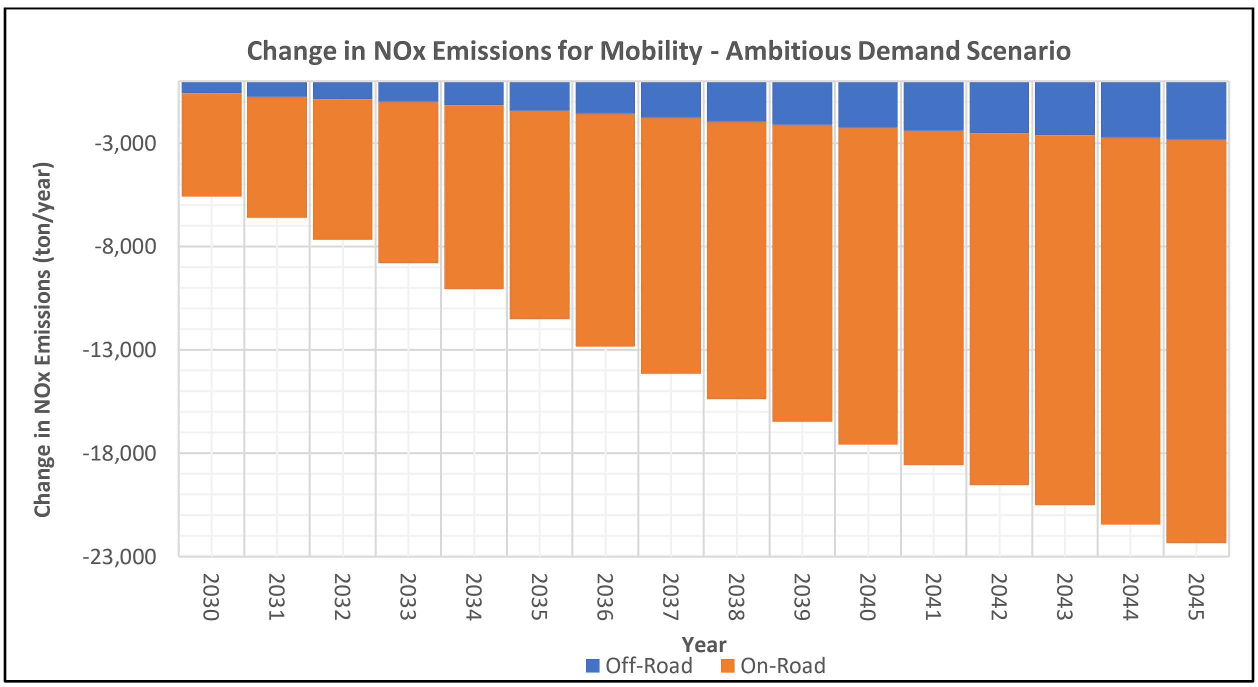

Figure 10b: Change in NOx Emissions for Mobility Sector: On-Road and Off-Road - Ambitious Demand Scenario

7.3.2 Demand Scenarios Power Generation Results

Reductions in NOx emissions were calculated for Power Generation facilities associated with the use of hydrogen demand projected by the Demand Study. The power generation sector is broken into two sub-sectors, “Peaker and Baseload” and “Cogeneration.” Table 18 below illustrates the change in NOx emissions (ton/year) from power generation in 2030, 2035, 2040, and 2045 for each of the three Hydrogen Demand Scenarios. Figures 11a and 11b below display the annual NOx change in emissions (ton/year) for the power generation sector broken out between the two sub-sectors associated with the conservative Demand Scenario and the ambitious Demand Scenario.

Table 18
Power Generation NOx Reductions (ton/year) for Each Demand Scenario

Scenario	2030	2035	2040	2045
Conservative	0.2	2.9	9.0	19.0
Moderate	0.5	6.8	20.9	44.1
Ambitious	0.7	11.0	33.9	71.7

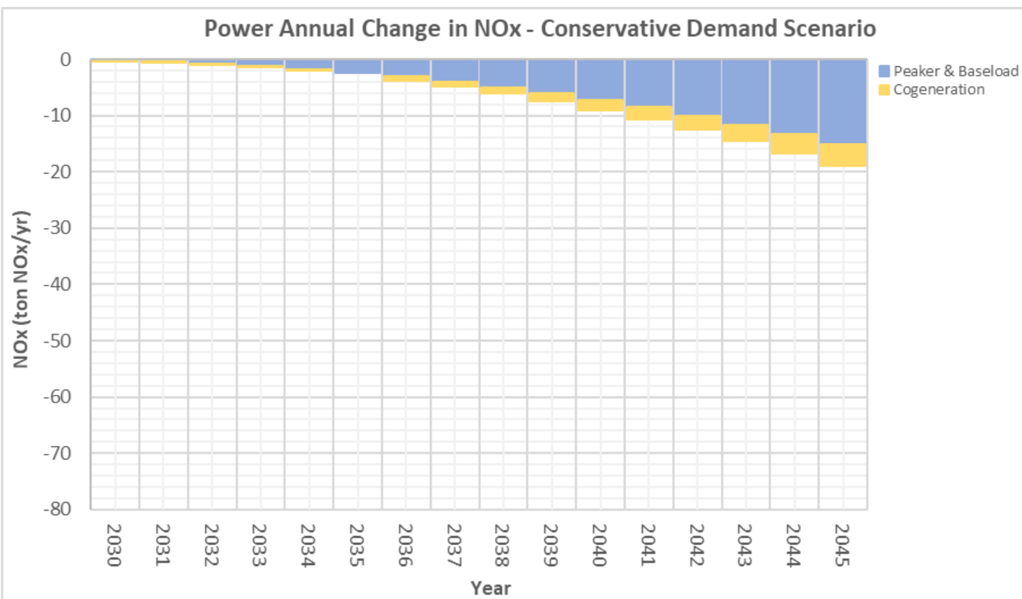

Figure 11a Power Generation Change in NOx Emissions (ton/year) - Conservative Hydrogen Demand Scenario

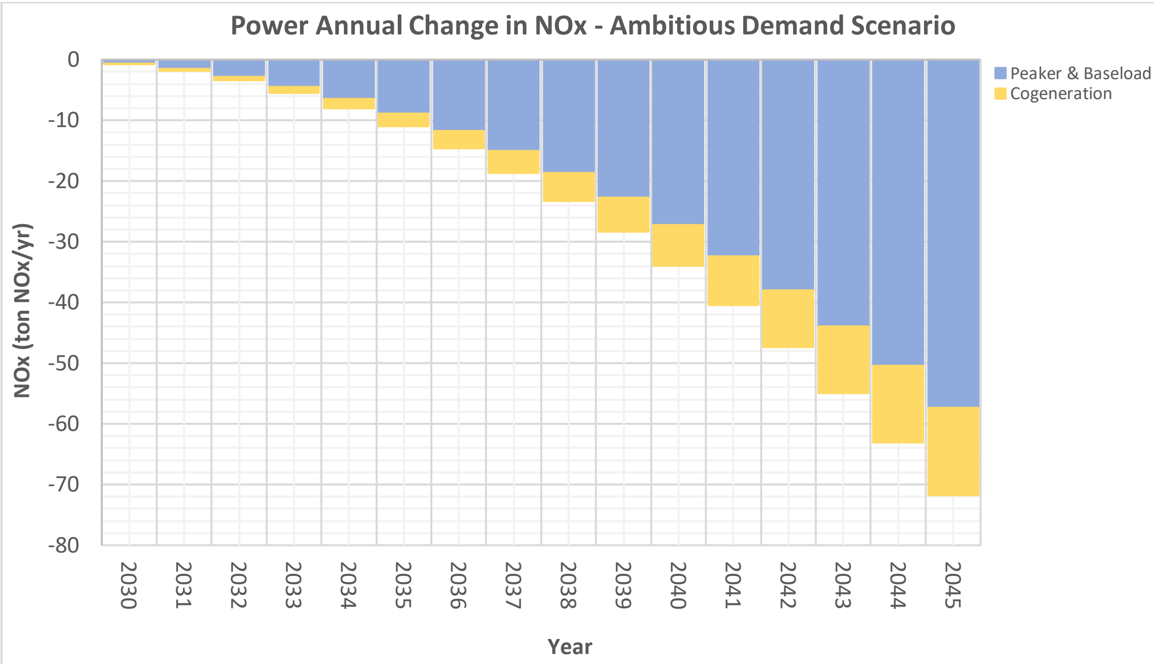

Figure 11b Power Generation Change in NOx Emissions (ton/year) - Ambitious Hydrogen Demand Scenario

As mentioned above, the magnitude of the reductions in NOx mass emissions (ton/year) from the power generation sector increase over time from 2030 to 2045. Annual NOx reductions in the ambitious Demand Scenario are 0.7 ton/year in 2030 and 71.7 ton/year in 2045, representing a hundred-fold increase in reductions.

Figure 12 below represents the percentage of the change in NOx emissions (seen as reductions) attributable to peaker and baseload versus cogeneration for the ambitious Demand Scenario in the years 2030 and 2045. The results presented in these figures are relatively similar across Demand Scenarios. Comparing the percentage of reductions within this one scenario over time demonstrates that the percentage of reductions attributable to cogeneration increases slightly over time from 13% in 2030 to 20% in 2045, while the percentage of reductions attributable to peaker and baseload decreases slightly over time from 87% in 2030 to 80% in 2045.

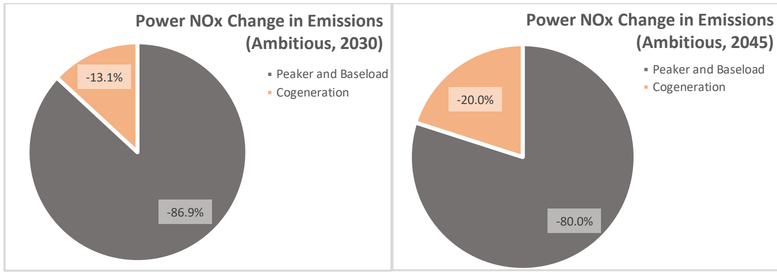

Figure 12: Percent of NOx Emission Changes Attributable to Sub-Sectors Ambitious Hydrogen Demand Scenario Years 2030 and 2045

7.3.3 Demand Scenarios Hard to Electrify Results

Change in NOx emissions associated with the use of hydrogen demand displacing fossil fuels as projected by the Demand Study in hard to electrify industrial sub-sectors was calculated. NOx emission reductions are experienced from displacing fossil fuels with hydrogen fuel in each of the hard to electrify industrial sub-sectors evaluated. Table 19 below illustrates the change in NOx emissions for the hard to electrify industrial sector for years 2030, 2035, 2040, and 2045 for each of the three Demand Scenarios. Figures 12a and 12b below show the change in emissions calculated for each hard to electrify industrial sub-sector associated with the displacement of fossil fuels by hydrogen as projected by the Demand Study for each sub-sector for each year of the study timeframe for the conservative Demand Scenario and the ambitious Demand Scenario.

Table 19
Hard to Electrify Industrial NOx Reductions (ton/year) for Each Demand Scenario

Scenario	**2030**	**2035**	**2040**	**2045**
Conservative	2.7	4.3	5.4	6.2
Moderate	3.5	6.1	8.0	9.9
Ambitious	7.4	12.5	16.2	19.3

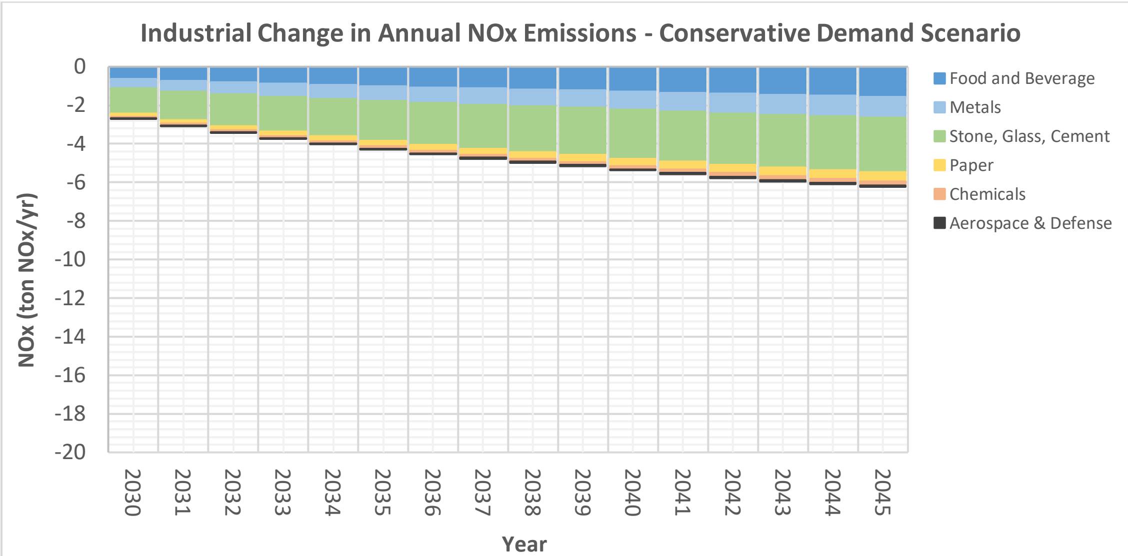

Figure 12a: Annual Change in NOx Emissions for Hard to Electrify Industrial Sector - Conservative Hydrogen Demand Scenario

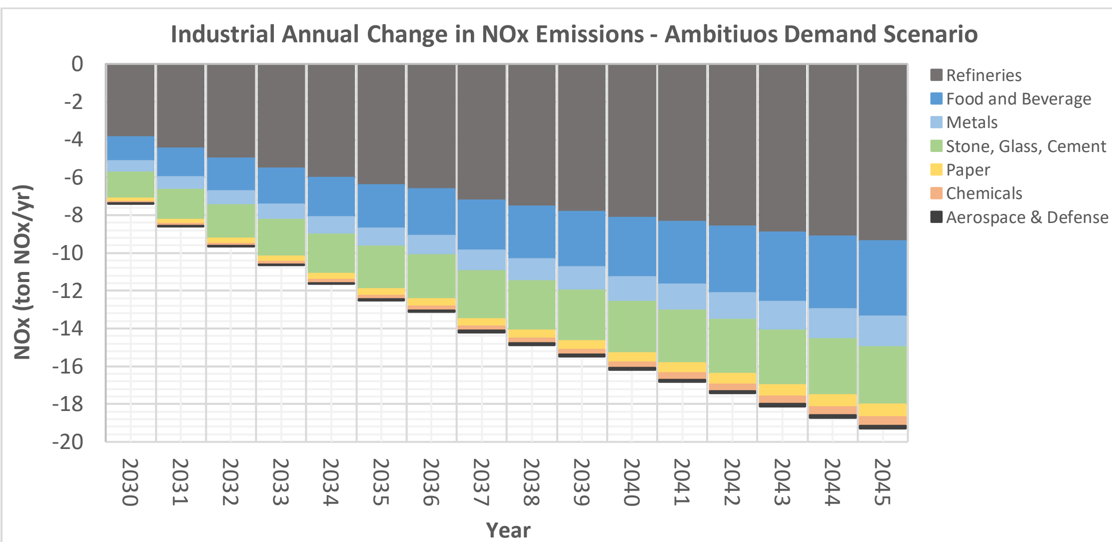

Figure 12b: Annual Change in NOx Emissions for Hard to Electrify Industrial Sector - Ambitious Hydrogen Demand Scenario

In the ambitious Demand Scenario calculated NOx reductions from hard to electrify industrial sectors are 7.4 ton/year in 2030 and 19.3 ton/year in 2045. Figures 13a and 13b below represent the percent of NOx mass emission change (ton/year) attributable to each hard to electrify industrial sub-sector evaluated in 2030 and 2045 for the conservative, moderate, and ambitious scenarios. The results presented in these figures are relatively similar across all years within each Demand Scenario. In the conservative Scenario, stone, glass, cement contributed the largest percentage of emissions reductions at 48.9% in 2030 and 45.6% in 2045, followed by food and beverage at 23.6% in 2030 and 24.8% in 2045, then metals at 18.1% in 2030 and 17.3% in 2045. The moderate Scenario was similar to the conservative Scenario, with top three sub-sectors contributing to overall reductions as stone, glass, cement then food and beverage then metals. In the ambitious Scenario, the proportions differ because refineries account for 52.2% of reductions in 2030 and 48.7% of reductions in 2045. The next highest sub-sectors contributing to reductions in the ambitious scenario are stone, glass, cement then food and beverage then metals. The reason for this difference in allocation for results is that the Demand Study did not consider hydrogen demand from the refinery sub-sector in the conservative or moderate Demand Scenarios.

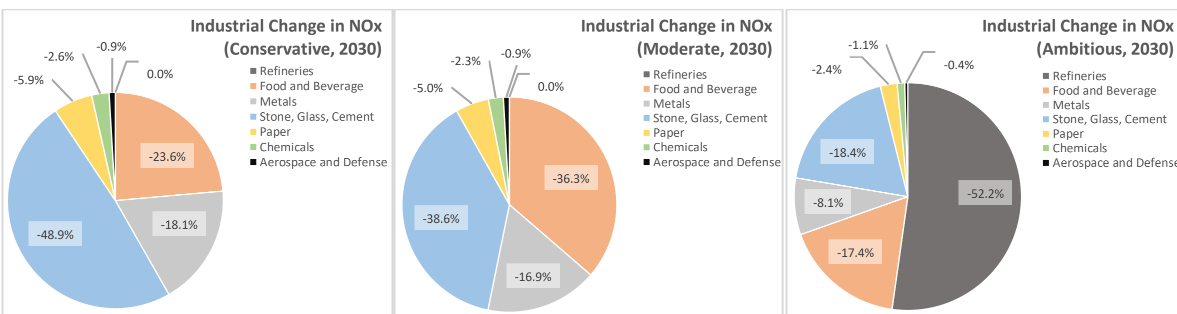

Figure 13a: Percent of NOx Emissions Change Attributable to Each Hard to Electrify Industrial Sub-Sector Each Demand Scenario Year 2030

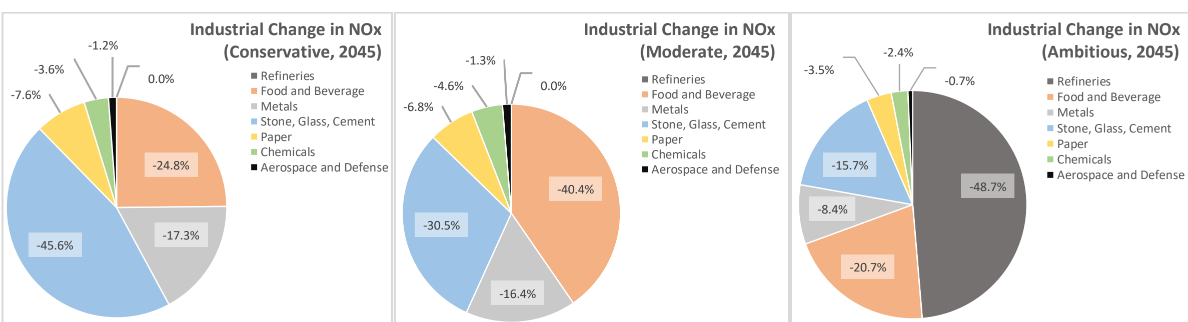

Figure 13b: Percent of NOx Emissions Change Attributable to Each Hard to Electrify Industrial Sub-Sector Each Demand Scenario Year 2045

8.0 ANGELES LINK THROUGHPUT SCENARIOS EMISSION CHANGE RESULTS

This study evaluated the potential for both NOx emissions increases and reductions associated with Angeles Link. This included accounting for emissions from infrastructure, not just transmission of hydrogen, but also from third-party production and third-party storage, as well as anticipated NOx reductions for end users in the mobility, power generation, and hard-to-electrify industrial sectors. The three throughput scenarios were used for this analysis.

8.1 ANGELES LINK THROUGHPUTS OVERALL RESULTS

Overall results for NOx based on the three throughput scenarios are provided in Table 20 below. Projected NOx reductions for end users is followed by estimated NOx emissions for infrastructure and the total overall results are shown at the bottom of the table.

In the low throughput scenario, the hydrogen volumes provided assumed that 26.85% of the market hydrogen demand projected by the Demand Study in the conservative demand scenario would be supplied by Angeles Link. In the medium throughput scenario, the hydrogen volumes provided assumed that 31.12% of the market hydrogen demand projected by the Demand Study in the moderate Demand Scenario would be supplied by Angeles Link. In the high throughput scenario, the hydrogen volumes provided assumed that 25.36% of the market hydrogen demand projected by the Demand Study in the ambitious Demand Scenario would be supplied by Angeles Link. These percentages for each of the three scenarios were applied consistently to the NOx emissions for infrastructure and to NOx emission reductions for each of the three end-use sectors, and all sub-sectors, provided in this draft Study Report.

Figures 15a and 15b depict the estimated annual NOx emissions associated with infrastructure as compared to the projected emission reductions for each of the mobility, power generation, and hard to electrify industrial end use sectors, for the conservative and ambitious demand scenarios, respectively. The values presented for infrastructure are the upper range of the estimates.

As shown in Table 20, as well as Figures 14a and 14b, the results of this study indicate that the anticipated NOx reductions associated with the displacement of fossil fuels by hydrogen far exceeds the potential NOx emissions related to new infrastructure. Therefore, an overall NOx emissions reduction is projected for each of the throughput scenarios.

Table 20
Overall Annual Change in NOx Emissions for each Throughput Scenario (tpy)

Category	Scenario	2030	2035	2040	2045
End-Users	Low	-301	-1,276	-2,536	-3,958
	Medium	-893	-2,335	-4,045	-5,658
	High	-1,420	-2,925	-4,466	-5,687
Infrastructure	Max - Low	11	45	97	165
	Max – Med	28	90	186	312
	Max – High	91	188	320	481
	Max - Low	0	0	0	0
	Max – Med	0	0	0	0
	Max – High	0	0	0	0
TOTAL	Low	-289	-1,231	-2,439	-3,793
	Medium	-865	-2,245	-3,859	-5,347
	High	-1,329	-2,737	-4,146	-5,206

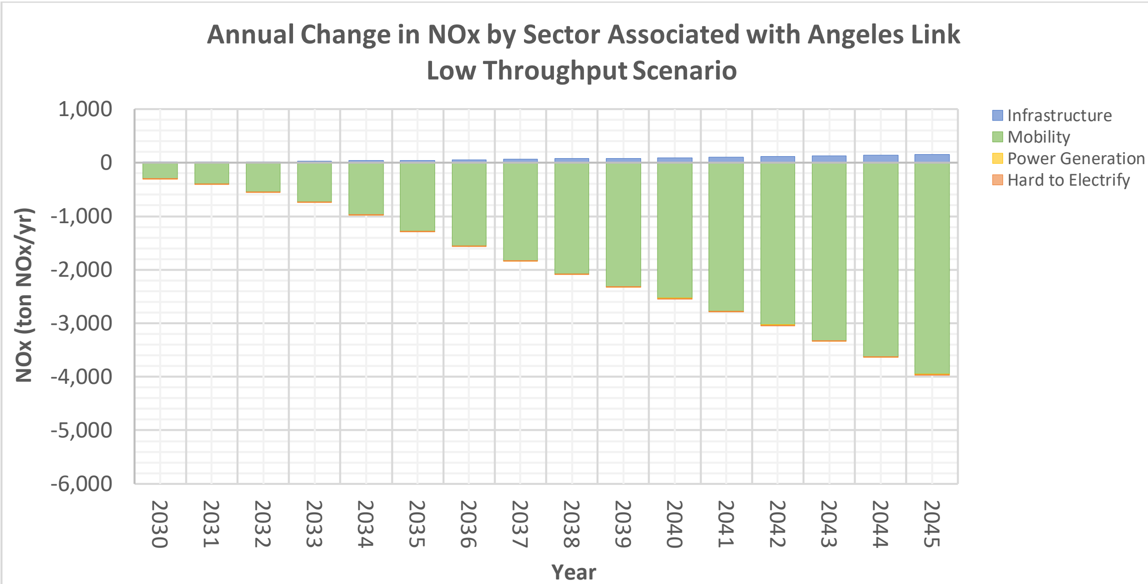

Figure 14a: Annual Change in NOx by Sector Associated with Angeles Link – Low Throughput Scenario

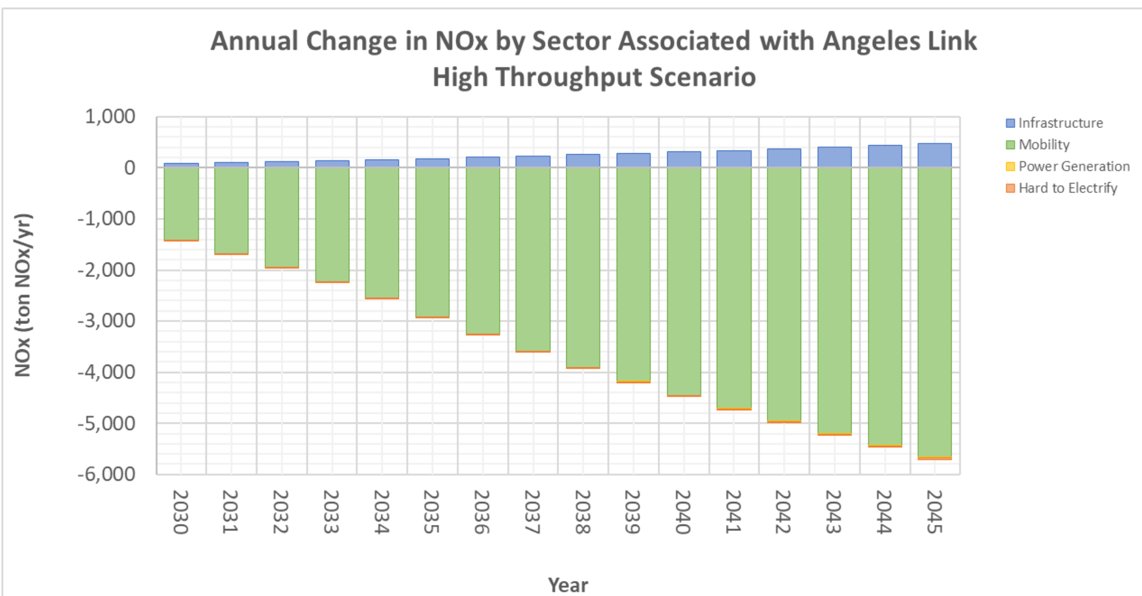

Figure 14b: Annual Change in NOx by Sector Associated with Angeles Link – High Throughput Scenario

The largest reduction in annual end-user NOx is in the high throughput scenario in 2045 is 5,687 tons NOx/year. This is a three-fold increase in reductions for the high throughput scenario in 2045 versus the beginning of the study timeframe in 2030 when annual reductions are 1,420 tons NOx/year. During this same time frame, infrastructure emissions are estimated to be xx in 2030 and xx in 2045, for the high throughput scenario. The overall estimated NOx reductions for the low and high throughput scenarios in 2045 are 3,793 tons NOx/year and 5,206 tons NOx/year, respectively.

The specific results from each end-user and infrastructure sector will be explored in more detail throughout the next few sections.

8.2 INFRASTRUCTURE RESULTS

Within the scope of this study, potential NOx emissions from the operation of new infrastructure associated with third-party production, third-party storage, and transmission of the projected hydrogen demand within the geographic region of this study were evaluated. These new infrastructure emissions were estimated based on hypothetical scenarios developed through research. Infrastructure designs must be completed to refine emissions calculations for infrastructure.

8.2.1 Third-Party Production Results

Three hydrogen third-party production methods were identified for analysis: electrolysis, biomass gasification, and biogas (renewable natural gas) for SMR with a heater fueled by 100% hydrogen.

Electrolysis is driven by electricity, and this study assumed only renewable electricity for third-party production. Therefore, it was assumed that there is no potential for NOx emissions. Biomass gasification is a non-combustion process. As no combustion is occurring during the process, it was assumed that there was no pathway for the formation of NOx emissions. SMR does require the use of an external combustion unit. Therefore, NOx emissions were calculated from the combustion of hydrogen occurring within the external combustion unit.

Production emissions were calculated for the same six cases as was done for the Demand Scenarios. The minimum case is zero NOx emissions for the scenario where third-party production of hydrogen is produced by electrolysis or biomass gasification.

Table 21 below provides the estimated emissions associated with the maximum and minimum cases for each of the evaluated throughput scenarios in 2030, 2035, 2040, and 2045. NOx emissions from production increases throughout the study time frame as the volume of hydrogen estimated increases. The maximum estimated third-party production emissions for the high throughput scenario is 187 tons/year NOx.

Table 21 Estimated Potential NOx Emissions for Third-Party Production of Hydrogen					
Throughput Scenario	**Emissions (tons/year)**				**Production Scenario**
	2030	**2035**	**2040**	**2045**	
Low - Min	0	0	0	0	100% Electrolysis or Biomass Gasification
Low - Max	4	18	38	64	100% SMR (Avg + Std. Dev)
Medium - Min	0	0	0	0	100% Electrolysis or Biomass Gasification
Medium - Max	11	35	72	122	100% SMR (Avg + Std. Dev)
High - Min	0	0	0	0	100% Electrolysis or Biomass Gasification
High - Max	35	73	125	187	100% SMR (Avg + Std. Dev)

8.2.2 Third-Party Storage and Transmission

Emissions estimates for NOx were prepared based on research and assumptions made for a range of hypothetical hydrogen third-party storage and transmission cases. Four different third-party storage and transmission cases were evaluated based on a range of input variables representative of various design options for each of the three throughput scenarios. This led to a total of twelve different NOx emissions cases. The minimum case was the zero-emissions scenario where all compression was driven by electric motors. In this minimum case NOx emissions were zero.

Tables 22 and 23 below summarize the NOx emissions from third-party storage and transmission of hydrogen for the years 2030, 2035, 2040, and 2045 for each throughput scenario. Estimated NOx emissions for third-party storage range from 0 ton/year to 74 ton/year, and estimated NOx emissions for transmission range from 0 ton/year to 220 ton/year by the year 2045.

Table 22 Estimated Potential NOx Emissions for Third-Party Storage of Hydrogen						
Throughput Scenario	**Emissions (tons/yr)**				**Scenario**	
	2030	**2035**	**2040**	**2045**	**Storage Pressure**	**Power Source**
Low - Min	0	0	0	0	All pressures	Renewable Electricity
Low - Max	2	7	15	25	2,900 psi	Reciprocating Engine
Medium - Min	0	0	0	0	All pressures	Renewable Electricity
Medium - Max	4	14	28	48	2,900 psi	Reciprocating Engine
High - Min	0	0	0	0	All pressures	Renewable Electricity
High - Max	14	29	49	74	2,900 psi	Reciprocating Engine

Table 23 Estimated Potential NOx Emissions for Transmission of Hydrogen						
Throughput Scenario	**Emissions (tons/yr)**				**Scenario**	
	2030	**203**	**2040**	**2045**	**Transmission Distance**	**Power Source**
Low - Min	0	0	0	0	All distances	Renewable Electricity
Low - Max	5	21	44	75	450 miles	NA
Medium - Min	0	0	0	0	All distances	Renewable Electricity
Medium - Max	13	41	85	142	450 miles	NA
High - Min	0	0	0	0	All distances	Renewable Electricity
High - Max	41	86	146	220	450 miles	NA

8.3 ANGELES LINK OVERALL END-USER RESULTS

Hydrogen to be supplied by Angeles Link was estimated for three throughput scenarios: low, medium, and high. Hydrogen supplied by Angeles Link in each scenario increases each year during the study time frame of 2030 to 2045.

8.3.1 Angeles Link Mobility Results

Hydrogen usage in the mobility sector was assigned to hydrogen fuel cells or FCEV. The only emissions from hydrogen fuel cells are water vapor and heat. Therefore, NOx emissions associated with the use of FCEV are zero. Thus, the diesel and gasoline volumes displaced by hydrogen account for a 100% reduction in emissions by unit displaced. Table 24 below illustrates the NOx emissions reductions (ton/year) for the years 2030, 2035, 2040, and 2045 for each of the three throughput scenarios. Figures 15a and 15b below illustrate the annual change in NOx emissions broken out by each sub-sector for all years of the study timeframe in the low and high throughput scenarios, respectively. The overall NOx reductions from mobility in 2045 for the high throughput scenario were estimated at 5,664 ton/year.

Table 24
Mobility NOx Emission Reductions for Angeles Link Throughput Scenarios (tpy)

Throughput Scenario	2030	2035	2040	2045
Low	300	1,274	2,532	3,951
Medium	892	2,331	4,036	5,641
High	1,418	2,919	4,453	5,664

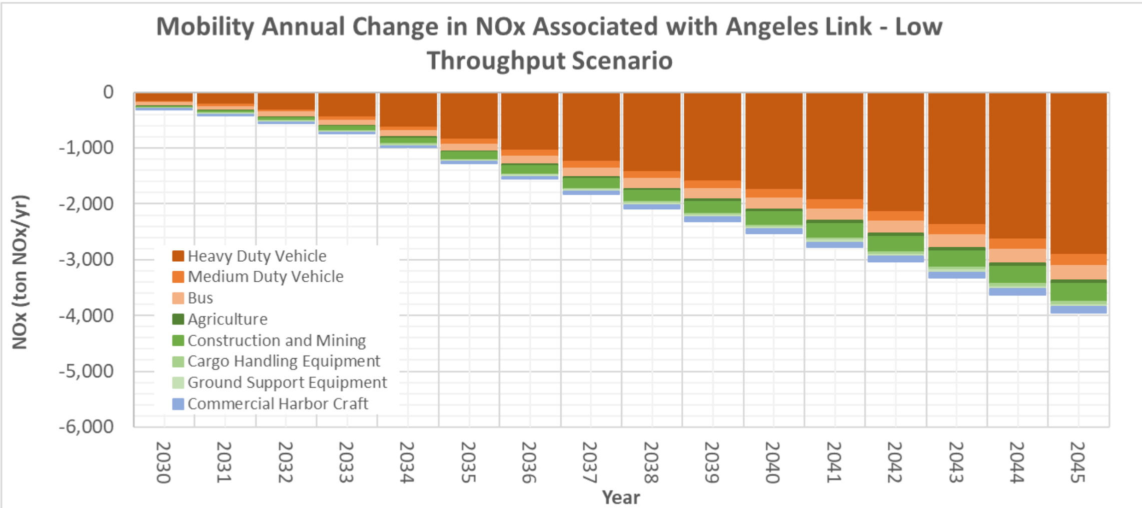

Figure 15a: Mobility Annual Change in NOx Emissions Associated with Angeles Link – Low Throughput Scenario

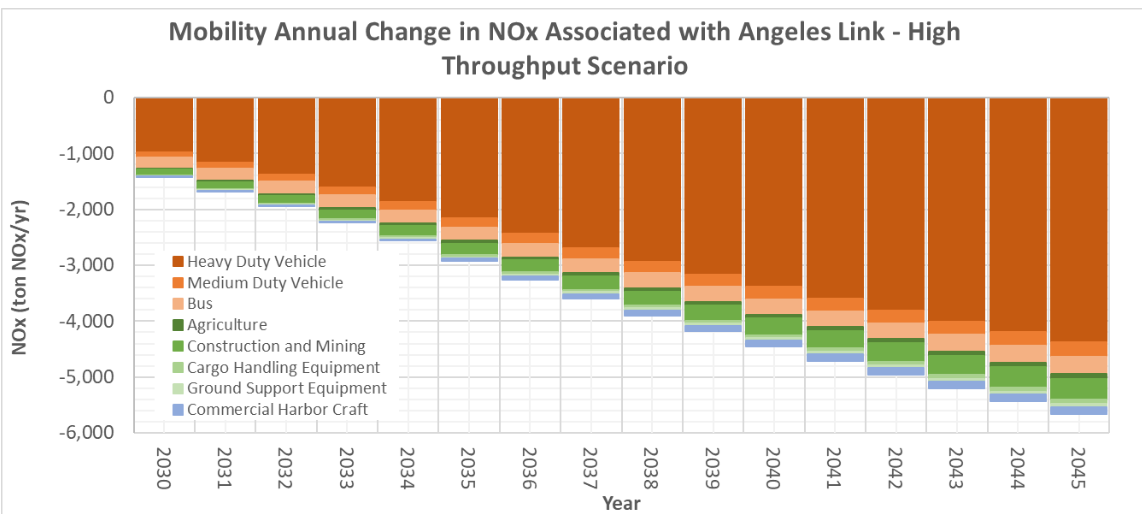

Figure 15b: Mobility Annual Change in NOx Emissions Associated with Angeles Link – High Throughput Scenario

Tables 25 and 26 and Figures 16a and 16b below show the NOx mass emission reductions from on-road and off-road sources in the low and high throughput scenarios, respectively. NOx mass emission reductions from on-road sources are larger than calculated NOx mass emission reductions attributable to off-road sources for each of the throughput scenarios for each year within the study time frame.

Table 25 NOx Reductions from On-Road and Off-Road Mobility for Diesel and Gasoline in the Low Throughput Scenario						
Year	**Diesel On-Road (ton/year)**	**Diesel Off-Road (ton/year)**	**Gasoline On-Road (ton/year)**	**Gasoline Off-Road (ton/year)**	**% On-Road**	**% Off-Road**
2030	209	24	41	27	83%	17%
2035	953	92	100	129	83%	17%
2040	1,911	186	194	241	83%	17%
2045	3,105	252	258	336	85%	15%

Table 26 NOx Reductions from On-Road and Off-Road Mobility for Diesel and Gasoline in the High Throughput Scenario						
Year	**Diesel On-Road (ton/year)**	**Diesel Off-Road (ton/year)**	**Gasoline On-Road (ton/year)**	**Gasoline Off-Road (ton/year)**	**% On-Road**	**% Off-Road**
2030	1,125	65	145	83	90%	10%
2035	2,374	155	189	200	88%	12%
2040	3,618	266	267	302	87%	13%
2045	4,626	319	321	397	87%	13%

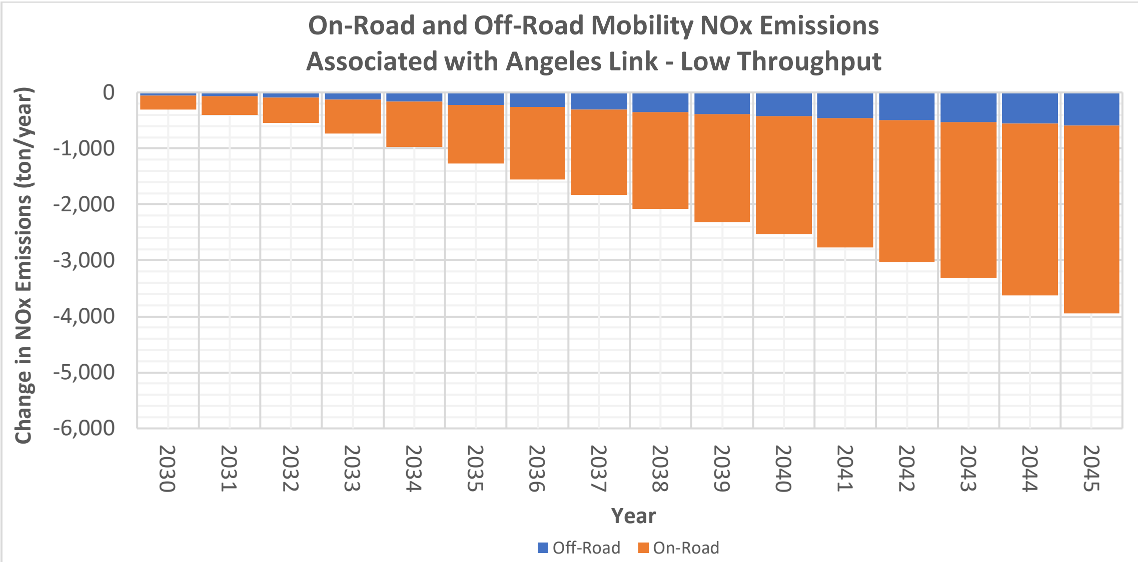

Figure 16a: On-Road and Off-Road Mobility Change in NOx Emissions Associated with Angeles Link - Low Throughput Scenario

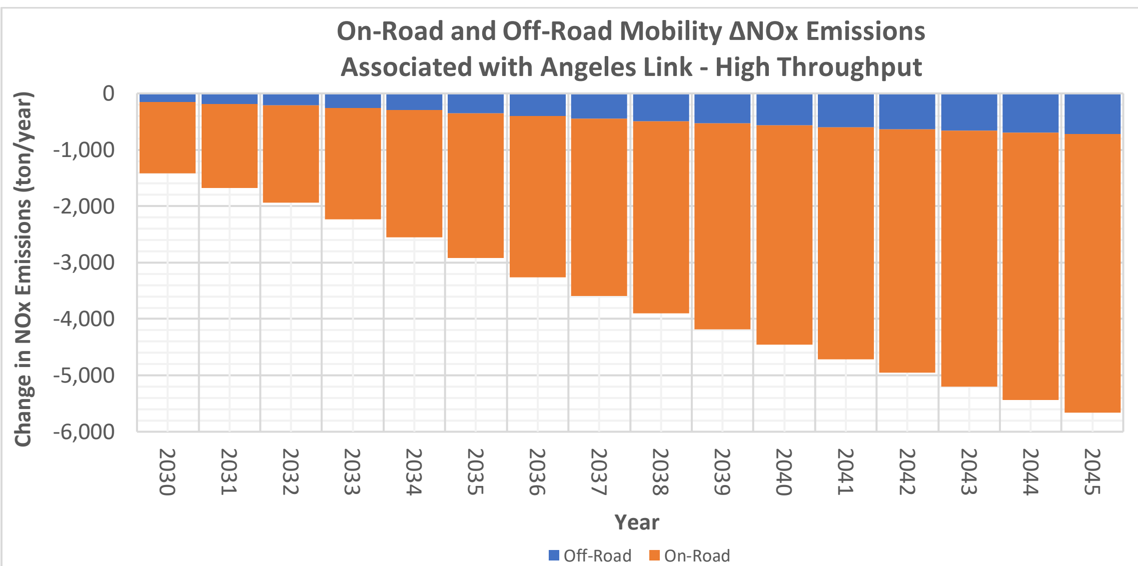

Figure 16b: On-Road and Off-Road Mobility Change in NOx Emissions Associated with Angeles Link - High Throughput Scenario

8.3.2 Angeles Link Power Generation Results

Reductions in NOx emissions were calculated for the power generation sector which is broken into two sub-sectors: peaker and baseload, and cogeneration. Table 27 below illustrates the estimated change in NOx emissions (ton/year) from power generation in 2030, 2035, 2040, and 2045 for each of the three throughput scenarios. Figures 17a and 17b below display the annual NOx change in emissions (ton/year) for the power generation sector for the low and high throughput scenarios, respectively.

Table 27
Power Generation NOx Emission Reductions for AL Throughput Scenarios (tpy)

Throughput Scenario	2030	2035	2040	2045
Low	0.1	0.8	2.4	5.1
Medium	0.1	2.1	6.5	13.7
High	0.2	2.8	8.6	18.2

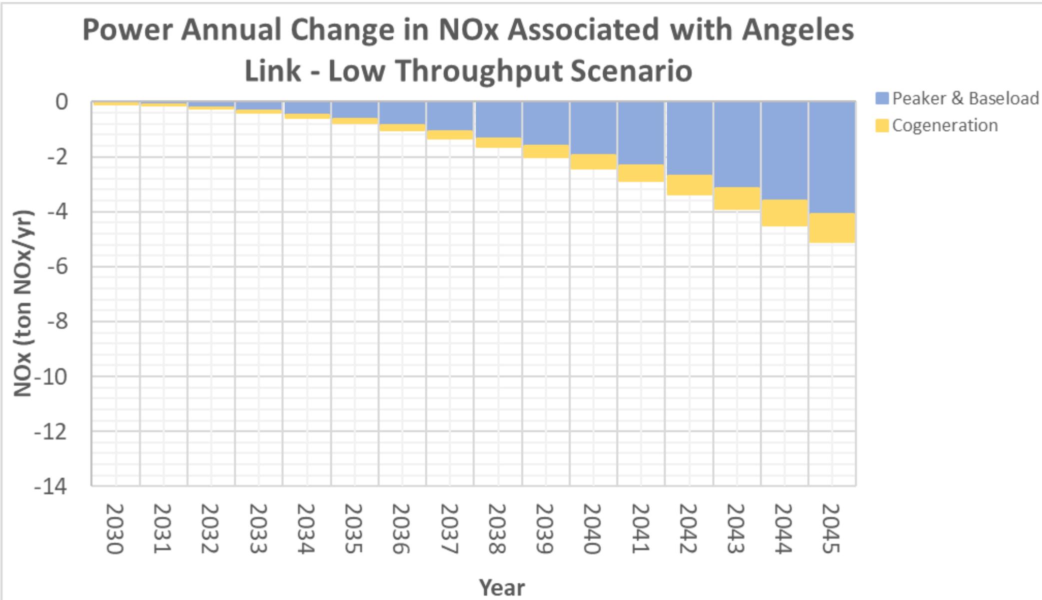

Figure 17a: Power Generation Change in NOx Emissions Associated with Angeles Link – Low Throughput Scenario

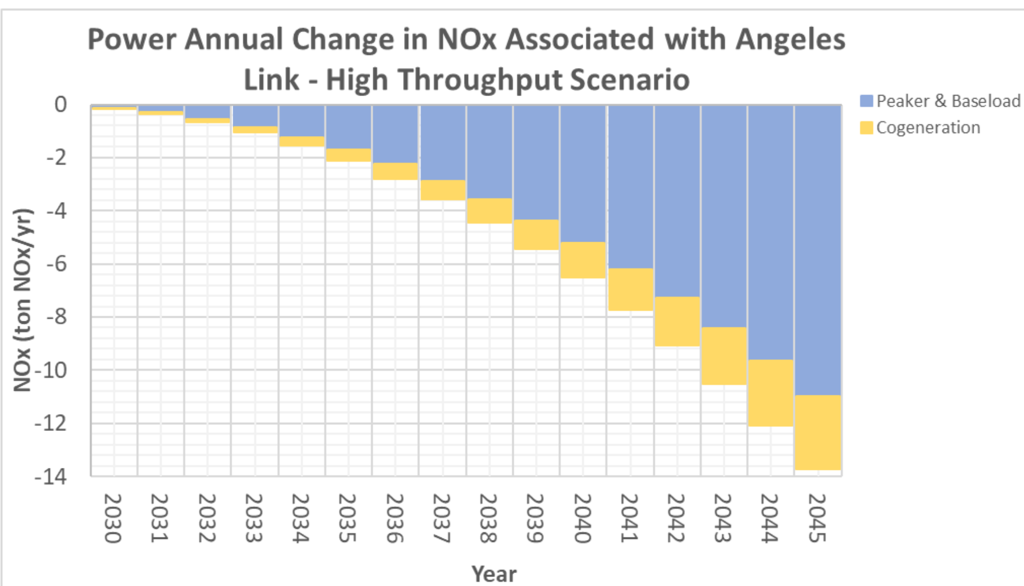

Figure 17b: Power Generation Change in NOx Emissions Associated with Angeles Link – High Throughput Scenario

8.3.3 Angeles Link Hard to Electrify Industrial Results

This study calculated a reduction in NOx emissions associated with the displacement of natural gas fuel with hydrogen fuel as supplied by Angeles Link in the hard to electrify industrial sector. Table 28 below illustrates the change in NOx emissions for the hard to electrify industrial sector for years 2030, 2035, 2040, and 2045 for each of the three throughput scenarios. Figures 18a and 18b below show the change in emissions calculated for each hard to electrify industrial sub-sector associated with the displacement of natural gas by hydrogen for each year of the study time frame for the low and high throughput scenarios, respectively.

Table 28
Hard to Electrify NOx Emissions Reductions for AL Throughput Scenarios (tpy)

Throughput Scenario	2030	2035	2040	2045
Low	0.7	1.2	1.4	1.7
Medium	1.1	1.9	2.5	3.1
High	1.9	3.2	4.1	4.9

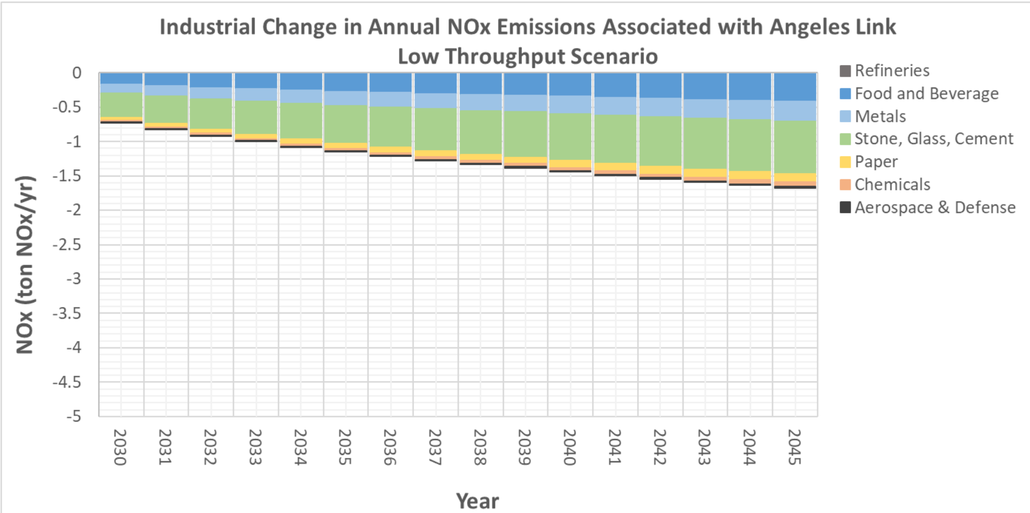

Figure 18a: Hard to Electrify Industrial Change in Annual NOx Emissions Associated with Angeles Link – Low Throughput Scenario

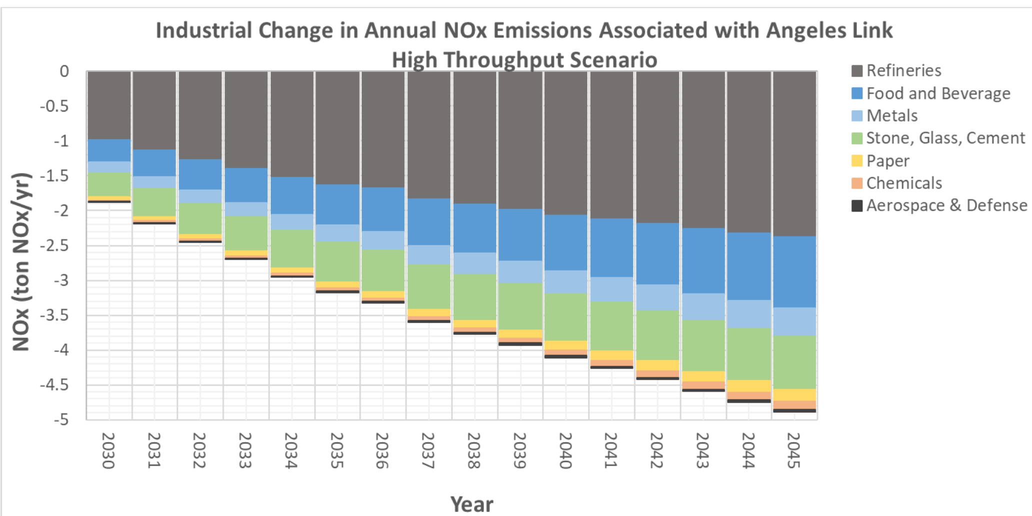

Figure 18b: Hard to Electrify Industrial Change in Annual NOx Emissions Associated with Angeles Link – High Throughput Scenario

9.0 RESULTS DISCUSSION

An overall reduction in NOx emissions is estimated associated with each of the three Demand Scenarios and each of the three Angeles Link throughput scenarios when comparing the potential increase in emissions from new infrastructure and the reduction in NOx emissions from end-users. The overall reductions were calculated assuming the maximum emissions case for new infrastructure comprised of third-party production, third-party storage, and transmission in each applicable Demand Scenario and throughput scenario. Design decisions that align more closely with the lower emissions infrastructure scenarios may yield a larger increase in overall NOx emissions reductions.

9.1 OVERALL END-USER DISCUSSION

Reductions in NOx emissions associated with the adoption of hydrogen increase each year from 2030 to 2045 for each of the three end-use sectors within each of the three Demand Scenarios and each of the three throughput scenarios. Of the three end-user sectors, the mobility sector makes up the bulk of the NOx emission reductions associated with the displacement of fossil fuels by hydrogen. There are three primary contributing factors. One factor is volume since hydrogen demand projections from the Demand Study are highest for mobility. Another factor is that the use of hydrogen in mobility produces zero NOx emissions as the hydrogen is in fuel cells. However, the use of hydrogen in the power generation and hard to electrify industrial sectors is assumed to be in internal and external combustion equipment which produces NOx emissions. Lastly, fossil fuel usage displaced by hydrogen in power generation and hard to electrify industrial sectors was natural gas whereas for mobility it was gasoline and diesel displacement. Emissions factors for NOx from diesel and gasoline combustion are generally higher than for natural gas, which may also contribute to the larger fraction of reductions estimated from mobility.

For stationary sources, there are a few high-level reasons to anticipate a reduction in NOx emissions over time and with the implementation of hydrogen combustion equipment. Air District emission limitations become stricter and decrease over time to support compliance with NAAQS and CAAQS, especially in areas designated as non-attainment.

As older equipment ages out, and newer equipment that is subject to these newer standards is installed, a reduction in emissions should occur. Manufacturers developing equipment to combust pure hydrogen fuel will need to meet the most recent regulatory emission limitations and standards when it comes to NOx emissions. The scientific literature shows that it is possible to design a burner that will have equal or fewer NOx emissions on a mass basis when combusting hydrogen as compared to natural gas or other fossil fuels. Therefore, it is anticipated that as older fossil fuel combustion units are replaced with new hydrogen combustion equipment required to meet the newest emission limitations and standards, a reduction in NOx emissions will be seen.

The Study assumed that technological advancements for combustion and emission controls would be in place so that the NOx emissions would stay the same or decrease with the combustion of hydrogen in equipment in the power generation and hard to electrify industrial sectors.

The study made a very conservative assumption that emission factors for stationary combustion sources will not change over the study period. Emissions factors for stationary combustion sources were developed based on most stringent existing emissions limitations, including BACT guidelines, for the geographic region at the time the calculations were performed. It is likely that these emissions limitations will decrease over time. Data on specific regulatory NOx emission limitation changes in the future was not available and thus emissions factors for stationary sources were held constant throughout the study timeframe.

There are numerous opportunities to minimize the formation of NOx emissions from hydrogen combustion through equipment design. The unique combustive properties of hydrogen allow manufacturers options to minimize the formation of NOx. Combustion expertise exists at equipment manufacturing companies to develop systems that will produce low NOx emissions when operated on pure hydrogen. It is anticipated that as the hydrogen market firms up, equipment development will accelerate, and low emission combustion systems specifically designed for pure hydrogen will start to emerge.[175]

9.1.1 Power Generation Discussion

A net reduction in NOx emissions from the displacement of fossil fuels by hydrogen as projected by the Demand Study for Power Generation was calculated for each of the three Demand Scenarios and each of the three Angeles Link Throughput Scenarios. The reductions in NOx emissions are relatively minor, and largely result from the correction factor approach used to correlate natural gas emissions factors to a hydrogen emissions factor. Using the correlation factor method, the mass-based emissions factor for pure hydrogen combustion is roughly 6% lower than the correlated emissions factor for natural gas. This leads to a roughly 6% reduction in mass emissions from combusting pure natural gas as compared to pure hydrogen. There is also the potential within the Power Generation sector to replace fossil fuel combustion technology with non-combustion technologies such as hydrogen fuel cells. This would lead to additional NOx emissions reductions.

The magnitude of the reduction in NOx emissions from the project scenario increases over time. This is likely due to multiple factors. One factor is the increasing projected hydrogen demand over the years,. As the demand for hydrogen increases, more natural gas demand is displaced by hydrogen, and as mentioned above, the emissions factor for pure hydrogen demand is roughly 6% lower than the emissions factor for pure natural gas. Therefore, the more fuel demand for hydrogen, the more fuel combustion that is multiplied by the lower emissions factor, and the lower

[175] McDonell, V, 2023, personal communication, Ibid

the overall NOx emissions. Particularly in gas turbines, which constitute most of the combustion equipment in power generation, research has shown that replacing natural gas with hydrogen may lead to a higher power output and slightly higher efficiency. This may in turn lead to a reduced NOx lb/kw-hr emissions factor.[176]

Another factor relates to blending. For the first few study years, it was assumed that combustion units in the peaker and baseload sub-sector would combust 27% hydrogen blends and, in the cogeneration sub-sector, they would combust 17% hydrogen blends. It was assumed that hydrogen combustion technology would improve over time, and that turbines would eventually combust 100% hydrogen. The amount of blending impacts the resultant formation of NOx emissions as the composition of fuel changes. The formation of NOx emissions is impacted by the proportion of natural gas to hydrogen in the fuels for stationary combustion sources.

Figure 19 below represents the energy obtained from pure hydrogen, blended hydrogen, pure natural gas, and blended natural gas from 2030 to 2045 for the project scenarios and the overall energy consumed from all fuel types. In Figure 22, blended hydrogen refers to hydrogen combusted in a blend of hydrogen and natural gas whereas blended natural gas is natural gas combusted in a blend of hydrogen and natural gas. These two categories are being presented separately since they represent different volumes and energy contents. Total energy consumption is represented in black at the top of the graph. This provides a visual representation of the decrease in blended hydrogen and natural gas anticipated to occur over time in the power generation sector.

[176] Pyo, M. et al., 2021, A Comparative Feasibility Study, Ibid

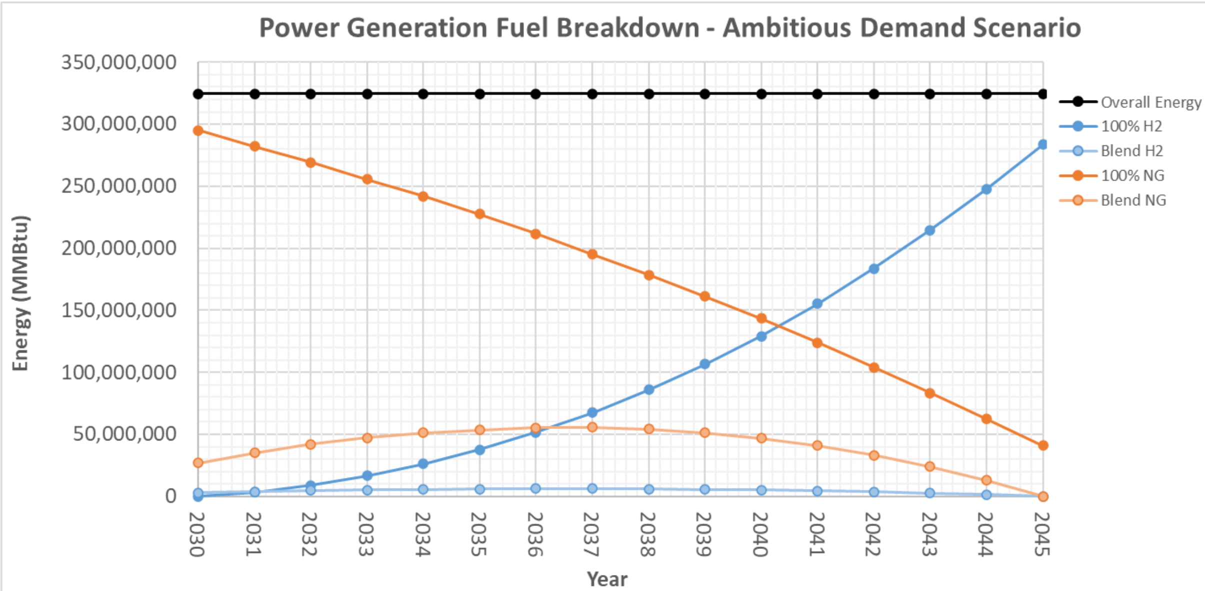

Figure 19: Energy (MMBtu) Obtained from Fuels for Power Generation Sector Ambitious Hydrogen Demand Scenario

The percentage of NOx mass emission (ton/year) reductions attributable to peaker and baseload decreases over time while the percentage of reductions attributable to cogeneration increases. This is attributable to an increase over time in the fraction of hydrogen demand in the power generation sector to cogeneration versus peaker and baseload. Cogeneration hydrogen demand is 15% of peaker and baseload hydrogen demand in 2030 and increases to 29% by 2045. Another contributing factor is the impact of the breakout of equipment types and their associated emissions factors.

9.1.2 Hard to Electrify Industrial Discussion

Similar to the power generation sector, overall NOx emissions reductions are calculated for each of the three Demand Scenarios and each of the three Angeles Link throughput scenarios for hard to electrify industrial end-users. The reductions in NOx emissions are relatively minor and result largely from the correction factor approach used to correlate natural gas emissions factors to a hydrogen emissions factor. Using the correction factor method, the emissions factor for hydrogen combustion is roughly 6% lower than the correlated emissions factor for natural gas. This leads to a roughly 6% reduction in mass emissions from combusting pure natural gas as compared to pure hydrogen. The volume of hydrogen that is blended with natural gas decreases throughout the study time frame. The higher the percentage of hydrogen in the fuel, the greater the emissions reductions calculated.

The refinery sub-sector contributes to major reductions in NOx mass emissions in the ambitious Demand Scenario and high throughput scenario. For the year 2030 in the ambitious Demand Scenario and high throughput scenario, over 50% of the change in NOx mass emissions is attributable to the refinery sub-sector. However, the Demand Study did not consider demand from the refinery sub-sector in the conservative and moderate Demand Scenarios or the low and medium throughput scenarios. In 2018, refineries used 70% of the hydrogen produced in the United States to remove sulfur from petroleum products (hydrotreating) and breaking larger molecules into smaller, higher value molecules (hydrocracking).[177] Given the high demand for hydrogen in the refining sub-sector and their existing relationships with third-party suppliers, this industry is poised for a transition to clean renewable hydrogen if the economics became favorable for use in their hydrotreating and hydrocracking processes, or to begin fueling their combustion equipment.

The steel sub-sector is another industry with potential to transition to the use of clean renewable hydrogen in their operations. A large pilot project completed to test the use of pure electrolytic hydrogen in direct reduction of iron was successful.[178] Additional projects have been planned following the success of this pilot. Hydrogen-based direct reduced iron (DRI) and hydrogen blending in DRI or blast furnaces, have been important developments for the steel industry.

The food and beverage and stone, glass, cement hard to electrify industrial sub-sectors also account for a percentage of the change in NOx mass emissions. Both of these industries have high heat demands which contributes to an increase in their ability to transition to the use of hydrogen, and likelihood of transitioning to hydrogen as a preferred method of decarbonization compared with electricity. The Chemicals industry is a hard to electrify industrial sub-sector that contributes to a smaller percentage of the overall change/reduction in NOx mass emissions associated with the implementation of Angeles Link.

9.1.3 Mobility Discussion

Emission reductions associated with the displacement of gasoline and diesel fuels as projected by the Demand Study for each of the three Demand Scenarios and each of the three throughput scenarios were quantified for eight different sub-sectors within the mobility sector. NOx emission reductions from the displacement of fossil fuels with hydrogen were calculated using emissions factors developed from EMFAC model data and fossil fuel displacement volumes from the Demand Study. The Demand Study provided gasoline and diesel displacement volumes for these eight mobility sub-sectors. To calculate the gasoline and diesel displacement volumes for the

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177 Shell, 2017, Use and Optimization of Hydrogen at Oil Refineries, presentation by Aimee LaFleur, process engineer, at DOE's H2@Scale Workshop, University of Houston, May 23, https://www.energy.gov/sites/prod/files/2017/05/f34/fcto_may_2017_h2_scale_wkshp_lafleur.pdf

178 International Energy Agency (IEA), 2019, The Future of Hydrogen – Seizing today's opportunities, report prepared for the G20 by the IEA, June, https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

three Angeles Link throughput scenarios, the gasoline and diesel displacement volumes were multiplied by the percentage of hydrogen demand to be supplied by Angeles Link in each throughput scenario.

The magnitude of emissions reductions from mobility increases over time as the projected hydrogen demand increases. However, during that time frame, emissions factors for fossil fuel combustion as developed from the EMFAC model decrease as EMFAC accounts for improvements in fuel efficiency and emissions control over time. Table 29 below provides the percent change in NOx emissions factors as developed by the EMFAC data from 2030 to 2045 for diesel and gasoline in each sub-sector for which emissions were calculated. As shown, NOx emission factors for each sub-sector and both fuel types decrease from 2030 to 2045. NOx emission factors from diesel combustion for HDV and gasoline combustion for construction and mining decrease the least during the study time frame.

Table 29
Percent Change in NOx Mobility Emissions Factors as Reductions from 2030 to 2045

Category	Diesel	Gasoline
MDV	-49.2%	-27.1%
HDV	-2.3%	-18.6%
Bus	-59.4%	-27.1%
Agriculture	-52.7%	-17.0%
CHC	-23.1%	NA
CHE	-76.4%	-0.1%
C&M	-36.9%	0.9%
GSE	-27.7%	-1.2%

The sub-sector, HDVs, contribute the largest total NOx mass emission reductions. The overall volume of hydrogen demand as projected by the Demand Study is the largest contributing variable to the percentage of reductions from each sub-sector. HDVs are anticipated to be an earlier adopter of hydrogen technology.

The sub-sector with the second largest percentage of overall NOx reductions is the bus sub-sector for 2030 and becomes the construction and mining sub-sector by 2045. The proportion of NOx reductions attributable to the bus sub-sector decreases over time, while the proportion of NOx reductions from construction and mining stays relatively constant over time. There are large regulatory drivers for the transition to ZEVs in the bus sub-sector, including the Innovative Clean Transit regulation that requires that 100% of new bus sales must emit zero emissions by 2029, and 100% of on-road transit buses must be ZEV by 2045, as well as the Zero Emission Airport Shuttle Rule requiring that 100% of on-road airport vehicles and equipment must be zero emission by 2035, where feasible.

Off-road sub-sectors currently have fewer regulatory pressures to transition to zero-emission vehicles. Executive Order N-79-20, signed in September of 2020, sets a goal of achieving 100% zero-emissions from off-road vehicles and equipment operations by 2035. However, this has not yet been developed into regulation for all off-road sub-sectors.

The remaining sub-sectors: agriculture, CHC, CHE, and GSE contribute less than 2.5% to overall NOx emission reductions. For GSE, Los Angeles World Airports (LAWA) has published the Ground Support Equipment Emissions Policy which sets NOx emission limitations for airport GSE. The Clean Air Action Plan for the Ports of Los Angeles and Long Beach sets a target for 100% zero-emission vehicles for CHE by 2030. For agriculture, the lack of existing commercially available hydrogen technology may hinder extensive reductions from hydrogen displacement of fossil fuels in the short term. CARB's Commercial Harbor Craft Regulation requires zero emission advanced technology (ZEAT) for new or replacement short-run ferries and excursion vessels after January 1, 2023.

9.1.4 Infrastructure Discussion

The emissions resulting from the operation of new infrastructure associated with third-party production, third-party storage, and transmission of hydrogen in the geographic region of this study are new emissions as this equipment does not currently exist. Facility and system designs have not yet been finalized for this new infrastructure. Therefore, different operational cases were evaluated to estimate potential emissions from research informed hypothetical infrastructure.

Total infrastructure account for a small percentage when compared with end-user emission reductions associated with the adoption of hydrogen. The NOx emissions from infrastructure in the maximum scenarios for the ambitious demand scenario and high throughput scenario equate to less than 4% and about 8%, respectively, of the magnitude of end-user reductions in 2045.

9.1.4.1 Third-Party Production Discussion

Three different production methods were proposed for the development of hydrogen to be delivered by Angeles Link; electrolysis driven by renewable electricity, biomass gasification, and biogas (renewable natural gas) used in steam methane reforming (SMR) where the external combustion unit is assumed to be driven by hydrogen. Based on research, it is assumed that no direct NOx emissions are formed during the processes of electrolysis by renewable electricity and biomass gasification. The proportion of hydrogen formed through each method is unknown at this time. Therefore, this study evaluated scenarios where 0%, 33%, and 100% of the hydrogen production was completed by SMR.

Calculations were run for each of these six cases, for each of the three Hydrogen Demand Scenarios and three Angeles Link Throughput Scenarios, yielding eighteen SMR NOx emissions cases for the Demand Scenarios and for the Throughput Scenarios. The estimated tons of NOx produced from external combustion on a unit of hydrogen production basis came out to 0.00000011 tons NOx per kg hydrogen produced in the maximum MMBtu/hr (this value was the same for each Hydrogen Demand Scenario and Angeles Link Throughput Scenario).

9.1.4.2 Third-Party Storage and Transmission Discussion

In each Hydrogen Demand Scenario and Angeles Link Throughput Scenario, the highest emissions scenario includes reciprocating engine as the power source and the storage pressure of 2,900 psi which corresponds to underground storage. The smallest emissions case for all scenarios was the use of electric motors to drive compressors, since using renewable electricity for powering these motors has no emissions.

For the storage and transmission scenarios with the highest emissions estimates, estimates for NOx emissions from storage and transmission are small in comparison to end-user emissions reductions. In the Ambitious Demand Scenario and High Throughput Scenario, assuming the highest NOx emissions case for storage and transmission, NOx emissions from storage and transmission account for 3.9% of total estimated end-user reductions associated with the displacement of fossil fuels by hydrogen as projected by the Demand Study in the year 2030, and this only increases to 5.4% by 2045.

10.0 OTHER AIR EMISSIONS

This study also provides a high-level analysis of anticipated reductions in particulate matter (PM), which is the primary pollutant associated with diesel combustion and, volatile organic compounds (VOC) emissions. For each displaced fossil fuel (natural gas, gasoline, and diesel) estimated emission reductions are provided. Displacement of fossil fuels results in lower PM and VOC emissions.

Diesel combustion is a known source of PM.[179] Hydrogen is a fuel that eliminates diesel particulate matter (DPM) when replacing diesel. VOCs are generally defined to include hydrocarbon compounds of propane and those that are larger than propane.[180] Hydrogen usage does not produce VOC emissions and VOC emissions are eliminated when replacing fossil fuels. Trace amounts of unburned hydrocarbons that are detected in exhaust gas are typically attributed to the complete and incomplete oxidation of lubricating oil within the engine rather than the hydrogen fuel itself.[181] Combustion of hydrogen fuel in stationary combustion sources has been shown to reduce these types of pollutants.[182]

When diesel, biogas, or natural gas are blended with hydrogen in a dual fuel system, there is a demonstrated decrease in pollutant emissions attributed to the enhanced combustion of gaseous fuel.[183] [184] Additionally, the integration of hydrogen in a singular and dual fuel configuration alongside Exhaust Gas Recirculation (EGR) techniques has been found to effectively reduce emissions of particulates[185] [186] [187] [188]

The EPA indicates that PM and VOC can have potential negative health effects. PM has been linked to irritation of the eyes and respiratory tract, asthma, bronchitis, heart attacks, and

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179 Wang, H., et al., 2012, Emissions reductions, Ibid.
180 US EPA, 2023c, What are volatile organic compounds (VOCs)?, US EPA website, https://www.epa.gov/indoor-air-quality-iaq/what-are-volatile-organic-compounds-vocs
181 Li, H. and G.A. Karim, 2005, Exhaust emissions from an SI engine operating on gaseous fuel mixtures containing hydrogen, International Journal of Hydrogen Energy 30(13–14): 1491-1499, https://doi.org/10.1016/j.ijhydene.2005.05.007
182 Bose, P.K. and D. Maji, 2009, Ibid.
183 Wang, H., et al., 2012, Emissions reductions, Ibid.
184 SinghYadav, V., et al., 2012, Performance and emission studies, Ibid.
185 Kosmadakis, G.M., C.D. Rakopoulos, J. Demuynck, M. De Paepe, and S. Verhelst, 2012, CFD modeling and experimental study of combustion and nitric oxide emissions in hydrogen-fueled spark-ignition engine operating in a very wide range of EGR rates, International Journal of Hydrogen Energy 37(14): 10917-10934, https://doi.org/10.1016/j.ijhydene.2012.04.067
186 Mallouppas, G., et al., 2022, The Effect of Hydrogen Addition, Ibid
187 Bose, P.K. and D. Maji, 2009, Ibid
188 Saravanan, N., G. Nagarajan, K.M. Kalaiselvan, and C. Dhanasekaran, 2008, An experimental investigation on hydrogen as a dual fuel for diesel engine system with exhaust gas recirculation technique, Renewable Energy 33(3): 422-427, https://doi.org/10.1016/j.renene.2007.03.01

premature deaths.[189] VOCs themselves have the potential to cause irritation to the body or be toxic or carcinogenic. Outdoors, VOCs are a precursor to ozone (as are NOx and CO) which contributes to photochemical smog.[190] Ozone can result in irritation of the airways, cause difficulty breathing, and worsen the symptoms of lung diseases (asthma, emphysema, and chronic bronchitis).[191] Where hydrogen fuel substitution can reduce PM and VOC emissions, positive public health outcomes could be achieved.

South Coast AQMD developed the MATES Program with the goals of providing public information about air toxics and associated health risks, evaluating progress in reducing air toxics exposure, and providing direction to future toxics control programs. They published the MATES V Report in 2021 based on monitoring completed from 2018 through 2019. The study found that DPM was the largest contributor to air toxics cancer risk, accounting for 50% of the cancer risk by pollutant, and that the highest air toxics cancer risks were in and around the port areas, as well as along goods movement corridors and major freeways.[192]

10.1 PM AND VOC CALCULATION METHODOLOGY

A high-level evaluation was conducted of the potential particulate matter with a diameter of 2.5 micrometers or smaller ($PM_{2.5}$), particulate matter with a diameter of 10 micrometers or smaller (PM_{10}), and VOC emissions reductions associated with the use of hydrogen by end users as projected by the Demand Study and Angeles Link Throughput Scenarios. For this evaluation, it was assumed that hydrogen combustion would not produce PM or VOC emissions and thus the reductions associated with hydrogen were estimated as the emissions associated with fossil fuel displacement.

Emission factors obtained from EPA AP-42 were deemed the most appropriate source for estimating $PM_{2.5}$, PM_{10}, and VOC from stationary sources. Stationary sources encompass the hard to electrify industrial and power generation sectors, where hydrogen is assumed within this study to displace natural gas. Sections 1.4 External Combustion Sources, 3.1 Stationary Internal Combustion Sources, and 3.2 Stationary Internal Combustion Sources from AP-42 were used for PM and VOC emissions factors for external combustion sources, turbines, and reciprocating

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[189] US EPA, 2024b, How Does PM Affect Human Health, agency webpage, https://www3.epa.gov/region1/airquality/pm-human-health.html#:~:text=Exposure%20to%20particle%20pollution%20can,%2C%20older%20people%2C%20and%20children

[190] US EPA, 2024c, Technical Overview of Volatile Organic Compounds, agency webpage, https://www.epa.gov/indoor-air-quality-iaq/technical-overview-volatile-organic-compounds#definition

[191] US EPA, 2024d, Health Effects of Ozone Pollution, agency webpage, https://www.epa.gov/ground-level-ozone-pollution/health-effects-ozone-pollution

[192] South Coast AQMD, 2023b, 2.Overview of Goals, Summary of Previous MATES Studies, and Projection Timeline, Presentation by S.A. Epstein, October 26, https://www.aqmd.gov/docs/default-source/planning/mates-vi/mates-tag-1-presentations.pdf?sfvrsn=8

engines, respectively.[193] [194] [195] A single factor for reciprocating engines was developed using an average of factors for 2-stroke lean burn, 2-stroke rich burn, and 4-stroke lean burn engines. Based on documentation associated with these emissions factors, it was assumed that particulate matter associated with natural gas combustion would be less than 2.5 microns. As a result, total PM emissions from natural gas combustion would be equivalent to PM_{10} and $PM_{2.5}$. Sector-level, equipment-weighted factors for PM and VOC were developed using sector-level equipment throughput fractions using the same methodology as NO_x emissions factors. The table below depicts the PM and VOC emissions factors for stationary sources that were used. Avoided emissions from stationary sources were then calculated by multiplying these sector-specific emissions factors by annual natural gas displaced by hydrogen.

Table 30
Stationary Source Equipment Fuel Percentages and Emissions Factors for PM and VOC

CARB Sector	Sub-Sector	Equipment Category	Through-put (%)	PM EF (lb/MMBtu)	VOC EF (lb/MMBtu)	AP-42 Sec	Note
Electric Utilities	Baseload and Peaker	External Combustion	5.7%	0.0071	0.0051	1.4	Single Factor
		Reciprocating Engine	0.1%	0.0258	0.0892	3.2	Average of Multiple (2SLB, 2SRB, 4SLB) Sum of filterable and condensable
		Turbine	94.2%	0.0066	0.0021	3.1	Single Factor
Co-generation	Cogeneration	General External Combustion	0.8%	0.0071	0.0051	1.4	Single Factor

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193 US EPA, 1998, 1.4 Natural Gas Combustion in Compilation of Air Pollutant Emissions Factors from Stationary Sources (AP-42), Fifth Edition, Volume I Chapter 1: External Combustion Sources, July, https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-fifth-edition-volume-i-chapter-1-external-0

194 US EPA, 2000a, 3.1 Stationary Gas Turbines in Compilation of Air Pollutant Emissions Factors from Stationary Sources (AP-42), Fifth Edition, Volume I Chapter 3: Stationary Internal Combustion Sources, April, https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-fifth-edition-volume-i-chapter-3-stationary-0

195 US EPA, 2000b, 3.2 Natural Gas-fired Reciprocating Engines in Compilation of Air Pollutant Emissions Factors from Stationary Sources (AP-42), Fifth Edition, Volume I Chapter 3: Stationary Internal Combustion Sources, August, https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-fifth-edition-volume-i-chapter-3-stationary-0

Table 30 Stationary Source Equipment Fuel Percentages and Emissions Factors for PM and VOC							
CARB Sector	**Sub-Sector**	**Equipment Category**	**Through-put (%)**	**PM EF (lb/MMBtu)**	**VOC EF (lb/MMBtu)**	**AP-42 Sec**	**Note**
		Reciprocating Engine	0.2%	0.0258	0.0892	3.2	Average of Multiple (2SLB, 2SRB, 4SLB) Sum of filterable and condensable
		Turbine	99.0%	0.0066	0.0021	3.1	Single Factor
Food and Beverage	Food and Beverage	General External Combustion	98.6%	0.0071	0.0051	1.4	Single Factor
		Oven	0.1%	0.0071	0.0051	1.4	Single Factor
		Reciprocating Engine	1.1%	0.0258	0.0892	3.2	Average of Multiple (2SLB, 2SRB, 4SLB) Sum of filterable and condensable
		Turbine	0.3%	0.0066	0.0021	3.1	Single Factor
Manufacturing and Industrial	Metals, Stone, Glass, Cement	General External Combustion	81.2%	0.0071	0.0051	1.4	Single Factor
		Oven	0.2%	0.0071	0.0051	1.4	Single Factor
		Reciprocating Engine	12.8%	0.0258	0.0892	3.2	Average of Multiple (2SLB, 2SRB, 4SLB) Sum of filterable and condensable
		Turbine	5.8%	0.0066	0.0021	3.1	Single Factor
Refining	Refineries	General External Combustion	21.2%	0.0071	0.0051	1.4	Single Factor
		Reciprocating Engine	0.2%	0.0258	0.0892	3.2	Average of Multiple (2SLB, 2SRB, 4SLB) Sum of filterable and condensable
		Turbine	78.6%	0.0066	0.0021	3.1	Single Factor

Mobile $PM_{2.5}$, PM_{10}, and VOC emissions were estimated using factors developed from CARB's EMFAC database. Mobile sources encompass the mobility sector where hydrogen would displace gasoline and diesel fuels. The EMFAC on-road and off-road emissions models were used to develop individual emissions factors for each mobility sub-sector by fuel type and year. These factors were developed by weighting the tons of pollutant per gallon of fuel consumed for each vehicle category by the percentage of the sub-sectors' fuel consumption attributable to that vehicle category.

Diesel particulate matter (DPM) was also assessed and DPM is solid material in diesel combustion exhaust. DPM is a subset of $PM_{2.5}$.[196] For the purposes of this study, the assumption was made that all $PM_{2.5}$ from diesel combustion was DPM. Table 31 below depicts a summary of the average $PM_{2.5}$, PM_{10}, and VOC emissions factors for mobile sources. Avoided emissions from mobile sources were then calculated by multiplying these emission factors by annual mobility source-level fuel displacement.

Table 31
Mobility PM and VOC Emissions Factors

Sub-Sector	Fuel	Avg PM2.5 (ton/gal)	Avg PM10 (ton/gal)	Avg VOC (ton/gal)
MDV	Diesel	5.79784E-07	1.37309E-06	6.877120E-07
HDV	Diesel	5.13424E-07	1.16467E-06	4.525510E-07
Bus	Diesel	3.71824E-07	8.153E-07	4.316530E-07
Agriculture	Diesel	1.63835E-07	1.78101E-07	6.203640E-07
CHC	Diesel	4.21733E-07	4.41143E-07	2.701390E-06
CHE	Diesel	4.09287E-07	4.44842E-07	4.566850E-07
C&M	Diesel	5.62213E-07	6.24906E-07	4.066440E-07
GSE	Diesel	4.73703E-06	5.14895E-07	3.887810E-06
MDV	Gasoline	4.02406E-07	1.15658E-07	2.91013E-06
HDV	Gasoline	1.96824E-07	5.83383E-07	2.18934E-06
Bus	Gasoline	2.0225E-07	5.84393E-07	2.58640E-06
Agriculture	Gasoline	3.00707E-07	3.26856E-07	6.756950E-05
CHE	Gasoline	8.9181E-07	9.69352E-07	3.60713E-06
C&M	Gasoline	2.56347E-05	3.39282E-05	0.000104656
GSE	Gasoline	4.715E-07	6.24044E-07	5.47814E-06

[196] CARB, 2024a, Overview: Diesel Exhaust and Health, CARB webpage, https://ww2.arb.ca.gov/resources/overview-diesel-exhaust-and-health

The above table provides the average emissions factor for the fifteen years of the study time frame. However, emissions factors were developed and utilized for each individual year. The table below illustrates how the emissions factor for each sub-sector and fuel type changed throughout the study time frame from 2030 to 2045. The largest decreases in emissions factors throughout the study time frame come from diesel combustion.

Table 32
Change in Diesel PM2.5 and PM10 EMFAC Emissions Factors from 2030 to 2045

Sub-Sector	Fuel	PM2.5	PM10	VOC
MDV	Diesel	-12%	-5%	-36%
HDV	Diesel	12%	14%	9%
Bus	Diesel	-24%	-8%	-57%
Agriculture	Diesel	-60%	-60%	-40%
CHC	Diesel	-65%	-65%	-38%
CHE	Diesel	-69%	-69%	-10%
C&M	Diesel	-53%	-52%	-2%
GSE	Diesel	-53%	-53%	4%
MDV	Gasoline	12%	12%	0%
HDV	Gasoline	18%	18%	-16%
Bus	Gasoline	37%	36%	27%
Agriculture	Gasoline	-7%	-7%	-13%
CHE	Gasoline	0%	0%	0%
C&M	Gasoline	2%	2%	2%
GSE	Gasoline	0%	0%	-2%

10.2 PM AND VOC RESULTS

Tables 33 to 36 below illustrate the estimated annual reduction in $PM_{2.5}$, PM_{10} emissions from each fuel type for the years 2030, 2035, 2040, and 2045. DPM is represented by $PM_{2.5}$ from diesel combustion. The first two tables represent PM reductions associated with the market demand of hydrogen in the conservative and ambitious Demand scenarios, and the second two tables represent the PM reductions associated with the hydrogen supplied by Angeles Link in the low and high throughput scenarios.

Table 33
Hydrogen Conservative Demand Scenario - Annual PM Reductions by Sector and Fuel Type

Year	Diesel DPM PM2.5		Gasoline PM2.5		Natural Gas PM2.5		Diesel PM10		Gasoline PM10		Natural Gas PM10	
	Mobility On-Road	Mobility Off-Road	Mobility On-Road	Mobility Off-Road	Indus -trial	Power Gen	Mobility On-Road	Mobility Off-Road	Mobility On-Road	Mobility Off-Road	Indus-trial	Power Gen
2030	22	4	9	23	23	3	50	4	25	30	23	3
2035	114	11	31	128	37	38	258	12	90	168	37	38
2040	241	17	70	240	46	118	551	19	202	316	46	118
2045	400	22	105	327	54	250	919	24	303	429	54	250

Table 34
Hydrogen Ambitious Demand Scenario - Annual PM Reductions by Sector and Fuel Type

Year	Diesel DPM PM2.5		Gasoline PM2.5		Natural Gas PM2.5		Diesel PM10		Gasoline PM10		Natural Gas PM10	
	Mobility On-Road	Mobility Off-Road	Mobility On-Road	Mobility Off-Road	Indus -trial	Power Gen	Mobility On-Road	Mobility Off-Road	Mobility On-Road	Mobility Off-Road	Indus-trial	Power Gen
2030	127	10	33	88	77	10	285	11	94	116	77	10
2035	298	21	62	204	130	144	675	22	178	267	130	144
2040	477	26	102	307	169	446	1093	29	295	403	169	446
2045	627	30	139	400	201	943	1439	33	400	524	201	943

Table 35
Hydrogen Low Throughput Scenario - Annual PM Reductions by Sector and Fuel Type

Year	Diesel DPM PM2.5		Gasoline PM2.5		Natural Gas PM2.5		Diesel PM10		Gasoline PM10		Natural Gas PM10	
	Mobility On-Road	Mobility Off-Road	Mobility On-Road	Mobility Off-Road	Indus -trial	Power Gen	Mobility On-Road	Mobility Off-Road	Mobility On-Road	Mobility Off-Road	Indus-trial	Power Gen
2030	6	1	2	6	6	1	13	1	7	8	6	1
2035	30	3	8	34	10	10	69	3	24	45	10	10
2040	65	5	19	65	12	32	148	5	54	85	12	32
2045	107	6	28	88	14	67	247	7	81	115	14	67

Table 36
Hydrogen High Throughput Scenario - Annual PM Reductions by Sector and Fuel Type

Year	Diesel DPM PM2.5		Gasoline PM2.5		Natural Gas PM2.5		Diesel PM10		Gasoline PM10		Natural Gas PM10	
	Mobility On-Road	Mobility Off-Road	Mobility On-Road	Mobility Off-Road	Indus -trial	Power Gen	Mobility On-Road	Mobility Off-Road	Mobility On-Road	Mobility Off-Road	Indus-trial	Power Gen
2030	32	3	8	22	19	2	72	3	24	29	19	2
2035	75	5	16	52	33	37	171	6	45	68	33	37
2040	121	7	26	78	43	113	277	7	75	102	43	113
2045	159	8	35	101	51	239	365	8	101	133	51	239

Tables 37 to 40 below summarize the results of the estimated VOC reductions by fuel type for hydrogen displacement of diesel, gasoline, and natural gas. The results are presented for the conservative and ambitious Demand Scenarios and the low and high throughput scenarios in 2030, 2035, 2040, and 2045. These tables also differentiate between on-road and off-road emission reductions for the mobility sector for diesel and gasoline displacement.

Table 37 Conservative Demand Scenario - Annual VOC Reductions by Sector and Fuel Type						
	Diesel VOC (tpy)		Gasoline VOC (tpy)		Natural Gas VOC (tpy)	
Year	Mobility On-Road	Mobility Off-Road	Mobility On-Road	Mobility Off-Road	Industrial	Power Generation
2030	22	15	113	100	33	1
2035	105	61	381	539	54	13
2040	217	127	902	1,011	68	42
2045	357	182	1,201	1,397	79	88

Table 38 Ambitious Demand Scenario - Annual VOC Reductions by Sector and Fuel Type						
	Diesel VOC (tpy)		Gasoline VOC (tpy)		Natural Gas VOC (tpy)	
Year	Mobility On-Road	Mobility Off-Road	Mobility On-Road	Mobility Off-Road	Industrial	Power Generation
2030	124	45	425	372	61	3
2035	273	112	763	867	105	51
2040	428	187	1,312	1,303	136	157
2045	559	239	1,585	1,717	164	332

Table 39 Low Throughput Scenario - Annual VOC Reductions by Sector and Fuel Type						
Year	Diesel VOC (tpy)		Gasoline VOC (tpy)		Natural Gas VOC (tpy)	
	Mobility On-Road	Mobility Off-Road	Mobility On-Road	Mobility Off-Road	Industrial	Power Generation
2030	6	4	30	27	9	0.2
2035	28	16	102	145	14	4
2040	58	34	242	272	18	11
2045	96	49	323	375	21	24

Table 40 High Throughput Scenario - Annual VOC Reductions by Sector and Fuel Type						
Year	Diesel VOC (tpy)		Gasoline VOC (tpy)		Natural Gas VOC (tpy)	
	Mobility On-Road	Mobility Off-Road	Mobility On-Road	Mobility Off-Road	Industrial	Power Generation
2030	6	4	30	27	15	1
2035	28	16	102	145	27	13
2040	58	34	242	272	35	40
2045	96	49	323	375	42	84

Tables 41 to 46 below provide additional detail regarding the annual tons of $PM_{2.5}$, PM_{10}, and VOC displaced by hydrogen in mobility sector for the conservative, moderate, and ambitious Demand Scenarios and the low, medium, and high throughput scenarios in 2030, 2035, 2040, and 2045. These tables also indicate the percentage of these emission reductions attributable to on-road and off-road sources. Where applicable, these tables also include the percentage of PM emissions that are attributable to DPM. As depicted in each of these tables, $PM_{2.5}$, PM_{10}, and VOC annual reductions in the mobility sector increase over time as hydrogen demand increases despite a decrease over time in some of the emissions factors. For $PM_{2.5}$ and PM_{10}, on-road sources contribute a larger share of emissions than off-road sources. The relative contribution of on-road and off-road sources to VOC fluctuates, but each contributes approximately half of total VOC emissions reductions.

Table 41
Hydrogen Demand Scenarios - Mobility Annual PM2.5 Displacement

Year	Conservative				Moderate				Ambitious			
	PM2.5 (tpy)	On-road	Off-road	DPM	PM2.5 (tpy)	On-road	Off-road	DPM	PM2.5 (tpy)	On-road	Off-road	DPM
2030	58	54%	46%	45%	139	58%	42%	50%	258	62%	38%	53%
2035	283	51%	49%	44%	407	57%	43%	50%	584	62%	38%	55%
2040	568	55%	45%	45%	719	59%	41%	51%	913	63%	37%	55%
2045	855	59%	41%	49%	1,008	62%	38%	52%	1,196	64%	36%	55%

Table 42
Hydrogen Throughput Scenarios - Mobility Annual PM2.5 Displacement

Year	Conservative				Moderate				Ambitious			
	PM2.5 (tpy)	On-road	Off-road	DPM	PM2.5 (tpy)	On-road	Off-road	DPM	PM2.5 (tpy)	On-road	Off-road	DPM
2030	16	54%	46%	45%	43	58%	42%	50%	65	62%	38%	53%
2035	76	51%	49%	44%	127	57%	43%	50%	148	62%	38%	55%
2040	153	55%	45%	45%	224	59%	41%	51%	232	63%	37%	55%
2045	229	59%	41%	49%	314	62%	38%	52%	303	64%	36%	55%

Table 43
Hydrogen Demand Scenarios - Mobility Annual PM10 Displacement

Year	Conservative				Moderate				Ambitious			
	PM10 (tpy)	On-road	Off-road	DPM	PM10 (tpy)	On-road	Off-road	DPM	PM10 (tpy)	On-road	Off-road	DPM
2030	109	69%	31%	24%	267	72%	28%	26%	506	75%	25%	27%
2035	527	66%	34%	24%	778	71%	29%	26%	1,143	75%	25%	28%
2040	1,088	69%	31%	24%	1,405	73%	27%	26%	1,819	76%	24%	28%
2045	1,675	73%	27%	25%	1,998	75%	25%	26%	2,396	77%	23%	27%

Table 44
Hydrogen Throughput Scenarios - Mobility Annual PM10 Displacement

Year	Conservative				Moderate				Ambitious			
	PM10 (tpy)	On-road	Off-road	DPM	PM10 (tpy)	On-road	Off-road	DPM	PM10 (tpy)	On-road	Off-road	DPM
2030	29	69%	31%	24%	83	72%	28%	26%	128	75%	25%	27%
2035	141	66%	34%	24%	242	71%	29%	26%	290	75%	25%	28%
2040	292	69%	31%	24%	437	73%	27%	26%	461	76%	24%	28%
2045	450	73%	27%	25%	622	75%	25%	26%	608	77%	23%	27%

Table 45 Hydrogen Demand Scenarios - Mobility Annual VOC Displacement									
	Conservative			Moderate			Ambitious		
Year	VOC (tpy)	On-road	Off-road	VOC (tpy)	On-road	Off-road	VOC (tpy)	On-road	Off-road
2030	250	54%	46%	538	54%	46%	966	57%	43%
2035	1,086	45%	55%	1,464	47%	53%	2,015	51%	49%
2040	2,258	50%	50%	2,677	51%	49%	3,230	54%	46%
2045	3,137	50%	50%	3,570	51%	49%	4,099	52%	48%

Table 46 Hydrogen Throughput Scenarios - Mobility Annual VOC Displacement									
	Conservative			Moderate			Ambitious		
Year	VOC (tpy)	On-road	Off-road	VOC (tpy)	On-road	Off-road	VOC (tpy)	On-road	Off-road
2030	67	54%	46%	167	54%	46%	245	57%	43%
2035	292	45%	55%	456	47%	53%	511	51%	49%
2040	606	50%	50%	833	51%	49%	819	54%	46%
2045	842	50%	50%	1,111	51%	49%	1,040	52%	48%

11.0 CONCLUSIONS

The NOx and other air emission estimates were developed from data from both the Demand Study Demand Scenarios and Angeles Link Throughput Scenarios. The emission estimates associated with Angeles Link set forth in this study are for informative purposes for Phase 1. As more information becomes available, emissions estimates can be further refined. This study acknowledges that limited data exists in the literature for actual measurements of NOx emissions associated with combustion of clean renewable hydrogen and that combustion technology and post-combustion treatment technology is anticipated to develop over time. As refinements have been made for natural gas combustion over the past decades, it is anticipated that developments will similarly be made for hydrogen combustion to minimize NOx emissions. The design details of the infrastructure, as well as further project refinements will inform future quantification estimates for NOx emissions and NOx minimization opportunities.

11.1 KEY FINDINGS

Key findings for NOx and other air emission reductions based on Demand Study Scenarios and Angeles Link Throughput Scenarios are as follows.

- In 2030, the Ambitious Demand Scenario estimates approximately 5,240 ton/year NOx reductions as shown in Table 6, associated with the displacement of fossil fuels by hydrogen for end-users minus emissions from infrastructure associated with third-party production, third-party storage, and transmission of hydrogen. Based on throughput values for Angeles Link, the High Throughput Scenario estimates that Angeles Link could supply 25.36% of the overall hydrogen demand project by the Demand Study. Therefore, overall NO_x emissions reductions associated with the Angeles Link High Throughput Scenario in 2030 are estimated at 1,329 tons per year as shown in Table 14. This value of 1,329 tons of NOx per year is the same as 23% of the NOx reductions South Coast Air Quality Management District (South Coast AQMD) has proposed to be achieved by 2037 for total stationary commercial and large combustion source NOx control measures in their 2022 Air Quality Management Plan (AQMP).[197]
- In 2045, the Ambitious Demand Scenario estimates NOx emissions reductions of 20,529 tons/year (as shown in Table 6) associated with the displacement of fossil fuels by hydrogen for end-users minus emissions from new infrastructure associated with the third-party production, third-party storage, and transmission of hydrogen demand. Based on throughput values for Angeles Link, the High Throughput Scenario estimates that Angeles Link could supply 25.36% of the overall hydrogen demand. Therefore, overall NO_x emissions reductions

[197] South Coast AQMD, 2022a, 2022 Air Quality Management Plan, Appendix IV-A, Stationary and Mobile Source Control Measures, https://www.aqmd.gov/docs/default-source/clean-air-plans/air-quality-management-plans/2022-air-quality-management-plan/final-2022-aqmp/appendix

associated with the Angeles Link High Throughput Scenario in 2045 are estimated at 5,206 tons per year. This value of 5,206 tons of NOx per year is the same as 90% of the NOx reductions South Coast AQMD has proposed to be achieved by 2037 for total stationary commercial and large combustion source NOx control measures in their 2022 AQMP.[198]

- Of the three end-user sectors, the mobility sector makes up the bulk of the NO_x emissions reductions (over 99% in the ambitious Demand Scenario). This parallels the 2018 emissions inventory used by South Coast AQMD in their 2022 AQMP which shows that 85% of emissions in the South Coast AQMD are from mobile sources and 15% are from stationary sources. Mobility NOx emissions (e.g., primarily heavy-duty transportation) is expected to be reduced with the conversion to zero emission vehicles (ZEVs). Options for ZEVs include hydrogen fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEVs). The Demand Study projected the anticipated fossil fuel displacement associated with FCEVs only. The associated NOx reductions were estimated only for conversion to FCEVs; this study does not project emission reductions related to fossil fuel displacement that will be associated with BEVs.
    - The study assumes that hydrogen is utilized in fuel cells in the mobility sector, and in combustion units for stationary applications within power generation and hard to electrify Industrial sectors. The use of hydrogen in fuel cells produces zero NO_x emissions, while the combustion of hydrogen does have the potential to form NO_x emissions.
- A relatively small reduction in NO_x emissions is expected from combusting hydrogen as compared to pure natural gas. The difference in NO_x emissions from the combustion of hydrogen fuel compared to fossil fuels is attributable to differences between NOx emission factors for hydrogen fuel as compared to NOx emission factors for natural gas. Current research into the scientific literature supports the potential for a reduction in NO_x emissions when transitioning from the combustion of fossil fuels to hydrogen fuels as 1) hydrogen has the potential to combust at a wider range of air to fuel ratios and lower temperatures than fossil fuels, 2) there are potentially favorable differences in the thermodynamic efficiency of hydrogen in turbines as compared to natural gas, and 3) certain burner technologies have proven experimentally to emit lower NO_x emissions from hydrogen combustion as compared to natural gas combustion. Since current data and scientific research is still evolving, the Study takes a conservative approach to estimating NOx and other air emissions.
- In the power generation sector, the estimated NO_x reductions associated with market adoption of hydrogen are approximately 0.7 ton/year in 2030 and up to approximately 72 ton/year in 2045 based on the Ambitious Demand Scenario. The bulk of the expected reductions from Power Generation (e.g. over 80%) are attributed to the peaker and baseload sub-sector for all years. Expected emissions reductions associated with Angeles Link in the power

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[198] South Coast AQMD, 2022a, 2022 Air Quality Management Plan, Appendix IV-A, Stationary and Mobile Source Control Measures, https://www.aqmd.gov/docs/default-source/clean-air-plans/air-quality-management-plans/2022-air-quality-management-plan/final-2022-aqmp/appendix

generation sector in 2030 are roughly 0.2 tons per year, and in 2045 are roughly 18.2 tons per year based on the Angeles Link High Throughput Scenario.

- In hard to electrify industrial sectors, the estimated NO_x reductions associated with market adoption of hydrogen are 7 ton/year in 2030 and 19 ton/year in 2045 using the Ambitious Demand Scenario. In the Ambitious Demand and High Throughput Scenarios, refineries account for the largest reductions (e.g. 52.2% Ambitious, 2030), followed by Stone, Glass, Cement (18.4% Ambitious, 2030), Food and Beverage (17.4% Ambitious, 2030), and Metals (8.1% Ambitious, 2030). These percentages are not expected to change much between 2030 and 2045. Expected emissions reductions associated with the Hard to Electrify Industrial sector in 2030 are roughly 1.9 tons per year, and in 2045 are roughly 4.9 tons per year using the Angeles Link High Throughput Scenario.

- In the Mobility sector, the estimated NO_x reductions associated with market adoption of hydrogen are roughly 5,600 ton/year in 2030 and 22,000 ton/year in 2045 using the Ambitious Demand Scenario. The largest percentage of overall NO_x reductions associated with market adoption of hydrogen in the Mobility sector in the Ambitious Demand and High Throughput Scenarios are attributable to heavy-duty vehicles (e.g. 69.1% in 2030 and 77.4% in 2045), followed by buses (exceeded by construction and mining by 2045) (14.2% in 2030 and 5.6% in 2045), construction and mining vehicles(6.8% in 2030 and 6.7% in 2045), and then medium-duty vehicles (6.4% in 2030 and 4.4% in 2045). Three of the top four sub-sectors contributing the greatest magnitude of NO_x emissions reductions are the three on-road sub-sectors. The magnitude of reductions from the collective on-road sub-sectors is much greater than the magnitude of reductions from the collective off-road sub-sectors. The largest variable impacting the magnitude of emissions reductions from on-road versus off-road vehicles is the estimated volume of fossil fuels displaced as projected by the Demand Study. Expected emission reductions associated with the Mobility sector in 2030 are roughly 1,400 tons per year, and in 2045 are roughly 5,660 tons per year, using the Angeles Link High Throughput Scenario

- Based on currently available information, new infrastructure potential emissions account for a relatively small percentage when compared with end-user emissions reductions. In 2030 the infrastructure NO_x emissions associated with the market adoption of hydrogen are estimated to be approximately 360 tons/year, which accounts for 6% of the total estimated NO_x reductions from end-users associated with the Ambitious hydrogen demand projections (2030) from the Demand Study. In the same scenario for the year 2045, infrastructure NO_x emissions are approximately 1,900 tons/year, which accounts for about 8% of total NO_x reductions from end-users associated with the Ambitious Demand Scenario projections (2045) from the Demand Study. Based on the High Throughput Scenario for Angeles Link, new infrastructure emissions in the maximum emissions scenario for 2030 are estimated at 91 tons per year of NO_x, and for 2045 are estimated at 481 tons per year of NO_x.

- The estimated annual reductions in $PM_{2.5}$ and PM_{10} emissions associated with end-users displacing fossil fuels with hydrogen fuel are estimated at approximately 2,339 and 3,539 tons, respectively, for 2045 in the Ambitious Demand Scenario. The South Coast Air Quality Management District (South Coast AQMD) projects annual $PM_{2.5}$ emissions in 2037 to be approximately 60.08 tons/day, PM_{10} to be 173.63 tons/day, and total PM to be 298.51 tons/day. This yields $PM_{2.5}$ emissions of 21,929 tons and PM_{10} emissions of 63,375 tons for the year 2037. Therefore, the estimated annual average reductions in $PM_{2.5}$ and PM_{10} emissions in the South Coast AQMD for the market adoption of hydrogen are potentially up to 11% and 6%, respectively. The total reductions in $PM_{2.5}$ and PM_{10} emissions associated with the Angeles Link High Throughput Scenario in 2045 are about 593 and 898 tons per year, respectively. These values are about 3% and 1% of projected 2037 $PM_{2.5}$ and PM_{10} emissions in the South Coast AQMD, respectively.

- Hydrogen is a non-carbon containing fuel that eliminates diesel particular matter (DPM) when replacing diesel fuel. Studies indicate that hydrogen fuel substitution of non-diesel fossil fuels almost entirely reduces PM emissions in spark-ignited engines and turbines. DPM reductions from the displacement of diesel fuel with hydrogen fuel in the Ambitious Demand Scenario are estimated to be approximately 656.37 tons per year by 2045.

- Hydrogen usage is not known to produce direct VOC emissions and VOC may be eliminated by replacing fossil fuels with hydrogen fuel. A reduction in VOC emissions associated with end-users displacing fossil fuels with hydrogen fuel as projected by the Demand Study was estimated at approximately 4,595 tons by 2045 in the Ambitious Demand Scenario. The South Coast AQMD projects their annual VOC emissions in 2037 to be 120,335 tons.[199] Therefore, the annual average reductions in VOC emissions estimated by the market adoption of hydrogen are about 3.8% of the VOC emissions in the South Coast AQMD region. The estimated reductions in VOC emissions associated with the Angeles Link High Throughput Scenario are roughly 1165.3 tons per year in 2045.

Emissions Minimization Opportunities: Opportunities to minimize NOx emissions or measures to reduce NOx emissions can be implemented to reduce NOx emissions, including with equipment design, control of combustion temperature, and application of existing and emerging aftertreatment technologies. Existing technologies include selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), and non-selective catalytic reduction (NSCR), while emerging technologies include electron beam irradiation and electrochemical reduction.

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[199] South Coast AQMD, 2022a, 2022 Air Quality Management Plan Appendix III Base and Future Year Emission Inventory, Adopted December 2, https://www.aqmd.gov/docs/default-source/clean-air-plans/air-quality-management-plans/2022-air-quality-management-plan/final-2022-aqmp/appendix-iii.pdf?sfvrsn=6

11.2 UNCERTAINTY

11.2.1 Third-Party Production

Specific design details for hydrogen third party production that would be transported by the Angeles Link system was not currently available when the calculations in this study were computed. Details on the specific process intended for use in producing hydrogen that could be transported by Angeles Link, additional design details for the hydrogen production process, and proportions of hydrogen intended to be produced from different methods, if more than one method is used, would reduce the uncertainty within the hydrogen production emissions estimates. Estimates were developed based on hypothetical electrolysis, biomass gasification, and biogas in steam methane reforming scenarios where the combustion equipment is fueled by hydrogen. More accurate emissions estimates can be made for hydrogen production once designs for those production facilities are further along.

11.2.2 Third-Party Storage and Transmission

Designs for the third-party storage and Angeles Link's transmission system were not completed before the finalization of the calculations in this study. Details regarding quantity of hydrogen storage, location, and types (above ground versus below ground) of storage will inform refinement of these initial estimates. Additionally, distances and locations of transmission pipelines will also provide details to refine the emission estimates. Once final designs are completed, more accurate emissions estimates can be made for the third-party storage and Angeles Link transmission system.

11.2.3 Mobility

Fossil fuel displacement volumes for diesel and gasoline from the Demand Study were utilized in the calculations within this study directly as provided. NOx emissions factors for each of the mobility sub-sectors were calculated based on projected emissions and fuel consumption from the current EMFAC model. The EMFAC model may be updated in the future and it is uncertain how these emissions factors will change in the future.

11.2.4 Power Generation and Hard to Electrify Industrial

A source of uncertainty within the stationary combustion calculations for this study was the lack of manufacturers emissions data and stack testing data for pure hydrogen combustion. There is minimal existing emissions data for pure hydrogen combustion as the technology is largely still in development. Of the hydrogen combustion data that is available, most tests were not completed for pure hydrogen combustion, and there is a large variation in emission results. As technology is improved, and more data is available, more specific emissions factors may be developed for NOx emissions from the combustion of pure hydrogen.

Natural gas displaced by hydrogen and hydrogen demand projections were provided by the Demand Study and utilized in the calculations within this study as provided. Current California BACT guidelines and emission limitations for the geographic region were utilized to develop NOx emissions estimates within this study. It is likely that emissions limitations and BACT guidelines will decrease over time, as has been seen historically. However, there are many variables that may impact future reductions in emissions limitations and to minimize uncertainty, this study did not attempt to estimate how emissions limitations will decrease or change in the future.

The heat input rating for a combustion unit is the amount of fuel the unit will burn, typically provided in Btu/hour. The energy content of different fuels in Btu/volume varies. For example, for hydrogen the energy content is roughly 134,510 Btu/kg (HHV 60920 Btu/lb), while gasoline is roughly 117,500 Btu/gallon (HHV 19948 Btu/lb), and diesel is 137,500 Btu/gallon (HHV 19604 Btu/lb). The actual heat input for a combustion unit may vary depending on the type of fuel used. This causes uncertainty to arise when estimating the impact of fuel swapping on the produced emissions from combustion. For the purposes of this study, the same heat input rating and efficiency as existing power generation equipment was assumed. It should be noted that some studies have found that hydrogen turbines can operate at higher efficiencies than natural gas turbines.

There is uncertainty in the correction factor calculation approach for converting natural gas emissions to a representative value for hydrogen. A source of uncertainty in this approach is the lack of information about how oxygen levels in the exhaust gas may vary between natural gas, hydrogen, and blends. In this study, it was assumed that a particular type of equipment combusting natural gas, hydrogen, or a blend would have the same exhaust oxygen concentration for all fuels. In-practice combustion characteristics for hydrogen turbines may result in higher or lower exhaust oxygen concentrations than what is observed in natural gas equipment. If exhaust oxygen concentration is higher for hydrogen than natural gas, emissions from hydrogen will increase compared to what is forecasted in this study. Using this study's calculation methods, an exhaust oxygen content for hydrogen of 16% versus 15% for natural gas would result in greater NOx emissions from hydrogen than natural gas.

12.0 STAKEHOLDER COMMENTS

The input and feedback from stakeholders including the PAG and CBOSG has been informative to the development of this draft NOx and other Air Emissions Assessment Study Report. Some of the feedback that has been received related to this Study is summarized below. All feedback received is included, in its original form, in the quarterly reports submitted to the CPUC and published on SoCalGas' website.[200] Topics that were not incorporated into this report due to being out of scope, examined in another study, or expected to be examined in a future phase, are also identified.

Quarter 1 to Quarter 4 2023 Reports:

- **PAG/CBOSG Feedback Themes**
    - Interest in both positive and negative health impacts tied to hydrogen. Comments regarding the potential benefits of displacing fossil fuel use with hydrogen in reducing pollution in industrial and heavily trafficked areas, especially as it relates to disadvantaged communities. Question on how study will determine geographical impacts to disadvantaged communities.
    - Comment that NOx emissions assessment will be dependent upon results from the demand study and that NOx emissions result from end use (e.g., combustion) rather than electrolytic production.
    - Questions regarding identification of sectors that combust hydrogen, expected NOx levels for Los Angeles Basin, and whether hydrogen could be entirely green and emit zero emissions.
    - Questions on whether NOx study will include end uses of hydrogen, potential NOx emissions from the pipeline infrastructure, and additional air pollutants including PM.
    - Clarification on whether NOx reduction strategies were specifically for the power sector and the expected degree of NOx reductions in the power sector if such improvements are implemented. Question on the assumption of maintaining current efficiency levels when switching from natural gas to hydrogen.
    - Comment that there is an anticipation of a reduction in NOx emissions from power generation, partly due to mandates from the South Coast AQMD to lower NOx for Clean Air Act compliance.

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200 https://www.socalgas.com/sustainability/hydrogen/angeles-link

- Inquiry on whether there are plans to investigate the difference between current emissions and permitted emissions to better understand the potential for increases in NOx emissions under existing permit constraints.
- Request for detailed background information on data sources and methodologies used to estimate NOx and other air emissions.
- Recommendation that the public health risks of projected NOx emissions should be evaluated. The existing emission levels in the communities local to the proposed Angeles Link pipeline route, to the proposed compressors, and to the proposed power generation units should be examined. Given that many communities are already disproportionally burdened by pollution, an assessment of cumulative impacts for NOx is considered important.

- **Environmental Defense Fund (EDF) and National Resources Defense Council (NRDC) Comments**
  - Recommends that emissions related to industrial, commercial, and residential combustion of hydrogen be analyzed.
  - Suggests that NOx reductions should be evaluated by end use sector. Specifically, to understand impacts to anticipated reductions associated with the mobility sector subject to new regulations as compared to sectors that do not yet have a mandate from the state of California such as the hard-to-electrify industrial sector.
    - ➔ Sections 7 and 8 of this Draft Study Report present results by end use sector for Demand Scenarios and Angeles Link Throughput Scenarios, respectively.
  - Adjustments to achieve NOx emissions with hydrogen combustion that are "no worse" than for fossil fuel combustion, including changes in after-treatment performance, should be considered.
  - Recommends a geographic depiction of the cumulative impact of NOx emissions. This should include data from environmental justice screening tools.

- **South Coast AQMD Feedback**
  - Recommends that the evaluation should include reference to the South Coast AQMD's 2022 Air Quality Management Plan, which outlines air quality goals and zero emission technology adoption rates in the South Coast AQMD. An analysis of NOx from the mobility sector should be included, as well as an air quality impact analysis for NOx emissions.

- **Utility Consumers Action Network (UCAN)**
  - UCAN recommends consideration of non-combustion pathways for production and transportation of hydrogen, as well as for end uses.

- ➔ As discussed in Section 3.2, non-combustion pathways for third-party production (including electrolyzers and biomass gasification) and transmission (electric driven compressors) have been evaluated in this Draft Study Report. Additionally, Section 3.5.2.1 discusses non-combustion options for end uses such as hydrogen fuel cells and FCEV for the mobility sector. Detailed information regarding hydrogen fuel cells is provided in Section 5.1.1.

- UCAN also requests that spreadsheets used to prepare NOx emission calculations be shared with stakeholders. UCAN is concerned that NOx reductions have been overstated.

  - ➔ Appendix C of this Draft Study Report provides the emissions calculation spreadsheets.

Preliminary Data & Findings Document (Q1 2024):

- Letters with comments regarding the NOx Study were received from Communities for a Better Environment (CBE), Food and Water Watch, Protect Playa Now, and Physicians for Social Responsibility – Los Angeles (PSR), and Air Products

  - CBE requested that details regarding NOx emissions associated with various production, storage and transmission methods and technologies be discussed. This information has been included in Section 3.6.1 of this Draft Study Report. CBE also requested that information regarding opportunities to minimize NOx emissions be included, as well as the technological feasibility of the control options being considered. This information has been provided in Section 6.2 including Table 5 of this Draft Study Report. Additionally, a request for information regarding the assumptions used to develop the emissions, as well as the spreadsheets showing the calculations, was made. The calculation spreadsheets are being provided as Appendix C to this Draft Study Report.

  - Food and Water Watch shared concerns regarding use of a uniform methodology to estimate NOx emissions that does not differentiate between end use sectors.

  - Protect Playa Now requested that more information regarding NOx control technologies be provided in the Study.

  - PSR requested more information regarding end users and anticipated displacement of fossil fuels for the power generation sector.

  - Air Products requested clarification regarding estimated NOx reductions for refineries. There was also a question regarding whether the assumed blending percentages were based on volume or energy and clarification regarding NOx impacts related to blending.

Additional Detail Regarding How Comments were Addressed:

- The NOx Study report is a feasibility study that estimates anticipated NOx emissions based on information available at this time. There are many variables that impact these estimates and those may change in the future.
  - The projected NOx emissions have been prepared using technical data, regulatory emissions requirements, and industry best management practices.
- This draft NOx report includes analysis based on both (1) the three scenarios from the Demand Study and (2) the three throughput scenarios for Angeles Link.
- This NOx Study evaluates NOx emissions associated with hydrogen combustion associated with new infrastructure, specifically third-party production, third-party storage, and transmission of hydrogen, as well as NOx emissions reductions associated with displaced fossil fuels by end users in the mobility, power generation, and hard-to-electrify industrial sectors.
  - The Study does not evaluate hydrogen combustion for commercial or residential end users.
  - The Study does not conduct an air quality impact analysis for NOx emissions.
- The Study considers non-combustion pathways for third-party production, third-party storage, and transmission of hydrogen, as well as for end uses.
- This Draft NOx Study indicates FCEV do not combust hydrogen. As such, FCEV don't have combustion emissions such as NOx or VOC or PM emissions.
- The draft NOx study report assumes that production of hydrogen will use renewable electricity with zero NOx emissions regardless of production method – electrolysis, biomass gasification, or steam methane reforming, although electricity is only assumed to be used for electrolysis.
- This Study does not evaluate the NOx associated with water conveyance or the transportation of other materials such as biomass to the production site or biomass feed preparation as those details are beyond the scope of this feasibility study.
- This study evaluated NOx associated with Steam Methane Reforming using Renewable Natural Gas as a feedstock and clean renewable hydrogen as a fuel for the heating equipment.
- This Phase 1 Study summarizes at a high level a number of local and state air quality plans and requirements including the South Coast AQMD's 2022 Air Quality Management Plan (AQMP) which outlines air quality goals and anticipated zero emission technology adoption rates in the South Coast AQMD.

- The Draft NOx Study Report provides detailed information regarding anticipated NOx reductions and how those estimates were developed for each of the end-user sectors including power generation and hard-to-electrify industrial. The Study clarifies that local air districts' and the State's obligations to meet state and federal ambient air quality standards are requiring combustion equipment to continue to meet current and future emission limits as defined by the local air districts, the California Air Resources Board, and the federal Environmental Protection Agency. For example, air permitting of new and modified equipment requires New Source Review including applicable emission limits such as Best Available Control Technology (BACT) and Best Available Retrofit Control Technology (BARCT).

- For refineries, hydrogen demand data from the following were excluded: legacy process feedstock, demand for renewable diesel (RD), and demand for sustainable aviation fuel (SAF). These sources of hydrogen for refineries were excluded from stationary combustion calculations for NOx because they were deemed either non-combustion (i.e., legacy process feedstock, which is not combusted, will not contribute to NOx) or outside of the scope of this analysis.

- The limitations regarding development of NOx emission factors for the power generation sector has been documented. Details are provided in Section 18 and Appendix A.

- In order to estimate NOx reductions at end users, assumptions regarding hydrogen adoption rates were made based on information regarding currently available equipment and technologies and their anticipated evolution over time. This includes assumptions regarding blending percentages, which are on a volume basis.

- Section 10 of this Study summarizes opportunities to mitigate and minimize NOx emissions associated with combustion. This includes emerging technologies for after-treatment performance, as well as discussion regarding SCR and NSCR.

- Section 10.3 discusses the health effects of NOx and VOC as pollutants, as well as precursors to ozone. Section 10.3 also discusses the health effects of PM and DPM.

- A public health study related to NOx emissions and a cumulative impact assessment of NOx emissions are not part of the scope of this Phase 1 feasibility study. However, given the projections for NOx reductions, the health impacts are anticipated to be benefits.

- Appendix A and Appendix B of this Draft NOx Study Report provides extensive detail regarding the development of NOx emission factors for both fossil fuel combustion and hydrogen combustion including assumptions and data used to prepare the calculations. Appendix C includes the spreadsheets used to prepare the calculations.

- Maps have been prepared that identify the projected NOx emissions reductions by zip code. Additionally, maps of Environmental Justice Communities have been prepared by census tract. The maps are included in a separate technical memorandum. Both sets of maps include preliminary pipeline routing information and will be available in the Living Library.

Parallel Angeles Link Phase 1 Study Reports may be reviewed for additional information including Demand, Production, Pipeline Sizing and Routing, and Alternatives.

Summary of Literature Provided by Stakeholders:

- Specific literature provided has been evaluated and relevant information has been incorporated, as appropriate, including, but not limited to:
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    - CARB, Innovative Clean Transit Regulation, https://ww2.arb.ca.gov/our-work/programs/innovative-clean-transit/about
    - South Coast Air Quality Management District (South Coast AQMD), 2022, 2022 Air Quality Management Plan (AQMP), https://www.aqmd.gov/home/air-quality/air-quality-management-plans/air-quality-mgt-plan

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14.0 APPENDICES

APPENDIX A NO_X CALCULATION METHODOLOGY

The purpose of this Appendix is to describe the calculation approach for determining NOx emissions associated with the adoption of hydrogen within the project region. For the displaced fossil fuel, NOx emissions were calculated by multiplying an emissions factor (i.e., quantity of pollutant emitted per unit of activity data) by activity data (e.g., fuel usage, vehicle miles traveled). This is the standard approach used to calculate combustion emissions in air permitting and was used to determine the emissions from the combustion of both hydrogen and fossil fuels. This study found that while stoichiometric and standard chemical formulaic calculations for the formation of NOx from the combustion of hydrogen may exceed that for fossil fuels, there are numerous variables that can be adjusted within the combustion technology to minimize the NOx formed from the combustion of hydrogen.

Calculation methods differ between stationary and mobile source calculations. Stationary source calculations follow the "emissions factor multiplied by the activity data" approach.

Equation 1

$$Emission\ Factor\ x\ Activity\ Data = Emissions$$

Emissions factors for the combustion of fossil fuels such as natural gas, gasoline, and diesel have been studied and developed over many years. Multiple sources of these stationary source emissions factors have been considered including those published by the US EPA in AP-42 "Compilation of Air Emissions Factors from Stationary Sources"[201] and those published by South Coast AQMD and other air management districts in their rules as equipment specific emission limits. This study sought similarly established emissions factors for the combustion of hydrogen by stationary sources. In addition to emissions factors for hydrogen combustion, scientific studies, manufacturer's test data, and manufacturer's NOx emissions guarantees for the combustion of hydrogen fuels were evaluated.

In the mobility sector for the purpose of this study, it was assumed that hydrogen demand as projected by the Demand Study will be utilized in fuel cells. Fuel cells only emit water vapor and heat, therefore, emissions associated with the use of hydrogen as projected by the Demand Study in the mobility sector are zero. Therefore, to calculate NOx emission reductions from mobility, the

[201] EPA, AP-42 Compilation of Air Emissions Factors from Stationary Sources, https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors-stationary-sources

equation was the volume of fossil fuel displaced times the NOx emissions factor for that specific equipment type combusting that specific fossil fuel.

Equation 2

$$Displaced\ Fossil\ Fuel\ (gal)\ x\ Emissions\ Factor\ \left(\frac{ton}{gal}\right) = Emission\ Reduction\ (ton)$$

Developing emissions factors from mobile sources was different than stationary sources because mobile sources must account for multiple modes of operation and can require multiple emissions factors to represent these various modes of operation and speeds at which a vehicle is operated. This study sought emissions factors for fossil fuel combustion to establish emissions reductions from displaced fossil fuel combustion.

Activity Data

Various activity data was required for the emission calculations within this study. At a high level, those data needs included emissions factors representative of fossil fuel combustion, emissions factors representative of hydrogen combustion, hydrogen consumption data for each end-use sector and sub-sector within the geographic region from 2030 to 2045, and fossil fuel volumes displaced by hydrogen for each end-use and sub-sector within the geographic region from 2030 to 2045.

For the purposes of this study, end-user calculations were completed on a sector or sub-sector level, while emissions factors are generally provided on an equipment level. Therefore, data was needed to determine what equipment was in each sector or sub-sector and the proportion of fuel utilized by each equipment type within the sector or sub-sector.

For infrastructure emissions estimates, data on typical operations within the sectors being evaluated was required to establish representative hypothetical scenarios. The volume of hydrogen needing to be produced, stored, and transmitted was also a data need.

Data Sources

An internally consistent data set representative of the study geography and time frame was sought for development of emissions factors and data regarding the breakout of equipment types and categories, and the breakout of fuel consumption for these equipment categories within each end-use sector so that hydrogen demand and fossil fuel displacement data from the Demand Study could be appropriately applied to the emissions calculations for end-users. The goal when selecting data sources was to minimize the number of different sources referenced so as to minimize complexity and assumptions. Many different sources were initially reviewed, including state and local implementation plans and air quality management plans, which referenced the CARB Standard Emission Tool (CEPAM2019v1.03) as a consistent source for their data. The CARB Standard Emission Tool (CEPAM2019v1.03) was determined to be a representative source of emissions data that that could be used to estimate NOx emissions and understand equipment categories and the magnitude of fuel throughput within each equipment category.

The CARB Standard Emission Tool (CEPAM2019v1.03) provides the emissions for criteria air pollutants (including NOx) for stationary and mobile sources. Data from the CARB Standard Emission Tool (CEPAM2019v1.03) can be exported at the state-, air basin-, or county-level and includes aggregated emissions for various sources and fuel/material types. Stationary combustion emissions are provided for a variety of industry sectors including electric utilities, cogeneration, petroleum refining, food and agriculture processing, and manufacturing and industrial. Mobile emissions are provided for many on- and off-road vehicle categories. The CARB Standard Emission Tool (CEPAM2019v1.03) baseline year is 2017 and data is given at five-year increments starting at 2020 through 2050.

The CARB Standard Emission Tool (CEPAM2019v1.03) provides NOx and other air pollutant emissions estimates for mobile sources; however, it does not include the emissions factors utilized to develop those estimates, nor does it include the volumes of fuel consumed by those vehicles. The CARB Standard Emission Tool (CEPAM2019v1.03) provides background information on their methodologies used. Background methodologies for mobile sources were reviewed and it was determined that the mobile source data in the CARB Standard Emission Tool (CEPAM2019v1.03) was obtained from the CARB EMFAC model, the most recent version being EMFAC2021 (v1.0.2). The CARB EMFAC model provides activity data and emissions factors for on-road and off-road mobile sources. The EMFAC model provides population counts, vehicle miles traveled, fuel consumption, and emissions factors and data for most on-road and off-road mobile vehicle categories (which can be rolled up into the designated sub-sectors) within the scope of this study. The model contains sufficient data to estimate NOx mobile emissions. Data from the EMFAC model was also used to estimate mobile source hydrogen demand and fossil fuel volumes displaced by hydrogen in the Demand Study. As a result, EMFAC is a singular source of calculation data for mobile combustion that is consistent across the scopes of this study and parallel Demand Study.

The Demand Study was a source of activity data for all end-user sectors. The Demand Study provided projected hydrogen consumption demand data and associated volumes of displaced fossil fuel consumption. The results of the Demand Study were provided annually across three different scenarios of hydrogen fuel adoption (Conservative, Moderate, and Ambitious). Emissions reductions from hydrogen demand projected by the Demand Study were evaluated from 2030 to 2045.

Local air district rules provide NOx emissions limitations (source-specific standards or not-to-exceed prohibitions) for various fuels and equipment types. These emissions limits, in conjunction with BACT and LAER requirements, provide wide coverage on the upper limit of emissions for the variety of equipment and fuel types. This emissions limitation information can be used to estimate the overall emissions for a particular industry based on its equipment and fuel consumption.

Development of Emission Factors

In the absence of published NOx emissions factors for hydrogen combustion, this study utilized the following approach to develop hydrogen emissions factors based on studies that evaluated volumetric variation of NOx emissions between hydrogen fuel and methane fuel.

NOx emissions are measured from combustion stacks as a volumetric value in parts per million by dry volume (ppmvd). Due to differences in the exhaust properties of methane and hydrogen, for an identical mass emission rate of NOx, measured NOx ppmvd values from pure hydrogen combustion are 37% greater than natural gas. This is because hydrogen exhaust has a higher water content which results in a more concentrated NOx ppmvd value when a sample is dehydrated before measurement and then corrected to standard oxygen conditions before reporting.[202] Therefore, volume-based emissions estimates of NOx are not directly comparable between these fuel types. Some studies and manufacturer data report NOx emissions on a volume basis without converting to a mass basis. In these cases, NOx emissions may inaccurately appear to increase between hydrogen and methane/fossil fuels even if they are not increasing on a mass basis. Some permits and regulations provide a volumetric basis for NOx emission limitations in parts per million by volume (ppmv) at fifteen percent oxygen (O_2) for internal combustion units and three percent O_2 for external combustion units.

Volumetric emissions values can be converted to a mass basis (lb/mmbtu, lb/hr, or ton/yr) using a fuel-dependent proportionality value. These proportionality values are typically referred to as a "fuel factor" or an "F-factor." F-factors do not vary much between fossil fuels but do vary much between fossil fuels and hydrogen. It is imperative to use accurate F-factors, and it has been noted in scientific literature that some studies do not properly utilize F-factors for these conversions. This can skew results resulting in an apparent increase in NOx emissions when combusting hydrogen fuels when an increase in mass-basis NOx emissions is not occurring.[203] This study utilized the method for calculating F-factors outlined in a textbook authored by Jahnke (1993),[204] which follows the same process as the US EPA's Method 19. This method was used to calculate F-factors for pure hydrogen and blended hydrogen-methane fuels. Table 19-2 "F-Factors for Various Fuels" from US EPA's Method 19 – Determination of Sulfur Dioxide Removal Efficiency and Particulate Matter, Sulfur Dioxide, and Nitrogen Oxide Emission Rates provides F-factors for commonly used fuels, including natural gas. This table lists 8,710 dscf/mmbtu as the EPA published F-factor for natural gas. This value was used in the calculations for this study. The US EPA has not published an approved F-factor for hydrogen fuel, so the F-factors calculated using the described method were utilized.

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[202] Douglas, C., B. Emerson, T. Lieuwen, T. Martz, R. Steele, B. Noble, 2022, NOx Emissions from Hydrogen-Methane Fuel Blends, Georgia Tech Strategic Energy Institute short paper, https://research.gatech.edu/sites/default/files/inline-files/gt_epri_nox_emission_h2_short_paper.pdf

[203] Douglas, C., et al, 2022, NOx Emissions from Hydrogen-Methane Fuel Blends, Ibid

[204] Jahnke, J.A., 1993, Continuous Emissions Monitoring, John Wiley & Sons

Equation A-5[205] below was utilized to calculate the F_d factor, oxygen based, dry factor. The percentage mass of each constituent within the fuel blend was multiplied by the appropriate factor as provided in the equation, summed, and divided by the GCV (HHV) value for the fuel blend in units of btu/lb. The calculated F_d is for the stoichiometric scenario. Values are then corrected to the appropriate oxygen level for the reporting basis (3% or 15% based on the equipment type).

Equation 3

$$F_d = \frac{10^6[3.64(\%H) + 1.53(\%C) + 0.57(\%S) + 0.14(\%N) - 0.46(\%O)]}{GCV} \quad \text{English units} \quad \text{(A-5)}$$

Note: Units for the conversion factors in the expressions are 10^{-5} kJ/J and 10^6 Btu/million Btu for GCV expressed in kilojoules per kilogram and in Btu per pound, respectively. The constants in the expressions are given in units of standard cubic meters per kilogram (e.g., 22.7 scm/kg) and standard cubic feet per pound (e.g., 3.64 scf/lb).

The equation below depicts the calculation of the F-factor for pure hydrogen @ 68F. Per Equation A-5 above, "Specific Weighted H2" = 364.0 scf/lb = 3.64 * 100 = 3.64 * (%H_2).

Equation 4

Fd (H2 @ 68 F) (scf/MMBtu) =	**Specific Weight H2**	**scf/lb**	**x**	**Conv (Btu-MMBtu)**	**Btu/MMBtu**	**÷**	**HHV-lb H2**	**Btu/lb**
Fd (H2 @ 68 F) (scf/MMBtu) =	364	scf/lb	x	1,000,000	Btu/MMBtu	÷	60,920	Btu/lb = 5975.05 (scf/MMBtu)

Volumetric (ppmvd) correction factors were utilized to convert emissions factors for pure natural gas to applicable factors for blended fuels and pure hydrogen. These correction factors account for differences in the exhaust properties of methane and hydrogen which, for an identical mass emission rate (lb/MMBtu), will have measured ppmvd (corrected to 15% O_2) values that are roughly 37% greater for hydrogen than natural gas. This is because, holding all combustion conditions the same, hydrogen exhaust has a higher water and oxygen content than natural gas. Stack gas samples (ppmvd) are dehydrated before measurement and then corrected to standard oxygen conditions before reporting. This process differentially skews measured ppmvd values between natural gas and hydrogen. This results in more concentrated ppmvd values from hydrogen exhaust for the same mass of NOx. These correction factors vary in magnitude across a spectrum of fuels from pure natural gas to pure hydrogen and were applied to pure natural gas emissions factors to develop representative blended or pure hydrogen emissions factors. These correction factors can also be applied in reverse to develop representative blended or pure natural

205 Jahnke, J.A., 1993, Ibid

gas emissions factors from pure hydrogen emissions factors. A plot of the correction factor over a range of hydrogen-natural gas fuel blends is depicted below, as well as this data in tabular form. Note that the data below depicts results from this publication at 1 bar of pressure, reactant temperature of 300K, and adiabatic flame temperature of 2000K. The publication also includes results, which are very similar (and not included below or used in this study), for 2 bar of pressure, reactant temperature of 700K, and adiabatic flame temperature of 2000K. [206] It was assumed that the correction factor from Douglas et al. was representative of all equipment types and fuel blends in this study where it was applied.

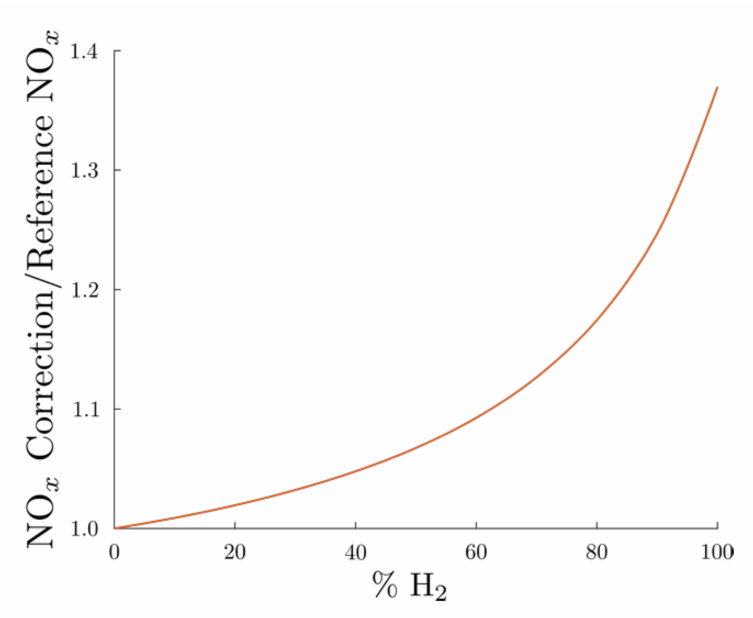

Figure A-1 Correction Factor Plot Over a Range of Hydrogen-natural Gas Fuel Blends[207]

Table A-1 Tabular Correction Factor Values of Hydrogen-Natural Gas Fuel Blends[208]

[206] Douglas, C., et al, 2022, NOx Emissions from Hydrogen-Methane Fuel Blends, Ibid
[207] Douglas, C., et al, 2022, NOx Emissions from Hydrogen-Methane Fuel Blends, Ibid
[208] Douglas, C., et al, 2022, NOx Emissions from Hydrogen-Methane Fuel Blends, Ibid

1 bar, 300 K reactants, Tad = 2000 K

Fuel % H_2	Fuel % CH_4	Prod. %CO_2	Prod. %H_2O	Prod. %O_2	NO_x corr.	Ratio
0	100	7.69	15.38	3.70	0.4264	1.000
20	80	7.15	16.07	3.82	0.4347	1.019
40	60	6.39	17.03	4.00	0.4468	1.048
60	40	5.27	18.45	4.25	0.4659	1.092
80	20	3.46	20.74	4.66	0.5008	1.174
100	0	0.00	25.13	5.45	0.5840	1.370

Representative NOx mass emissions factors for hydrogen and hydrogen-natural gas blends were calculated from NOx mass emission limits and BACT requirements from local regulations. Where emissions limits were given in lb/MMbtu rather than ppmvd, the following equation was used to convert to lb/MMbtu to ppmvd. It should be noted that values of scf in this equation correspond to exhaust volume.

Equation 5

$$\text{NOx NG EF Conc (ppm)} = \text{NG NOx EF}\ \frac{\text{lb}}{\text{MMBtu}} \div \text{MW (NO2)}\ \frac{\text{lb}}{\text{pmole}} \times \text{Molar Volume @ 68 F}\ \frac{\text{scf}}{\text{pmole}} \div \text{O2 Correction}\ \frac{\text{scf}}{\text{scf}} \div \text{Fd NG}\ \frac{\text{scf}}{\text{MMBtu}} \times \text{Conv (Conc-ppm)}\ \frac{\text{scf-ppm}}{\text{scf}}$$

To convert to a representative emissions factor, ppmvd emissions factors were then multiplied by the appropriate correction factor for the given hydrogen percentage of the fuel, ranging from 0 for 0% hydrogen in the fuel, to 1.37 for 100% hydrogen in the fuel (see table above). Once multiplied by the correction factor, the ppmvd emissions factor was representative of ppmvd emissions from hydrogen combustion. Corrected ppmvd values could then be converted back to a mass basis as demonstrated in the equation below. It should be noted that values of scf in this equation correspond to exhaust volume.

Equation 6

$$\text{Blend NOx EF (lb NOx/MMBtu)} = \text{NOx NG EF Conc}\ \text{ppm} \times \text{Correction Blend-H2 Ratio}\ \frac{\text{ppm}}{\text{ppm}} \div \text{Conv (Conc-ppm)}\ \frac{\text{scf-ppm}}{\text{scf}} \div \text{Volume @ 68 F}\ \frac{\text{scf}}{\text{pmole}} \times \text{MW (NO2)}\ \frac{\text{lb}}{\text{pmole}} \times \text{Fd Blend}\ \frac{\text{scf}}{\text{MMBtu}} \times \text{O2 Correction}\ \frac{\text{scf}}{\text{scf}}$$

The figure below demonstrates the overall impact of the correction factor approach (as depicted in the two equations above) on a mass basis emissions factor of 1 as the percentage of hydrogen in fuel increases. As the percentage of hydrogen in the fuel blend increases, the correction factor increases. However, this conversion is also driven by the ratio of the F-factor in the 1st equation to the F-factor in the 2nd equation which decreases as the percentage of hydrogen in a fuel increases. As a result, when a natural gas lb/MMBtu emissions factor is converted to a representative pure hydrogen emissions factor (by converting the natural gas lb/MMBtu value to a volumetric value [ppmvd] using the F-factor for natural gas of 8,710 dscf/MMBtu, then multiplying by the correction factor to determine the representative hydrogen volumetric value [ppmvd], and then converting from the hydrogen volumetric value [ppmvd] to a hydrogen lb/MMBtu value by using the calculated F-factor for hydrogen of 5,975 dscf/MMBtu, as outlined above), the resultant pure hydrogen emissions factor is approximately 6% smaller. It should be noted that the “choppy” slope of this function is due to the “piecewise” nature of the tabular correct factor data used to develop this function.

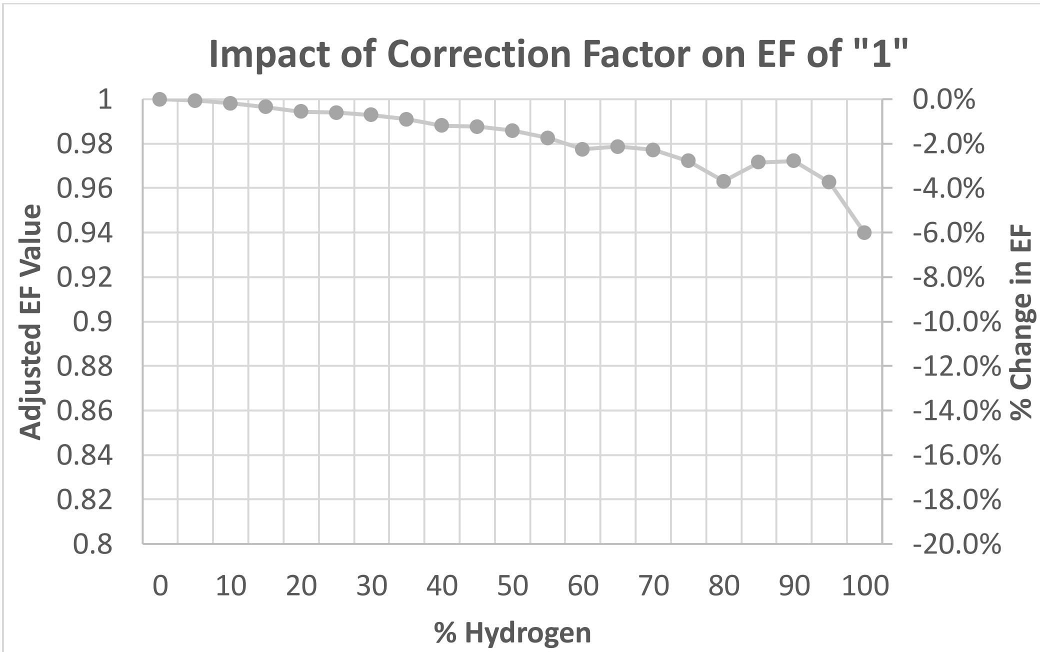

Figure A-2 Impact of Correction Factor on Emission Factor of "1"

The reduction in lb/MMBtu factors between natural gas and pure/blended hydrogen fuels in this calculation approach is primarily attributable to the differences in the natural gas and hydrogen F-factors. The F-factor for pure and blended hydrogen fuels are always less than the F-factor for natural gas. When the ratio of the pure/blended hydrogen F-factor to the natural gas F-factor is multiplied by the correction factor the result is less than 1. This ratio ranges from 0.94 – 1 depending on the percentage of hydrogen in the fuel, with 1 and 0.94 corresponding to 0% hydrogen and 100% hydrogen in the fuel, respectively. Therefore, the mass basis (lb/MMBtu) emissions factor for pure hydrogen combustion is calculated as 6% less than the mass basis emissions factor for pure natural gas.

These calculations were performed using the simplifying assumption that combustion conditions for hydrogen and natural gas are the same. There is particular uncertainty about exhaust oxygen concentration for hydrogen combustion systems. In this study it was assumed that exhaust oxygen concentration would be the same for hydrogen and natural gas. In practice, however it is possible that hydrogen combustion equipment may operate more optimally at different exhaust oxygen concentrations than natural gas equipment.

It is worth noting that roughly three times the volume of hydrogen is required to generate the same power output or heat (energy) output as natural gas. Hydrogen has a heating value of roughly 120-142 MJ/kg. Methane has a heating value of roughly 50-55 MJ/kg. For evaluation on a mass basis, this can be converted to kWh to indicate that 1 kg of hydrogen can produce about 33-39 kWh of energy, and 1 kg of methane can produce about 14-15.3 kWh of energy. This conversion does not account for thermal efficiencies. Accounting for turbine thermal efficiency and evaluating on a volumetric basis, the HHV of hydrogen is 325 Btu/scf and the HHV of natural gas is 1,020 Btu/scf, and the conversion for turbine thermal efficiency is 35 Btu/100-Btu per the EPA. This yields a range of 28 scf/kW-hr to 34 scf/KW-hr for hydrogen, and a range of 8 scf/kW-hr to 10 scf/kW-hr for methane (may be slightly lower for natural gas). As hydrogen is less dense and much lighter than methane or natural gas, pressure of the fuel supply or volumetric flow of hydrogen must be increased as compared to natural gas. The manufacturer GE notes that a fuel accessory system configured for necessary flow rates is required when operating a gas turbine on pure hydrogen fuel.

In this study, it was assumed that the combustion conditions would be the same for power generation equipment (and combustion equipment more broadly) combusting either hydrogen or natural gas. Given this assumption, the efficiency of hydrogen and natural gas equipment were assumed to be the same. As a result, the modeling approach of this study estimates that the NOx emissions per kWh from 100% hydrogen combustion will be 6% less than 100% natural gas. Using these assumptions, an example calculation of the possible range of lb NOx/kWh emissions for natural gas and hydrogen turbines can be determined. An average NOx emissions factor for turbines of 2.25 ppmvd (South Coast Air Quality Management District, Rule 1135)[209] will yield natural gas and hydrogen emissions factors of 0.00829 lb NOx/MMBtu and 0.00779 lb NOx/MMBtu respectively. Using a typical range of efficiencies for simple cycle turbines of 20% to 35%,[210] natural gas and hydrogen turbines would have emissions between 0.081 and 0.141 lb NOx/MW-hr and 0.076 and 0.133 lb NOx/MW-hr respectively. This comparison was developed using the same efficiencies for hydrogen turbines and natural gas turbines, however in practice some studies have indicated that hydrogen turbines are more efficient than natural gas turbines.[211] [212] For example, the DOE indicates that in the future hydrogen and syngas combined cycle plants are likely to achieve efficiencies of 60% or more.[213] Another consideration is that these equations apply concentration of NOx on a dry basis. With hydrogen exhaust typically

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[209] South Coast AQMD, 2022d, RULE 1135. Emissions of Oxides of Nitrogen from Electricity Generating Facilities, https://www.aqmd.gov/docs/default-source/rule-book/reg-xi/rule-1135.pdf

[210] US DOE, 2024, How Gas Turbine Power Plants Work, US DOE webpage, https://www.energy.gov/fecm/how-gas-turbine-power-plants-work#:~:text=A%20simple%20cycle%20gas%20turbine,of%2060%20percent%20or%20more

[211] Douglas, C.M. et al., 2022, Pollutant Emissions Reporting, Ibid

[212] Pyo, M., S. Moon, and T. Kim, 2021, A Comparative Feasibility Study of the Use of Hydrogen Produced from Surplus Wind Power for a Gas Turbine Combined Cycle Power Plant, Energies 14(24): 8342, https://doi.org/10.3390/en14248342

[213] US DOE, 2024, Ibid.

wetter than natural gas exhaust, once the water is removed, the concentration of NOx on a dry basis is expected to be lower for hydrogen than for natural gas. The table below summarizes the calculation methodology based on EPA Method 19 and results for power generation comparing NOx per MW-hr for natural gas combustion and hydrogen combustion.

Table A-2 Power Generation NOx per MW-hr Calculations							
NG Factor (lb NOx/MMBtu)							
Emission Factor		**Conv**	**MW NO2**	**Molar Volume @ 68F**	**O2 Percent**	**F-Factor**	**Emission Factor**
(ppmvd)		**(scf-ppm/ppm)**	**(lb/mole)**	**(scf/mole)**		**(scf/MMBtu)**	**lb/MMBtu**
2.25		1,000,000	46	385.22	0.15	8,710	0.00829
H2 Factor (lb NOx/MMBtu)							
Emission Factor	**Correction Factor**	**Conv**	**MW NO2**	**Molar Volume @ 68F**	**O2 Percent**	**F-Factor**	**Emission Factor**
(ppmvd)		**(scf-ppm/ppm)**	**(lb/mole)**	**(scf/mole)**		**(scf/MMBtu)**	**lb/MMBtu**
2.25	1.37	1,000,000	46	385.22	0.15	5,975	0.007791
NG Factor (lb NOx/MW-hr)							
Emission Factor	**Conversion**	**Efficiency 1**					**Emission Factor**
(lb/MMBtu)	**(MMBtu/KW-hr)**						**lb/MW-hr**
0.0082898	0.00341214	0.2					0.141
H2 Factor (lb NOx/MW-hr)							
Emission Factor	**Conversion**	**Efficiency 1**					**Emission Factor**
(lb/MMBtu)	**(MMBtu/KW-hr)**						**lb/MW-hr**
0.00779084	0.00341214	0.2					0.133
NG Factor (lb NOx/MW-hr)							
Emission Factor	**Conv**	**Efficiency 2**					**Emission Factor**
(lb/MMBtu)	**(MMBtu/KW-hr)**						**lb/MW-hr**
0.0082898	0.00341214	0.35					0.081

H2 Factor (lb NOx/MW-hr)				
Emission Factor	**Conversion**	**Efficiency 2**		**Emission Factor**
(lb/MMBtu)	**(MMBtu/KW-hr)**			**lb/MW-hr**
0.00779084	0.00341214	0.35		0.076

Fossil fuel and hydrogen fuel consumption activity data from the Demand Study was used to determine emissions reductions from displaced fossil fuels associated with the adoption of hydrogen as a fuel source. Activity data from the Demand Study was provided for sub-sectors of the Hard to Electrify Industrial sector and Power Generation sector, for which general NOx emissions factors were not available. NOx emissions factors for these industry sectors were not available because NOx emissions factors are typically developed at an equipment-level. Equipment-specific emissions factors compiled from the air districts (regulatory emission limits and BACT requirements) and inventory data from the CARB Standard Emission Tool (CEPAM2019v1.03), both within the geographic-scope of this project, were used to develop calculations for the industry and Power Generation sectors with data from the Demand Studies.

A review of regulatory information was performed, and four equipment categories were identified for which distinct emissions factors and BACT limitations were available that could be applied to the combustion information provided in the CARB inventories. These equipment-specific emissions factors were used to estimate the energy throughput for each equipment category using the NOx emissions reported in the CARB inventories. From this information, weighted emissions factors were developed at an industry sector-level or equipment-level based on overall energy throughput to a particular category of equipment. Similarly, this throughput data developed from the CARB inventories was used to determine the fraction of energy consumption in a particular industry sector being used by a particular equipment category. While the emissions factors from air district regulations and BACT only apply to fossil fuels, the correction factor approach outlined above was used to convert them to an equivalent factor for pure or blended-hydrogen fuels.

For the purposes of this study, it is assumed that emission sources within the Mobility sector will utilize hydrogen in hydrogen fuel cells. Hydrogen fuel cells are categorized by CARB as “zero emission vehicles” and only emit water vapor and heat. Therefore, the anticipated NOx and other air pollutant emissions factors for hydrogen fuel cells were zero. For the mobility sector, emissions factors for the combustion of fossil fuels utilized to calculate reductions were developed based on emissions and fuel consumption data from the CARB EMFAC model.

APPENDIX B MODELING AND DIRECT MEASUREMENT STUDY RESULTS FROM LITERATURE

Modeling Studies

In the modeling studies that were reviewed, various models, variable inputs, and boundary conditions are used to account for the unique properties of hydrogen and minimization of air pollutant emissions. One such study evaluating a micro gas turbine, conducted by Meziane and Bentebbiche (2019)[214], utilized computational fluid dynamic numerical simulations for various hydrogen fuel blends with experimental results of NOx emissions used as the boundary conditions for their model. This study notes that thorough and sufficient pre-mixing of the air and fuel is important for minimizing NO_x formation. The researchers evaluated the impact of blended hydrogen fuels on combustion performance, while considering pollutant emissions. They found that both carbon monoxide (CO) and nitric oxide (NO) decreased as the percentage of hydrogen in the fuel increased when they modeled a constant injection velocity for the blended fuel. A 14% decrease in NO emissions was seen with only 10% hydrogen in the fuel gas.

Another modeling study by Breer et. al.,[215] evaluated how fuel composition affects the production pathway for NOx formation. This study used the PREMIX package in ANSYS Chemkin[216] and the HyChem (Hybrid Chemistry) kinetic mechanism.[217] ANSYS Chemkin is a chemical kinetics simulation tool. HyChem is a combustion chemistry model for real liquid fuels that utilizes the physics of large hydrocarbon combustion at high temperatures[218] which utilizes two sub models to express the fuel pyrolysis and pyrolysis products oxidation.[219] They also evaluated results with GRI 3.0, Glarborg, and University of California San Diego (UCSD) mechanisms for comparison.

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[214] Meziane, S. and A. Bentebbiche, 2019, Numerical study of blended fuel natural gas-hydrogen combustion in rich/quench/lean combustor of a micro gas turbine, International Journal of Hydrogen Energy 44(29): 15610-15621, https://doi.org/10.1016/j.ijhydene.2019.04.128

[215] Breer. B., H. Rajagopalan, C. Godbold, H. Johnson II, B. Emerson, V. Acharya, W. Sun, D. Noble, T. Lieuwen, 2023, Numerical investigation of NOx production from premixed hydrogen/methane fuel blends, Combustion and Flame, Combustion and Flame 255: 112920, https://doi.org/10.1016/j.combustflame.2023.112920

[216] Ansys, 2023, Chemkin-Pro Chemistry Simulation Software, https://www.ansys.com/products/fluids/ansys-chemkin-pro

[217] Jiang, H., W. Shen, S. Bai, D. Chen, C. Wang, X. Liang, K. Wang, 2023, Revised HyChem modeling combustion chemistry of air-breathing high-energy density jet fuel: JP-10, Combustion and Flame 248: February, 112578, https://doi.org/10.1016/j.combustflame.2022.112578

[218] Wang, Hai, 2023a, HyChem – Combustion Reaction Models of Liquid Fuels - Home, Stanford Department of Mechanical Engineering web page, https://web.stanford.edu/group/haiwanglab/HyChem/

[219] Wang, Hai, 2023b, HyChem – Combustion Reaction Models of Liquid Fuels - Approach, Stanford Department of Mechanical Engineering web page, https://web.stanford.edu/group/haiwanglab/HyChem/

The study notes that some mechanisms such as GRI 3.0[220] have not been validated for pure hydrogen combustion. GRI 3.0 is a mechanism for modeling natural gas combustion, including 325 reactions and 53 species. The UCSD San Diego Mechanism is used for modeling combustion applications as a chemical-kinetic mechanism with 57 species in 268 reactions.[221]

The Breer study evaluated how hydrogen/methane fuel compositions impact the flame NO and the post-flame NO. Post-flame NO was defined as "the difference between actual NO levels and flame NO." Flame NO is generated primarily via the Fenimore mechanism, also referred to as prompt NO_x, demonstrated in the equations below.

$$CH + N_2 \leftrightarrow HCN + N$$

$$C + N_2 \leftrightarrow CN + N$$

The formation via this mechanism depends on the HCN conversion to NO. The amount of carbon available to form HCN decreases as the percentage of hydrogen in the fuel increases, which ultimately decreases the production of flame NO via this mechanism. The equations below demonstrate the pathway for conversion of HCN to NO.

$$HCN + O \leftrightarrow NCO + H$$

$$NCO + H \leftrightarrow NH + CO$$

$$NH + H \leftrightarrow N + H_2$$

$$N + OH \leftrightarrow NO + H$$

The study found that flame NO formation showed a large decrease as the percentage of hydrogen in the fuel increased. Post-flame (residence time of 10 ms) NO emission levels from pure hydrogen combustion decreased as compared to pure methane combustion for a fixed power condition and adiabatic flame temperature. However, for longer residence times, there is a weaker sensitivity to hydrogen addition than seen for flame NO, finding that post-flame NO production rates increase slightly with the increase of the percentage of hydrogen in the fuel at most conditions. The study found that quantity of post-flame NO emissions from hydrogen-methane blend combustion exceeds that of pure methane combustion at residence times roughly greater

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[220] Smith, G.P., D.M. Golden, M. Frenklach, N.W. Moriarty, B. Eiteneer, M. Goldenberg, C.T. Bowman, R.K. Hanson, S. Song, W.C. Gardiner, Jr., V.V. Lissianski, and Zhiwei Quin, 2023, GRI-Mech 3.0 webpage, http://www.me.berkeley.edu/gri_mech/

[221] UCSD, 2023, Chemical-Kinetic Mechanisms for Combustion Applications, University of California at San Diego Mechanical and Aerospace Engineering (Combustion Research), San Diego Mechanism web page, https://web.eng.ucsd.edu/mae/groups/combustion/mechanism.html

than 25 ms. Residence times greater than 25 ms exceed what is practical for gas turbine engine applications.

Table B-1 Findings from Modeling Studies		
Key Findings	**Year of Publication**	**Authors**
Sufficient pre-mixing is needed for minimizing NOx formation in micro turbines. NO decreased as the percentage of hydrogen in the fuel increased at constant injection velocity. 14% decrease in NO at 10% hydrogen in fuel gas.	2019	Meziane and Bentebbiche
Flame NO emission levels decreased as the percentage of hydrogen in the fuel increased. An increase in hydrogen in the fuel demonstrated a decrease in post-flame (residence time of 10 ms) NO emission levels as compared to pure methane. However, post-flame NO production rates increased slightly as the percentage of hydrogen increased in the fuel at most conditions. Hydrogen-methane fuel blends produce more NO than pure methane at residence times greater than 25 ms, which is impractical for gas turbine applications.	2023	Breer et al.

Direct Measurement Studies

Direct measurement studies addressing NO_x formation from the combustion of hydrogen have typically been performed on equipment that was originally designed to combust natural gas or other fossil fuels rather than being designed for the unique combustive properties of hydrogen. Such studies have evaluated the change in emissions as the percentage of hydrogen in the fuel was increased and no modifications were made to the equipment. One such study from the Combustion Laboratory at the University of California Irvine measured emissions from nine prototype and commercial burners that were not specifically designed to combust hydrogen, while operating on biogas (CO_2/methane), hydrogen-enriched natural gas, and natural gas with higher hydrocarbons.[222] The nine burners included; low-swirl burner (LSB), surface-stabilized combustion burner (SSCB), micro-turbine combustor Capstone C65 (MTC), oxygas burner, high speed jet burner (HSJ), turbine combustor GT333 FlexEnergy (GTC), radiant tube (RT), infrared

[222] Colorado, Andres; McDonell, Vincent. (University of California Irvine, Combustion Laboratory UCICL), 2016, Ibid.

burner (IRB), and slot burner (SB). The study ultimately found that NOx production by various combustion technologies with typical combustion and fuel composition variables was inconsistent. Six of the burners tested showed an increase in NO_x formation as the percentage of hydrogen in the fuel increased. These burners included LSB, MTC, Oxygas, HSJ, RT, and SB. The exhaust gas recirculation was not as effective in reducing temperature in these five units due to their common aerodynamic stabilization strategy where the mixing speed did not keep up with the chemistry due to the high reactivity of hydrogen. For the units where NO_x emissions were decreased with the increase of the percentage of hydrogen in the fuel, enhanced radiative heat losses from the reaction due to increased surface area and high emissivity materials were noted as the cause for the reductions. The units where NO_x emissions were decreased as the hydrogen in the fuel increased included SSCB and IRB. The variations in the combustion and burner technology appeared to be an important driver in the variation of NO_x formation among the hydrogen-enriched natural gas fuels.

A study released in September 2023 by Giacomazzi et. al., found that with methane/hydrogen fuel blends, NO_x ppm emissions (mass normalized to account for the different exhaust compositions) decreased as the mole fraction of hydrogen in the fuel increased. The strategy within this study involved decreasing the fuel to air ratio as the mole fraction of hydrogen increased. This effectively reduced combustion temperatures, thereby reducing NO_x formed via the thermal pathway. The combustion of hydrogen and air can be stable at lower fuel to air ratios than natural gas. The study notes that, "There is no fundamental chemical kinetic reason why hydrogen flames should produce more NO_x than natural gas flames." [223]

Real world examples of co-firing existing gas turbines at operating facilities with hydrogen were evaluated. The largest of these tests occurred at the Georgia Power McDonough-Atkinson Plant on their M401G gas turbine (facility unit ID GT 6B) with dry-low NOx (DLN) technology. The Electric Power Research Institute (EPRI) and Mitsubishi worked with Georgia Power on this study. At a hydrogen blend of 20% by volume in the fuel, the NOx level by volume stayed relatively constant with the NOx level by volume from combustion of pure natural gas in this unit at around 15 ppm (15% O_2). They found that power output turndown improved by about 10%, combustion efficiency improved, and CO emissions decreased.[224] Another test of co-firing hydrogen with natural gas at an operating facility was completed at the New York Power Authority's Brentwood site on their GE LM6000 Gas Turbine in association with GE and EPRI. This system does not rely on lean premixed operation for low NOx emissions. Instead, it uses water injection to reduce combustion temperatures produced by non-premixed "diffusion" flames, combined with exhaust gas scrubbing. Hydrogen at 5-44% by volume were used in this unit. They observed during the study that NOx mass emissions increased by 24% as the percentage of hydrogen in the fuel

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[223] Giacomazzi, E., G. Troiani, A. Di Nardo, G. Calchetti, D. Cecere, G. Messina, S. Carpenella,2023, Hydrogen Combustion: Features and Barriers to its Exploitation in the Energy Transition, Energies 16(20): 7174, https://doi.org/10.3390/en16207174

[224] Mitsubishi Power, 2023, Combustion of Hydrogen Blends in Mitsubishi Gas Turbines, Presentation, California Energy Commission Potential Growth of Hydrogen Workshop, September 8

increased. The report noted that compliance with permitted limits could still be maintained by increasing water injection, a form of thermal dilution, or adjusting the aftertreatment of the unit.[225] A third example of co-firing hydrogen was performed at the A.J. Mihm Power Plant in Michigan in October 2022. The plant tested one of their Wartsila 50SG 18.9 MW reciprocating engines by co-firing up to 25% hydrogen by volume. They found that they were able to maintain compliance with their existing NOx emission limits. The first three examples include hydrogen co-firing on existing natural gas combustion units. A fourth example from Daesan Korea in July 2023, tested a retrofitted GE 7E gas turbine at a 60% hydrogen blended fuel using PSM's FlameSheet Combustor Platform with a blending system providing fuel delivery. The test was completed by PSM, Thomassen Energy, and Hanwha Power Systems.[226] They found that the unit emitted single-digit emissions of NOx in ppmv at dry, baseload conditions.[227]

A direct measurement study completed by the Chevron Energy Technology Company in 2011 tested potential issues with switching refinery process heaters to hydrogen from natural gas. They tested an ultra-low NOx round flame burner and a low NOx flat flame burner on hydrogen fuel blends up to 100% at three firing rates: maximum design rate, normal rate, and minimum rate. The burners were capable of operating up to 95% hydrogen blend with no equipment modifications. They found that NOx emissions increased from 11 ppm (corrected to 3% O_2) for natural gas combustion to 13.5 ppm for hydrogen combustion for the ultra-low NOx round flame burner at 95% hydrogen, a 22.73% increase. NOx emissions increased from 42 ppm for natural gas combustion to 64 ppm for hydrogen combustion for the low NOx flat frame burner, a 52.4% increase. It is noteworthy that for the same mass emissions of NOx, NOx ppmv values from hydrogen combustion are roughly 36%-40% higher than NOx ppmv values from natural gas combustion[228]. Consistent with this observation, the Chevron study noted in its conclusion that NOx mass emissions (lb/MMBtu) for the ultra-low NOx burner decreased slightly when combusting hydrogen as compared to natural gas and low hydrogen fuel gases. There is no

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[225] Steele, R.C., T.D. Martz, A. Ettlinger, T. Zandes, M.J. Alexander, B.K. Hockman, J.S. Goldmeer, 2022, Hydrogen Co-Firing Demonstration at New York Power Authority Brentwood Site: GE LM6000 Gas Turbine, September, executive summary available at https://www.epri.com/research/products/000000003002025166

[226] Power Engineering, 2023, Frame 7E gas turbine operates with hydrogen blend at 60%, industry article, July 11, https://www.power-eng.com/hydrogen/hydrogen/

[227] McDonell, V., 2023, Gas Turbine and Industrial Combustion NOx Emissions and Hydrogen, UC Irvine Combustion Laboratory presentation July 14

[228] Douglas, C.M., S.L. Shaw, T.D. Martz, R.C. Steele, D.R. Noble, B.L. Emerson, T.C. Lieuwen, 2022, Pollutant Emissions Reporting and Performance Considerations for Hydrogen-Hydrocarbon Fuels in Gas

indication from the study that aftertreatment or controls were utilized on the external combustion units tested.[229] [230] A summary of findings is shown in the table below.

Table B-2 Findings from Direct Measurement Studies

Equipment Type	Key Findings	Year of Publication	Authors
Low-Swirl Burner (LSB) Surface-Stabilized Combustion Burner (SSCB) Micro-Turbine Combustor (MTC) – Capstone C65 Oxygen Burner High Speed Jet Burner (HSJ) Turbine Combustor GT333 – FlexEnergy Radiant Tube (RT) Infrared Burner (IRB) Slot Butner (SB)	NOx production between various burner technologies was inconsistent. Five burners showed an increase in NOx with increasing hydrogen, in part due to less effective EGR. Four burners showed a decrease in NOx with increasing hydrogen, potentially due to enhanced radiative heat losses from the reaction due to increased surface area and high emissivity materials.	2017	California Energy Commission and UCI Combustion Laboratory
Bunsen Burner	NOx ppm emissions (mass normalized) decreased as the mole fraction of hydrogen in the fuel increased. This was largely due to decrease in flame temperature due to the researchers increasing the equivalence ratio lambda (λ) as the mole fraction of hydrogen increased. Study notes, "There is no functional chemical kinetic reason why hydrogen flames should produce more NOx than natural gas flames".	2023	Giacomazzi et al.

[229] Turbines, Journal of Engineering for Gas Turbines and Power 144(9): 091003, https://doi.org/10.1115/1.4054949

[230] Lowe, C., N. Brancaccio, D. Batten, C. Leung, and D. Waibel, 2011, Technology assessment of hydrogen firing of process heaters, Energy Procedia 4: 1058-1065, https://doi.org/10.1016/j.egypro.2011.01.155

Table B-2 Findings from Direct Measurement Studies			
Equipment Type	**Key Findings**	**Year of Publication**	**Authors**
Turbine	NOx level by volume stayed relatively constant at hydrogen blends of 20% compared to 100% natural gas, roughly 15 ppm (15% O_2).	2023	Georgia Power McDonough-Atkinson Plant, Mitsubishi, EPRI
Turbine	NOx mass emissions increased 24% as the percentage of hydrogen in the fuel increased, co-firing 5-44% by volume.	2023	New York Power Authority's Brentwood site, GE, EPRI
Reciprocating Engine	They were able to maintain compliance with existing NOx limits when co-firing up to 25% hydrogen by volume.	2022	A.J. Mihm Power Plant in Michigan
Gas Turbine	They achieved single digit NOx ppmv emissions at dry, baseload conditions when co-firing 60% hydrogen on a retrofitted turbine.	2023	Daesan Korea retrofitted GE 7E gas turbine
Ultra-Low NOx Round Flame Burner Low NOx Staged Fuel Flat Frame Burner	Ultra-low NOx round flame burner NOx mass emissions (lb/MMBtu) decreased slightly when combusting hydrogen as compared to natural gas. Low NOx staged fuel flat frame burner emissions increased 52.4% by volume (dry basis) (compared with natural gas) when combusting 95% hydrogen, which also equated to an increase in NOx mass emissions (lb/MMBtu)	2011	Chevron Energy Technology Company, John Zink Co., LLC

APPENDIX C NO_X AND OTHER AIR EMISSIONS CALCULATION SPREADSHEETS

Please refer to the excel spreadsheets provided in the Appendix C folder in the Living Library.

ANGELES LINK PHASE 1

Maps of Projected NOx Reductions and Environmental Justice Communities

July 2024

SoCalGas commissioned these maps from Stantec Consulting Services Inc. The analysis was conducted, and this material was prepared, collaboratively.

Southern California Gas Company (SoCalGas) is proposing Angeles Link to develop a clean renewable hydrogen[1] pipeline system to facilitate transportation of clean renewable hydrogen from multiple potential regional third-party production sources to various delivery points and end users in Central and Southern California, including in the Los Angeles Basin. The CPUC Phase 1 Decision[2] requires SoCalGas to, among other things, evaluate nitrogen oxide emissions resulting from Angeles Link. This evaluation is included in SoCalGas's Nitrogen Oxides (NOx) and Other Air Emissions Assessment – Draft Report (NOx Report).

The goal of the spatial evaluation was to graphically present where projected NOx emission reductions would occur based on the Demand Scenarios and Throughput Scenarios[3] as presented in the NOx Report. This spatial evaluation of NOx emissions reductions as compared to a geographic depiction of environmental justice communities was prepared in response to stakeholders' requests. The removal of criteria pollutant emissions from on-road transportation (by transitioning to zero emission vehicles) can have significant benefits for disadvantaged communities in California.

The Demand Scenario mapping was prepared for the entire geographic area of SoCalGas's service territory. The Angeles Link mapping was conducted similarly to the Demand Scenario spatial evaluation, but with the geographic scope focused on the counties through which Angeles Link would potentially pass. Based on preliminary routing, Angeles Link will pass through four counties: Fresno, Kings, Kern, and Los Angeles. Sixteen NOx maps were developed, four each for the Conservative and Ambitious Demand Scenarios and four each for the Low and High Throughput Scenarios. The four maps for each scenario were developed using data for 2030, 2035, 2040, and 2045, respectively.

The objective of the spatial evaluation was to present how NOx emissions could change across the project geography due to end-user adoption of hydrogen. The specific results plotted in the spatial evaluation were the total change in annual NOx emissions from all end-users (mobility, power generation, and hard to electrify industrial) for a particular year for 2030, 2035, 2040, and 2045. These results were developed based on methodologies discussed in the NOx study.

The NOx emission reductions were not originally developed at the zip code-level since they were based on subsector-level summary data from the Demand Study. As a result, additional analysis was required to develop a spatial dataset. The spatial dataset of annual change in NOx emissions by zip code was developed using a disaggregation approach. This approach was based on hydrogen demand tonnages provided in the Demand Study for each subsector, scenario, year between 2030-2045, and applicable zip code. Disaggregation was conducted by determining the fraction of hydrogen demand within each zip code for a given subsector, scenario, and year between 2030-2045. Projected NOx emission reductions by zip code were determined by multiplying NOx emission reductions by subsector, scenario, and year by the particular fraction

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[1] In the California Public Utilities Commission (CPUC) Angeles Link Phase 1 Decision (D).22-12-055 (Phase 1 Decision), clean renewable hydrogen refers to hydrogen that does not exceed 4 kilograms of carbon dioxide equivalent (CO2e) produced on a lifecycle basis per kilogram of hydrogen produced and does not use fossil fuels in the hydrogen production process, where fossil fuels are defined as a mixture of hydrocarbons including coal, petroleum, or natural gas, occurring in and extracted from underground deposits.

[2] CPUC Decision 22-12-055.

[3] As detailed in the Demand Study Report, the Demand Scenarios refer to the conservative, moderate, and ambitious scenarios for the estimated total market demand for hydrogen in Central and Southern California; and the Throughput Scenarios refer to the low, medium, and high scenarios of hydrogen that could be served by Angeles Link at various potential market penetration rates.

of hydrogen demand by zip code for a given subsector, scenario, and year. Since subsector was the lowest level of granularity for the results in the NOx report, it was determined that disaggregation would yield the same results as recalculating the results of this study based on hydrogen quantity per zip code and subsector (assuming overall hydrogen demand is consistent between the summary and zip code data).

Maps depicting the potential pipeline routes[4] developed by SoCalGas and the anticipated change to NOx emissions based on zip code are included in Appendix A. Disadvantaged communities (DACs) and environmental justice (EJ) communities[5] with potential pipeline routes are included in SoCalGas' Environmental Social Justice Plan and also included herein in Appendix B. Two geospatial mapping/screening tools were selected for evaluation of DACs and EJ communities. These included CalEnviroScreen 4.0 and the Climate and Economic Justice Screening Tool (CEJST). CalEnviroScreen uses environmental, health, and socioeconomic information to produce scores for every census tract in the state. This tool was developed by the California Office of Environmental Health Hazard Assessment.[6] CJEST has datasets that are indicators of burdens in eight categories: climate change, energy, health, housing, legacy pollution, transportation, water and wastewater, and workforce development. This tool was developed by the Council on Environmental Quality in response to Executive Order 14008.[7]

Maps were prepared for Environmental Justice Communities. DACs were included in the spatial evaluation using data from CalEPA. The contemporary assessment of DACs was based, in large part, on results from the "California Communities Environmental Health Screening Tool: CalEnviroScreen 4.0" (CalEnviroScreen 4.0) from which census tracts were assessed based on indicators of pollution burden and population characteristics. Based on CalEPA's assessment, DACs were identified in this dataset based on four categories:

- Census tracts receiving the highest 25% of overall scores in CalEnviroScreen 4.0.
- Census tracts lacking CalEnviroScreen scores (due to data gaps), that received the highest 5% of CalEnviroScreen 4.0 pollution burden scores.
- Census tracts identified in the 2017 DAC designation as disadvantaged.
- Lands under the control of federally recognized Tribes.

Both CalEnviroScreen and CEJST datasets identify communities that are disproportionately burdened, and vulnerable to, multiple sources of pollution by census tract. Since anticipated NOx changes were disaggregated by the zip-code level and not by census tract, an analysis estimating the NOx emissions changes that could be expected in DAC and EJ communities as identified by census track was not conducted. However, when comparing the two map datasets, it can be visually observed that large emissions reductions occur in DAC and EJ communities.

Summary data from the Demand Study was used to prepare the NOx emission calculations provided in the NOx Report. To prepare this geospatial evaluation, the NOx emission reduction

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[4] SoCalGas's potential pipeline routes are discussed in the Preliminary Routing and Configuration Analysis report.

[5] For the purposes of this discussion, a community is considered as a disadvantaged community if it meets the CalEPA definition for a Disadvantaged Community (DAC) or the community has been identified as disadvantaged on the Climate and Economic Justice Screening Tool developed by the Biden Administration's Council on Environmental Quality. See: Final Designation of Disadvantaged Communities Pursuant to SB535, 2022 (ca.gov) for CalEPA definition of a DAC. See: https://screeningtool.geoplatform.gov/en/frequently-asked-questions#5.77/25.893/-86.555 for CEJST DAC designation.

[6] See: https://oehha.ca.gov/calenviroscreen

[7] See: https://screeningtool.geoplatform.gov/en/about

results for end-users were allocated to zip codes by calculating the ratio of hydrogen demand projected by the Demand Study for each zip code to total hydrogen demand and then applying that ratio to total NOx emission reductions for end-users to determine NOx emission reductions by zip code. The uncertainty of this method is that adoption of hydrogen by end-user sectors and sub-sectors is assumed to be the same across the geographical region even though the level of hydrogen adoption may also vary by zip code.

Appendix A: NOx Reduction Maps

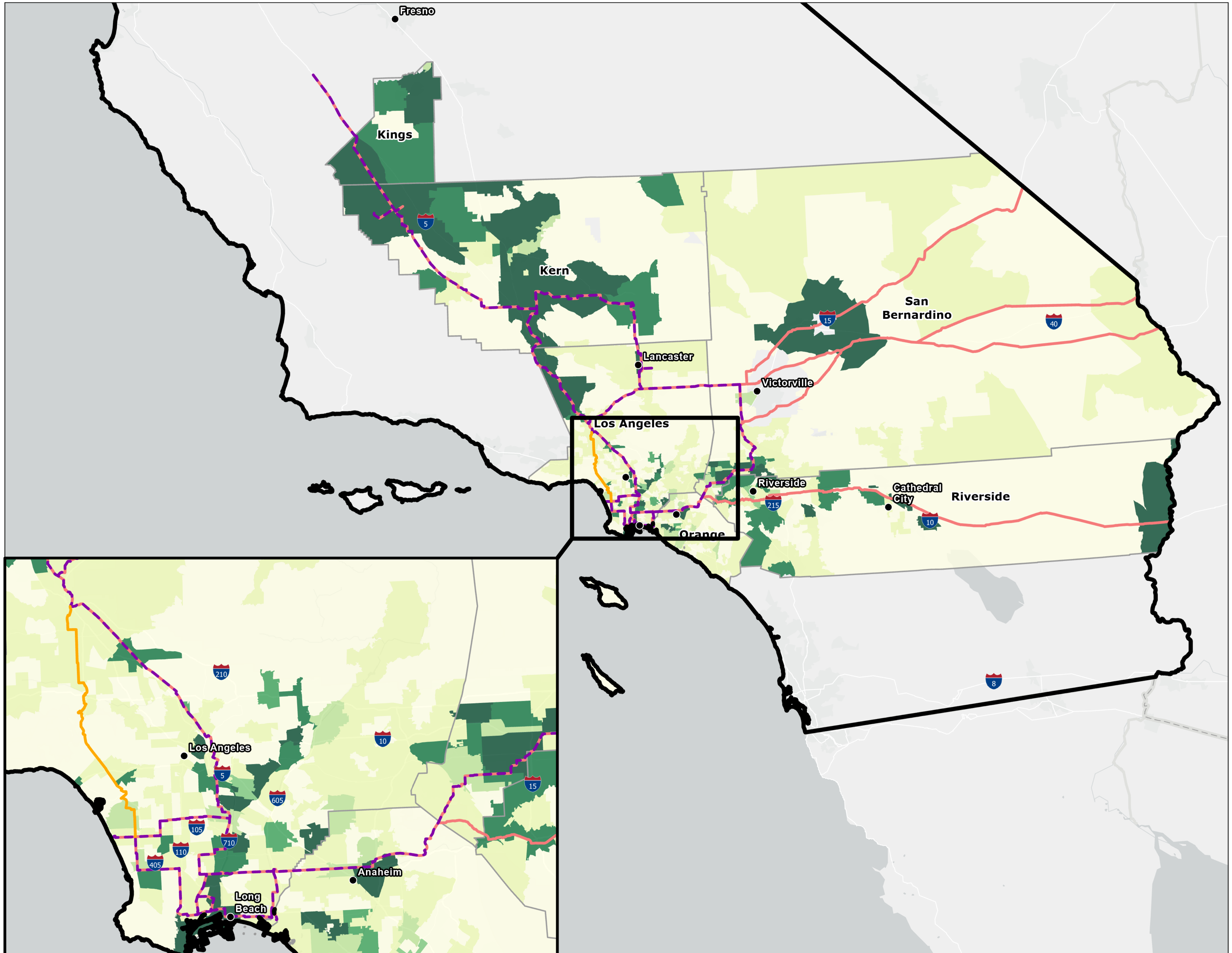


Figure No.

A-1

Title

NOx Emissions Reductions 2030, Market Demand: Total, Conservative

Client/Project 203723235

Southern California Gas Company (SoCalGas)
Phase One NOx Study

Project Location Prepared by BS on 2024-07-19

California

N

0 20 40 Miles

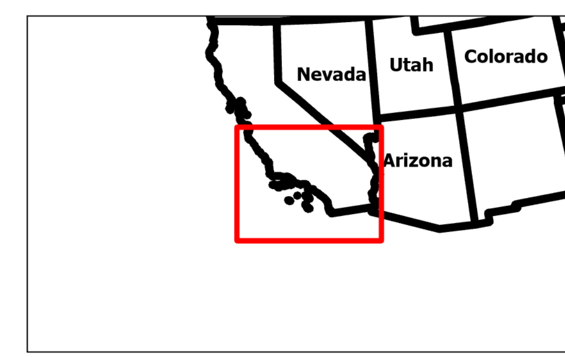
(At original document size of 11x17)
1:2,534,400

Legend

- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1
- Initial Corridors Evaluated

Reduction in NOx Emissions in 2030, Conservative Scenario

- 0.00 - 0.05 tons/year NOx
- 0.05 - 0.12 tons/year NOx
- 0.12 - 0.23 tons/year NOx
- 0.23 - 0.37 tons/year NOx
- 0.37 - 0.55 tons/year NOx
- 0.55 - 5.7 tons/year NOx
- >5.7 tons/year NOx



Notes

1. Coordinate System: NAD 1983 StatePlane California II FIPS 0402 Feet
2. Data Sources: USGS, OEHHA, CalEPA, CEQ
3. Background: ESRI Basemap
4. Figure depicts overall NOx emission reductions allocated by zip code
5. NOx emissions reductions by zip code are based on Demand Study hydrogen data
6. The NOx emissions reduction benefits depicted on the map are focused within the counties through which the Angeles Link would potentially pass. These benefits could potentially extend beyond these boundaries

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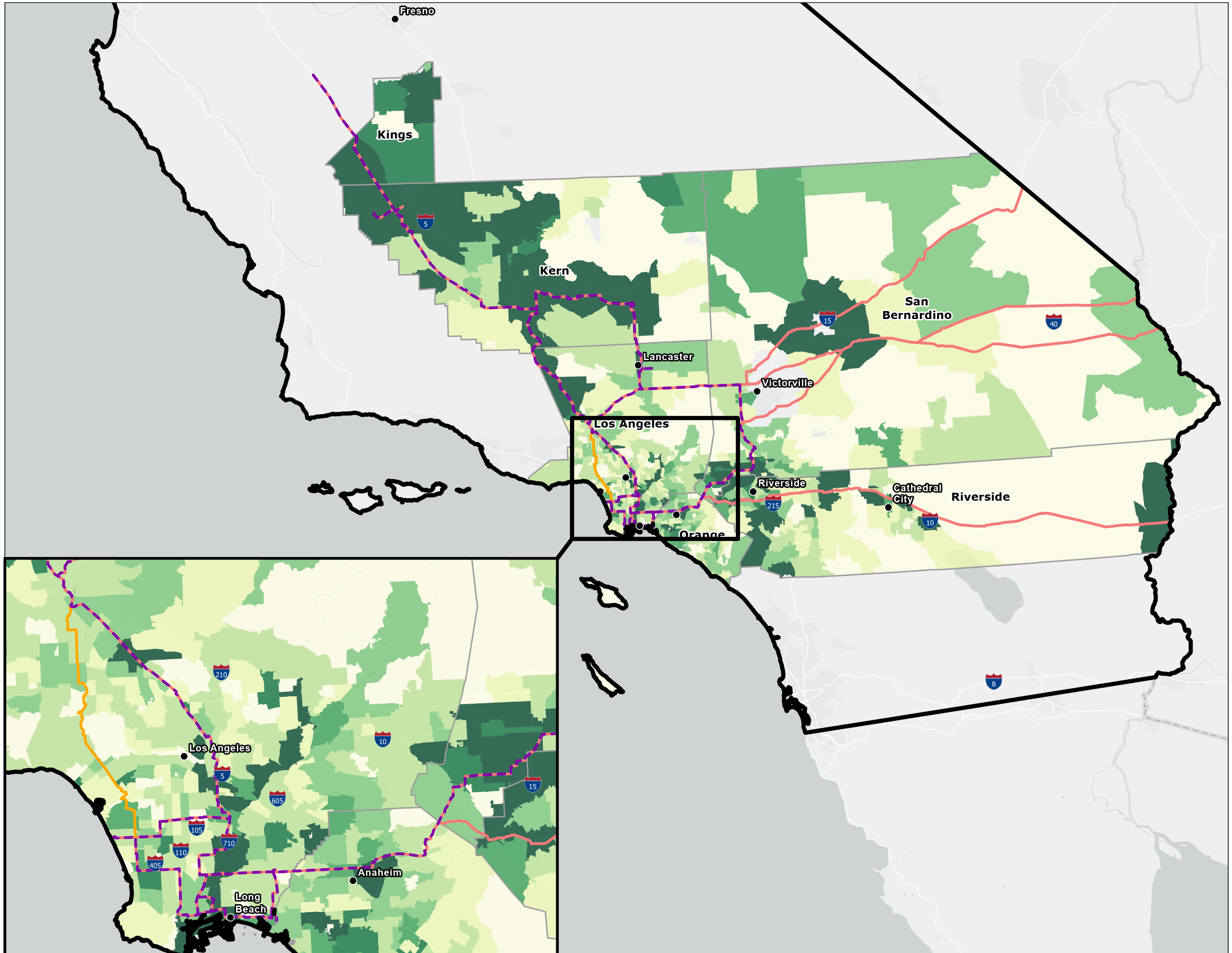


Figure No.
A-2

Title
NOx Emissions Reductions 2035, Market Demand: Total, Conservative

Client/Project 203723235
Southern California Gas Company (SoCalGas)
Phase One NOx Study

Project Location
California

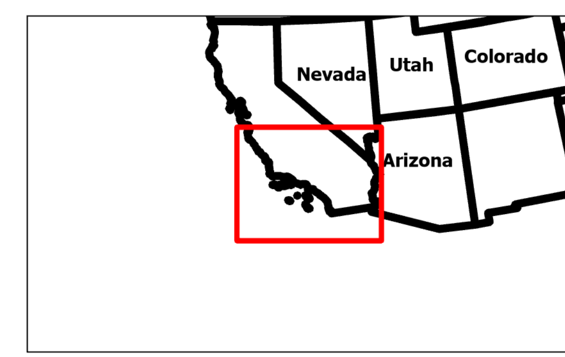
Prepared by BS on 2024-07-19

N

0 20 40 Miles
(At original document size of 11x17)
1:2,534,400

Legend
- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1
- Initial Corridors Evaluated

Reduction in NOx Emissions in 2035, Conservative Scenario
- 0.00 - 0.05 tons/year NOx
- 0.05 - 0.12 tons/year NOx
- 0.12 - 0.23 tons/year NOx
- 0.23 - 0.37 tons/year NOx
- 0.37 - 0.55 tons/year NOx
- 0.55 - 5.7 tons/year NOx
- >5.7 tons/year NOx



Notes
1. Coordinate System: NAD 1983 StatePlane California II FIPS 0402 Feet
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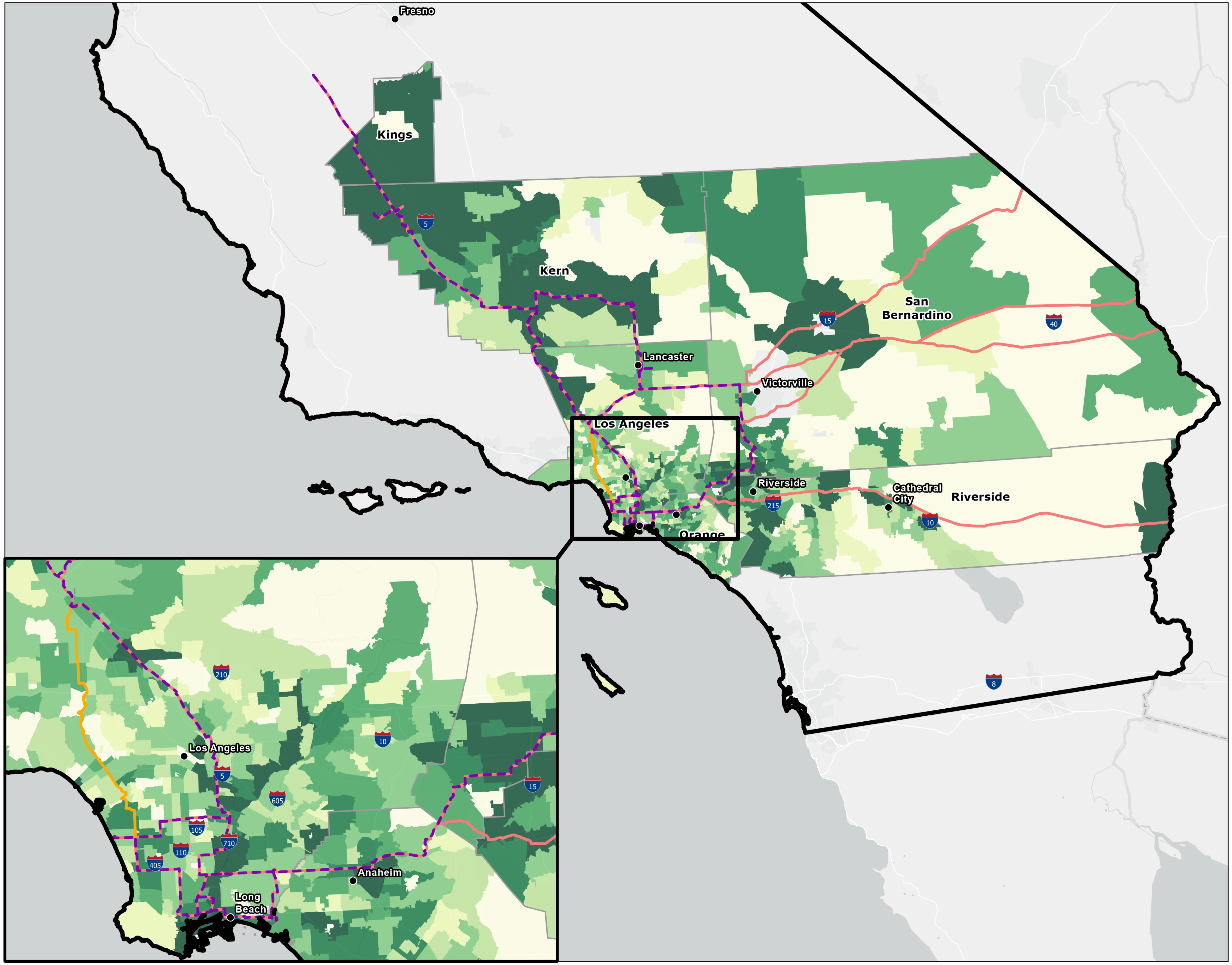


Figure No.
A-3

Title
NOx Emissions Reductions 2040, Market Demand: Total, Conservative

Client/Project 203723235
Southern California Gas Company (SoCalGas)
Phase One NOx Study

Project Location
California

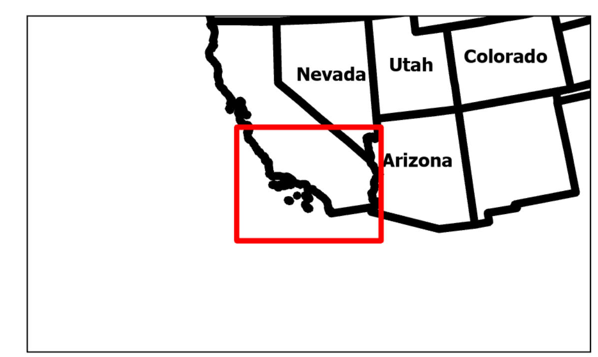
Prepared by BS on 2024-07-19

N

0 20 40 Miles
(At original document size of 11x17)
1:2,534,400

Legend
- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1
- Initial Corridors Evaluated

Reduction in NOx Emissions in 2040, Conservative Scenario
- 0.00 - 0.05 tons/year NOx
- 0.05 - 0.12 tons/year NOx
- 0.12 - 0.23 tons/year NOx
- 0.23 - 0.37 tons/year NOx
- 0.37 - 0.55 tons/year NOx
- 0.55 - 5.7 tons/year NOx
- >5.7 tons/year NOx



Notes
1. Coordinate System: NAD 1983 StatePlane California II FIPS 0402 Feet
2. Data Sources: USGS, OEHHA, CalEPA, CEQ
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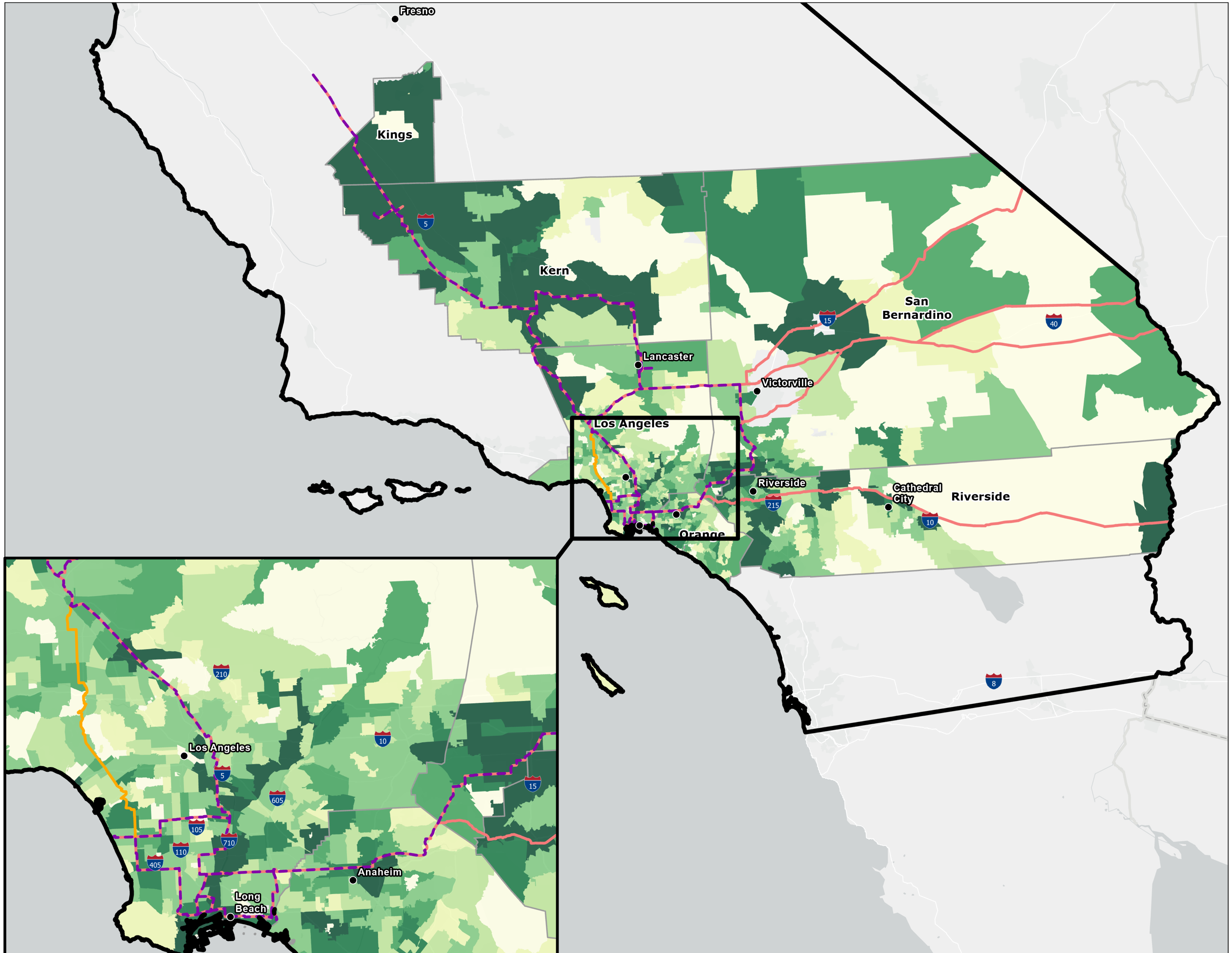


Figure No.
A-4

Title
NOx Emissions Reductions 2045, Market Demand: Total, Conservative

Client/Project 203723235
Southern California Gas Company (SoCalGas)
Phase One NOx Study

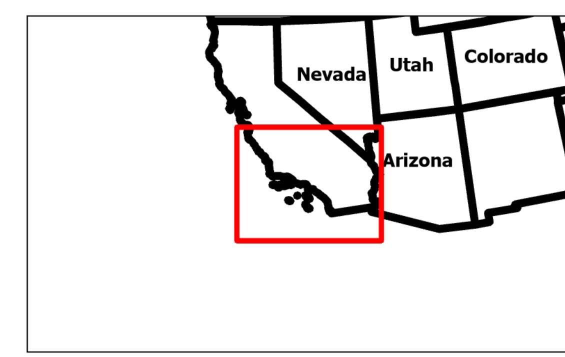
Project Location Prepared by BS on 2024-07-19
California

N

0 20 40 Miles
(At original document size of 11x17)
1:2,534,400

Legend
- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1
- Initial Corridors Evaluated

Reduction in NOx Emissions in 2045, Conservative Scenario
- 0.00 - 0.06 tons/year NOx
- 0.06 - 0.16 tons/year NOx
- 0.16 - 0.32 tons/year NOx
- 0.32 - 0.51 tons/year NOx
- 0.51 - 0.78 tons/year NOx
- 0.78 - 7.7 tons/year NOx
- >7.7 tons/year NOx



Notes
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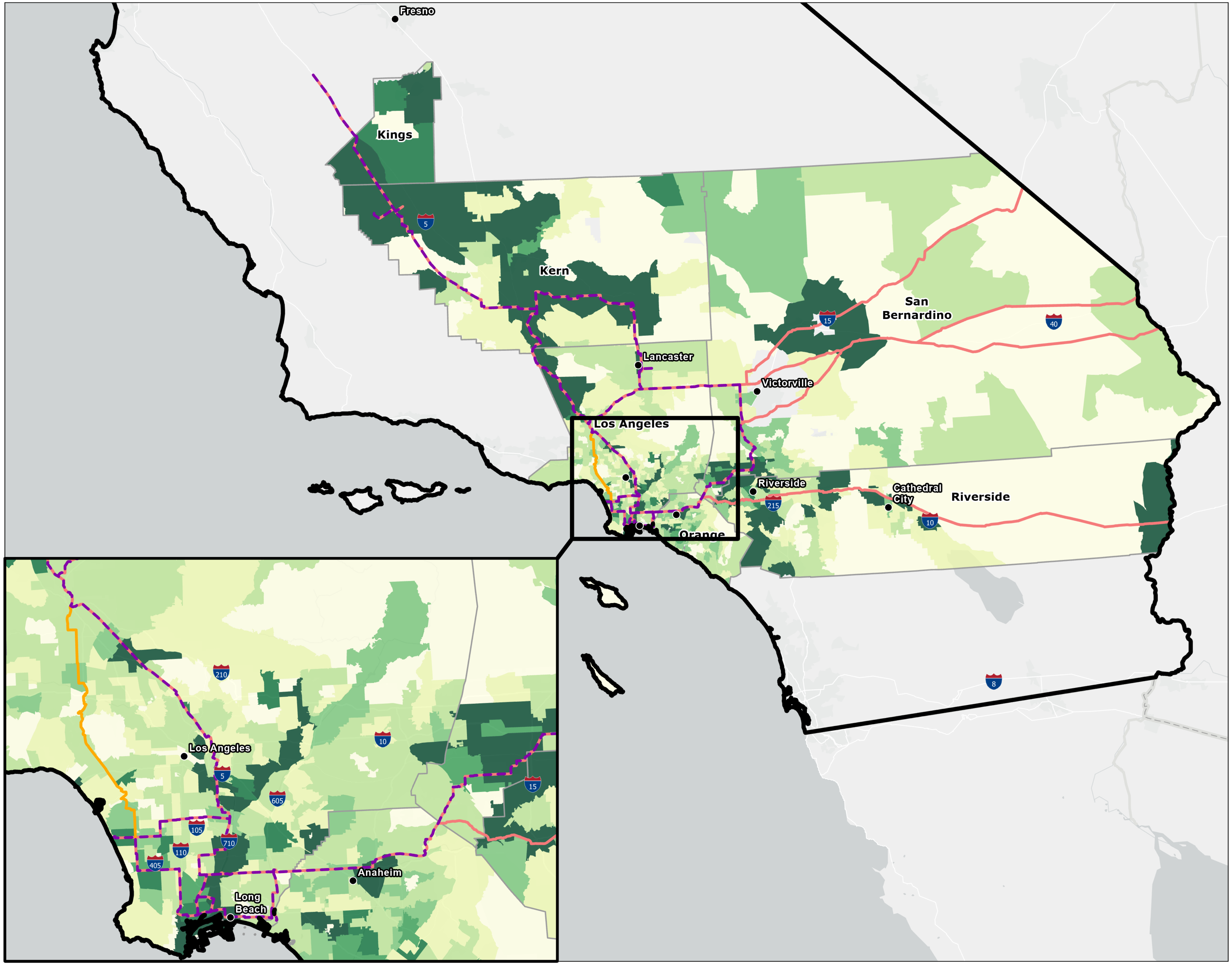


Figure No.
A-5

Title
NOx Emissions Reductions 2030, Market Demand: Total, Ambitious

Client/Project 203723235
Southern California Gas Company (SoCalGas)
Phase One NOx Study

Project Location
California

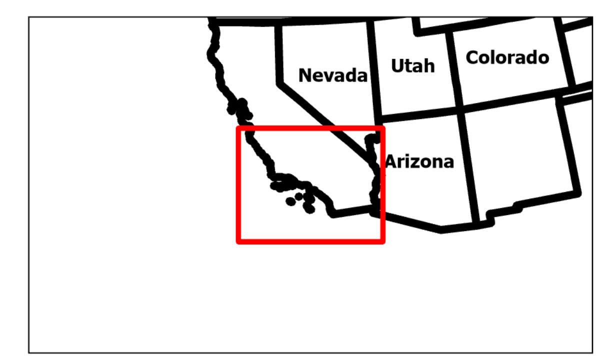
Prepared by BS on 2024-07-19

N

0 20 40 Miles
(At original document size of 11x17)
1:2,534,400

Legend
- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1
- Initial Corridors Evaluated

Reduction in NOx Emissions in 2030, Ambitious Scenario
- 0.00 - 0.06 tons/year NOx
- 0.06 - 0.16 tons/year NOx
- 0.16 - 0.32 tons/year NOx
- 0.32 - 0.51 tons/year NOx
- 0.51 - 0.78 tons/year NOx
- 0.78 - 7.7 tons/year NOx
- >7.7 tons/year NOx



Notes
1. Coordinate System: NAD 1983 StatePlane California II FIPS 0402 Feet
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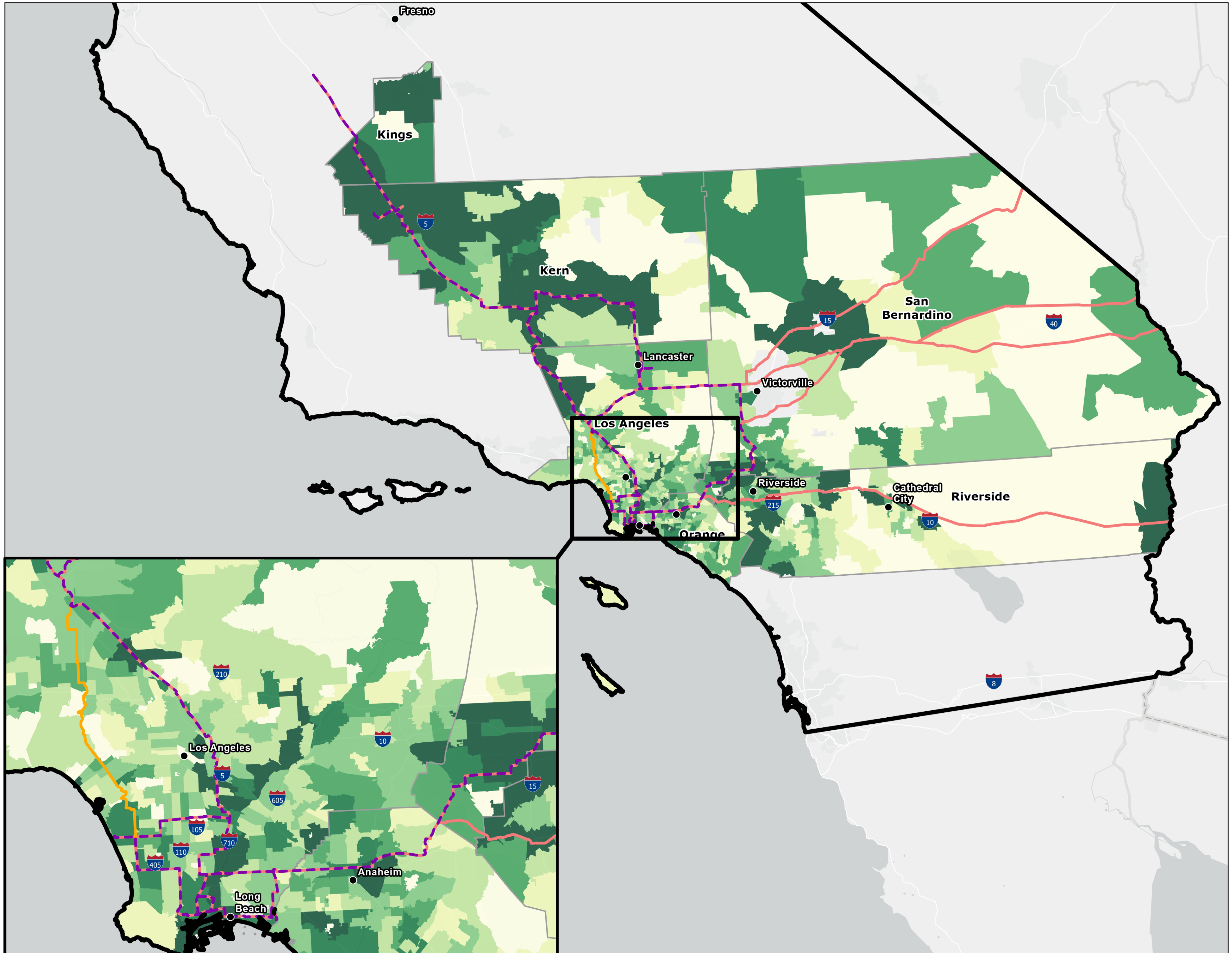


Figure No.
A-6

Title
NOx Emissions Reductions 2035, Market Demand: Total, Ambitious

Client/Project 203723235
Southern California Gas Company (SoCalGas)
Phase One NOx Study

Project Location
California

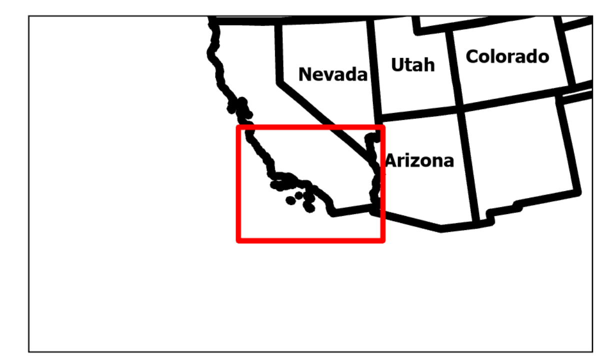
Prepared by BS on 2024-07-19

N

0 20 40 Miles
(At original document size of 11x17)
1:2,534,400

Legend
- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1
- Initial Corridors Evaluated

Reduction in NOx Emissions in 2035, Ambitious Scenario
- 0.00 - 0.06 tons/year NOx
- 0.06 - 0.16 tons/year NOx
- 0.16 - 0.32 tons/year NOx
- 0.32 - 0.51 tons/year NOx
- 0.51 - 0.78 tons/year NOx
- 0.78 - 7.7 tons/year NOx
- >7.7 tons/year NOx



Notes
1. Coordinate System: NAD 1983 StatePlane California II FIPS 0402 Feet
2. Data Sources: USGS, OEHHA, CalEPA, CEQ
3. Background: ESRI Basemap
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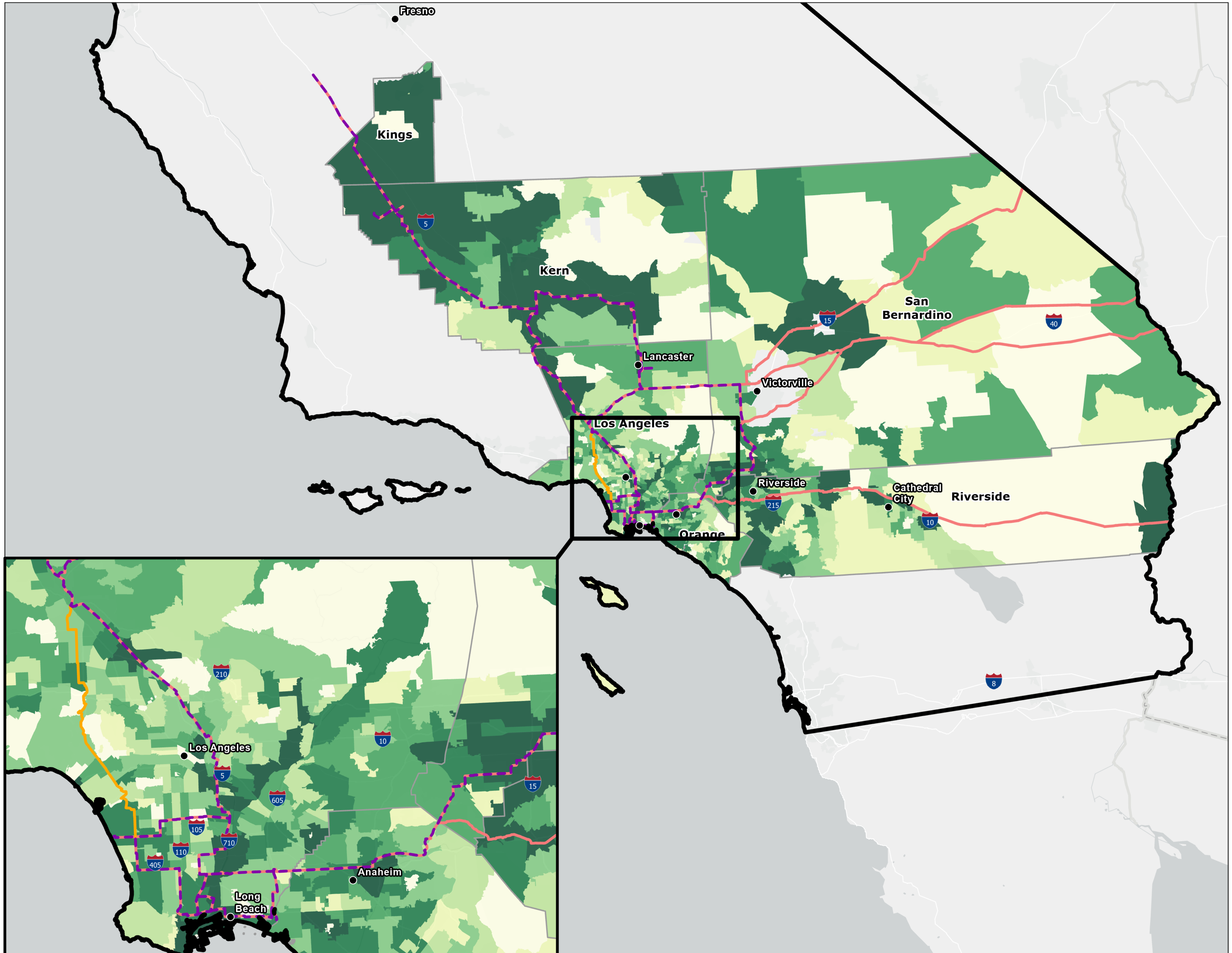


Figure No.
A-7

Title
NOx Emissions Reductions 2040, Market Demand: Total, Ambitious

Client/Project 203723235
Southern California Gas Company (SoCalGas)
Phase One NOx Study

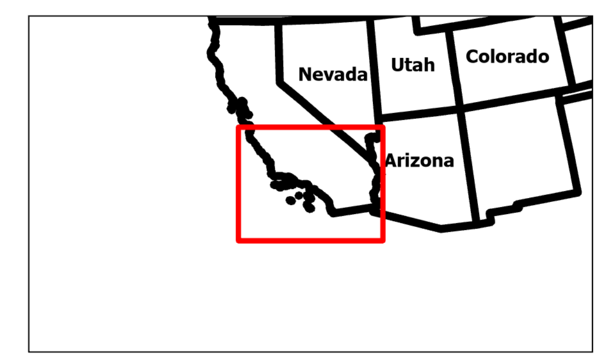
Project Location California
Prepared by BS on 2024-07-19

N

0 20 40 Miles
(At original document size of 11x17)
1:2,534,400

Legend
- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1
- Initial Corridors Evaluated

Reduction in NOx Emissions in 2040, Ambitious Scenario
- 0.00 - 0.06 tons/year NOx
- 0.06 - 0.16 tons/year NOx
- 0.16 - 0.32 tons/year NOx
- 0.32 - 0.51 tons/year NOx
- 0.51 - 0.78 tons/year NOx
- 0.78 - 7.7 tons/year NOx
- >7.7 tons/year NOx



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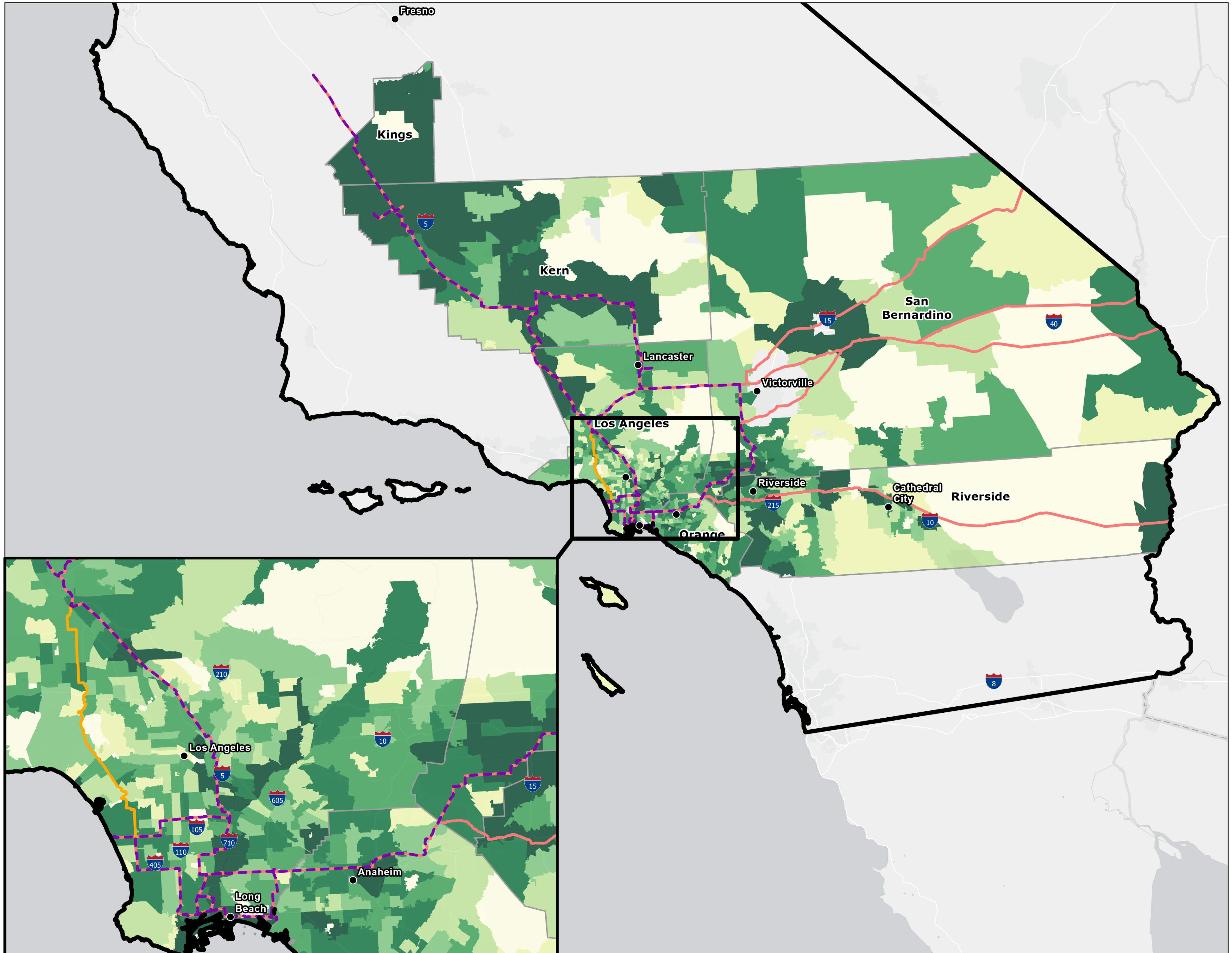


Figure No.
A-8

Title
NOx Emissions Reductions 2045, Market Demand: Total, Ambitious

Client/Project 203723235
Southern California Gas Company (SoCalGas)
Phase One NOx Study

Project Location
California

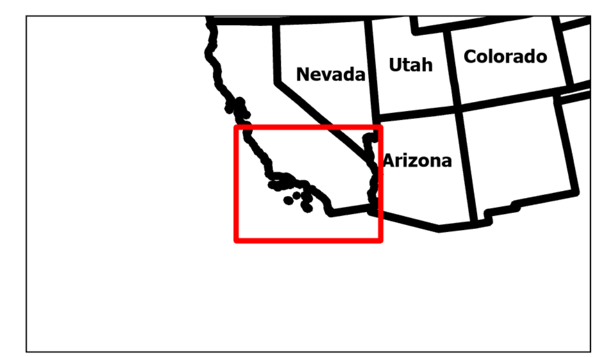
Prepared by BS on 2024-07-19

N

0 20 40 Miles
(At original document size of 11x17)
1:2,534,400

Legend
- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1
- Initial Corridors Evaluated

Reduction in NOx Emissions in 2045, Ambitious Scenario
- 0.00 - 0.06 tons/year NOx
- 0.06 - 0.16 tons/year NOx
- 0.16 - 0.32 tons/year NOx
- 0.32 - 0.51 tons/year NOx
- 0.51 - 0.78 tons/year NOx
- 0.78 - 7.7 tons/year NOx
- >7.7 tons/year NOx



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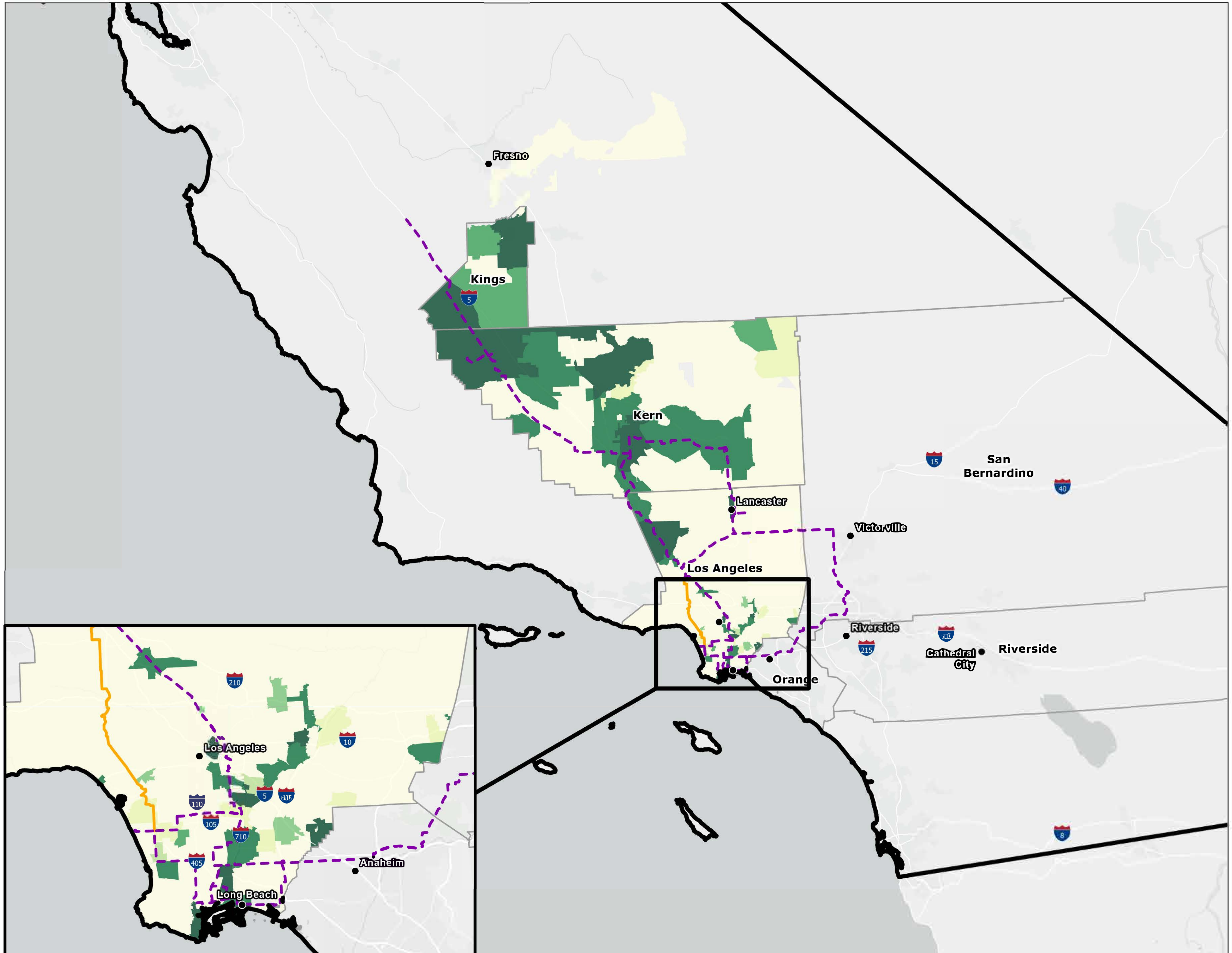


Figure No.
A-9

Title
NOx Emissions Reductions Associated With Angeles Link (AL) 2030 Total, Low Throughput

Client/Project 203723235
Southern California Gas Company (SoCalGas)
Phase One NOx Study

Project Location
California

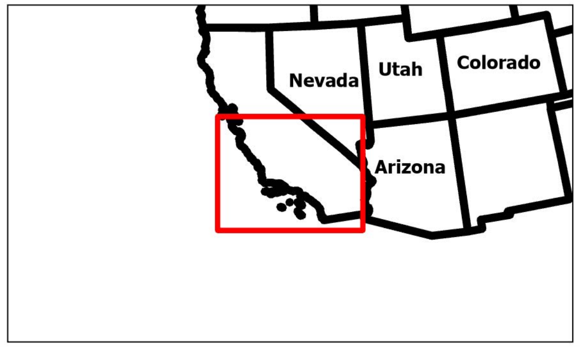
Prepared by BS on 2024-07-19

N

0 20 40 Miles
(At original document size of 11x17)
1:2,534,400

Legend
- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1

Reduction in NOx Emissions Attributable to AL in 2030, Low Scenario
- 0.00 - 0.05 tons/year NOx
- 0.05 - 0.12 tons/year NOx
- 0.12 - 0.23 tons/year NOx
- 0.23 - 0.37 tons/year NOx
- 0.37 - 0.55 tons/year NOx
- 0.55 - 5.7 tons/year NOx
- >5.7 tons/year NOx



Notes
1. Coordinate System: NAD 1983 StatePlane California II FIPS 0402 Feet
2. Data Sources: USGS, OEHHA, CalEPA, CEQ
3. Background: ESRI Basemap
4. Figure depicts overall NOx emission reductions allocated by zip code
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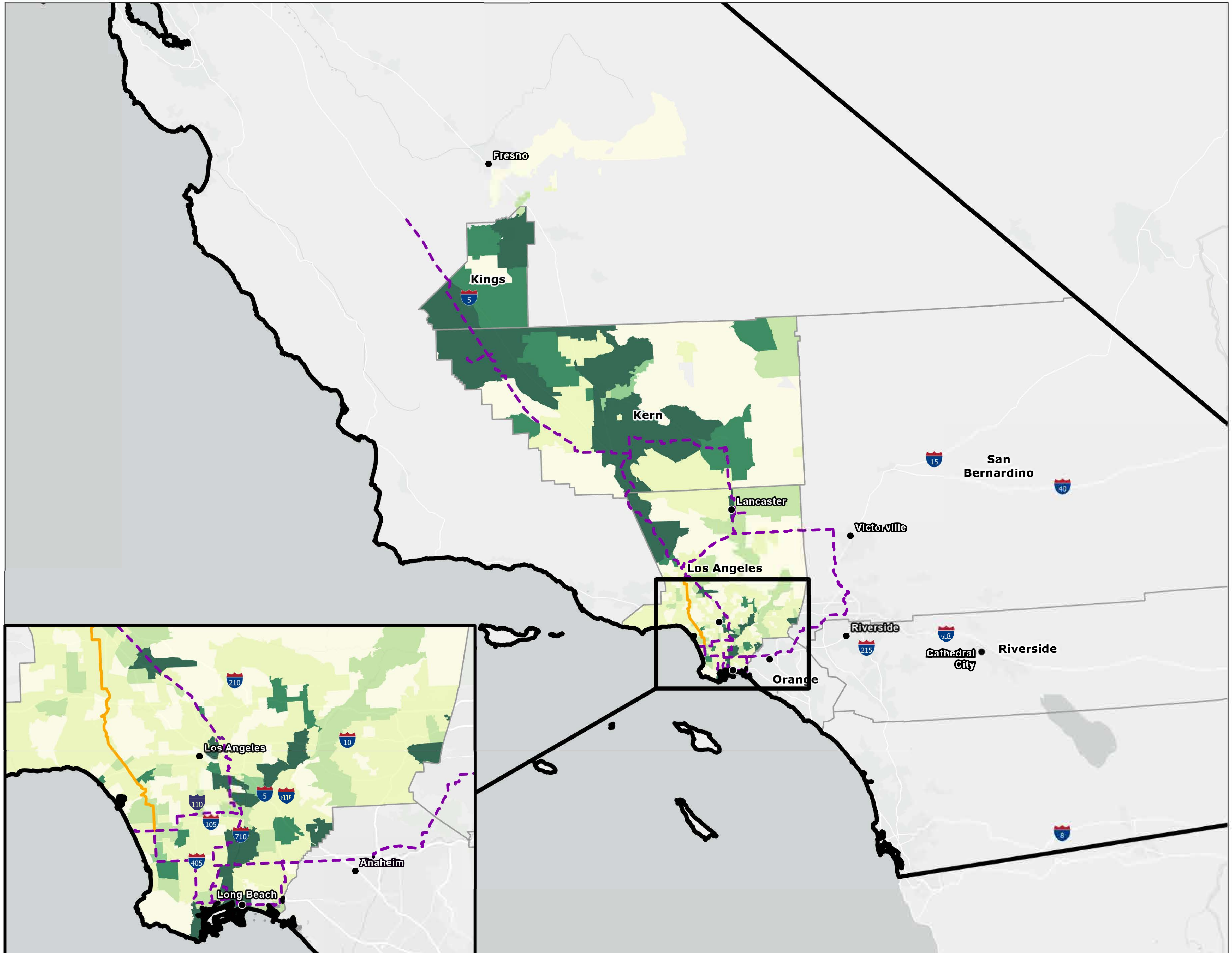

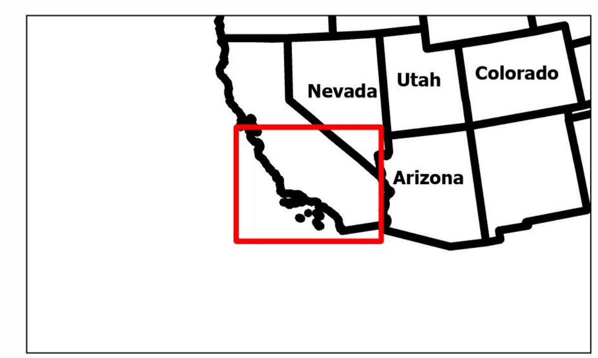

Figure No.

A-10

Title

NOx Emissions Reductions Associated With Angeles Link (AL) 2035 Total, Low Throughput

Client/Project 203723235

Southern California Gas Company (SoCalGas)
Phase One NOx Study

Project Location Prepared by BS on 2024-07-19
California

N

0 20 40 Miles
(At original document size of 11x17)
1:2,534,400

Legend

- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1

Reduction in NOx Emissions Attributable to AL in 2035, Low Scenario

- 0.00 - 0.05 tons/year NOx
- 0.05 - 0.12 tons/year NOx
- 0.12 - 0.23 tons/year NOx
- 0.23 - 0.37 tons/year NOx
- 0.37 - 0.55 tons/year NOx
- 0.55 - 5.7 tons/year NOx
- >5.7 tons/year NOx

Notes

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2. Data Sources: USGS, OEHHA, CalEPA, CEQ
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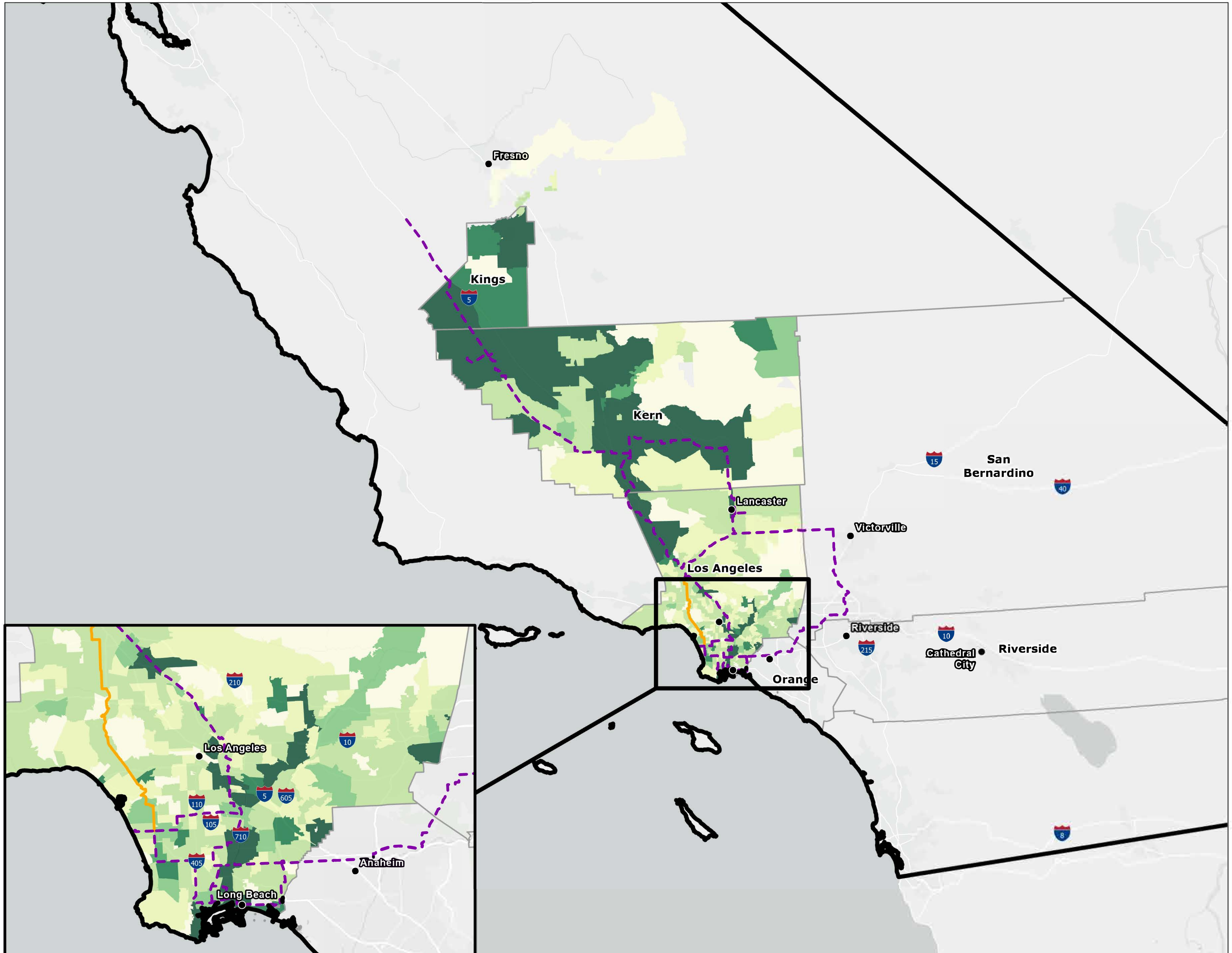


Figure No.
A-11

Title
NOx Emissions Reductions Associated With Angeles Link (AL) 2040: Total, Low Throughput

Client/Project 203723235
Southern California Gas Company (SoCalGas)
Phase One NOx Study

Project Location
California

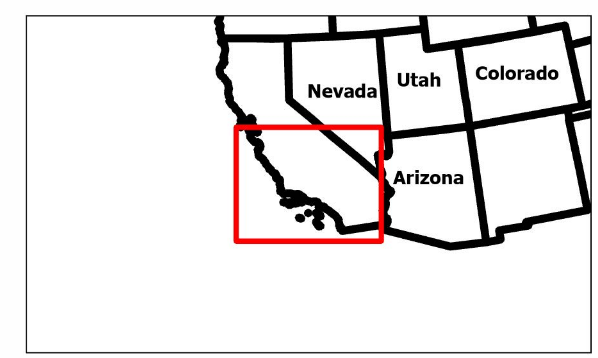
Prepared by BS on 2024-07-19

N

0 20 40 Miles
(At original document size of 11x17)
1:2,534,400

Legend
- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1

Reduction in NOx Emissions Attributable to AL in 2040, Low Scenario
- 0.00 - 0.05 tons/year NOx
- 0.05 - 0.12 tons/year NOx
- 0.12 - 0.23 tons/year NOx
- 0.23 - 0.37 tons/year NOx
- 0.37 - 0.55 tons/year NOx
- 0.55 - 5.7 tons/year NOx
- >5.7 tons/year NOx



Notes
1. Coordinate System: NAD 1983 StatePlane California II FIPS 0402 Feet
2. Data Sources: USGS, OEHHA, CalEPA, CEQ
3. Background: ESRI Basemap
4. Figure depicts overall NOx emission reductions allocated by zip code
5. NOx emissions reductions by zip code are based on Demand Study hydrogen data
6. The NOx emissions reduction benefits depicted on the map are focused within the counties through which the Angeles Link would potentially pass. These benefits could potentially extend beyond these boundaries

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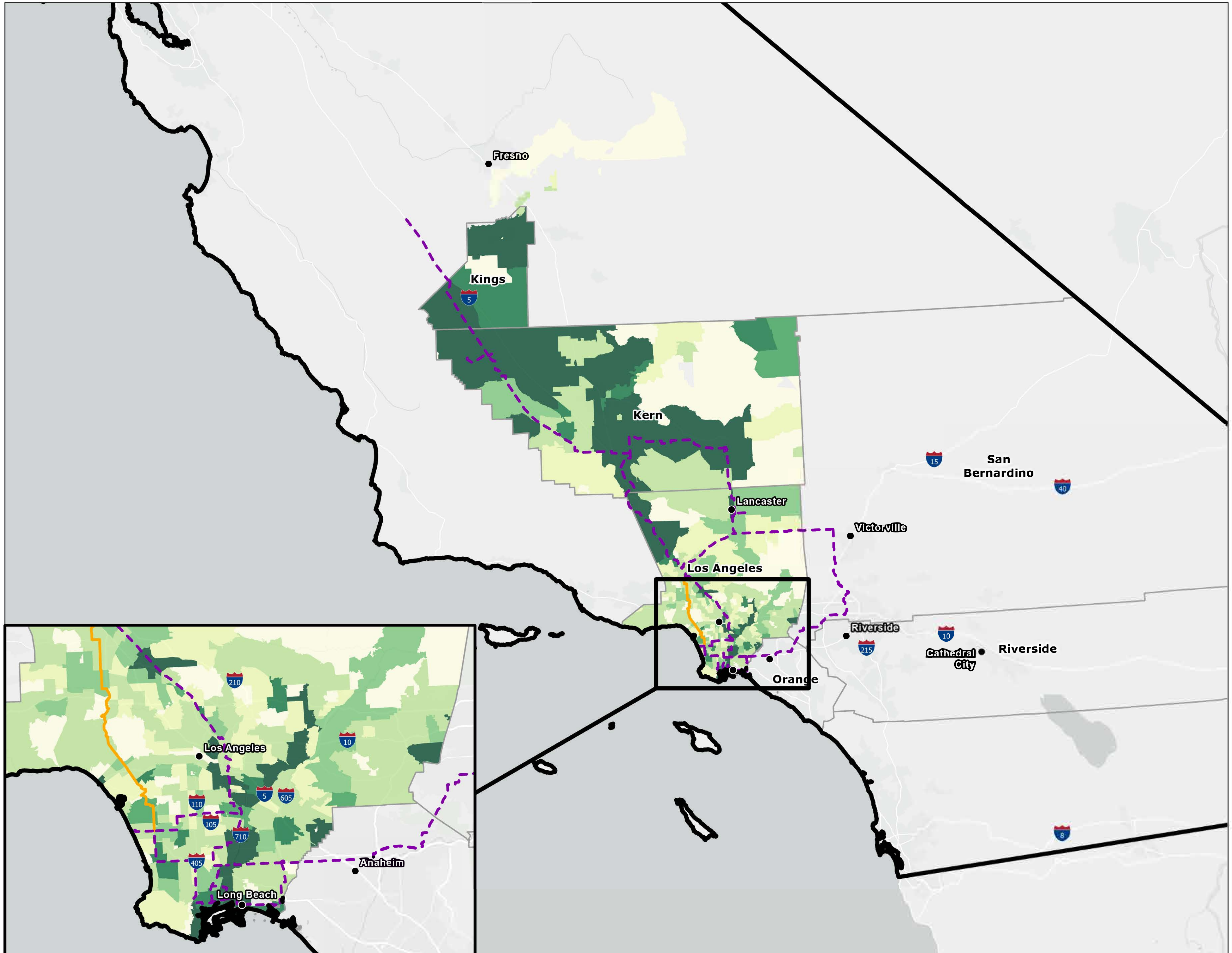


Figure No.
A-12

Title
NOx Emissions Reductions Associated With Angeles Link (AL) 2045: Total, Low Throughput

Client/Project 203723235
Southern California Gas Company (SoCalGas)
Phase One NOx Study

Project Location
California

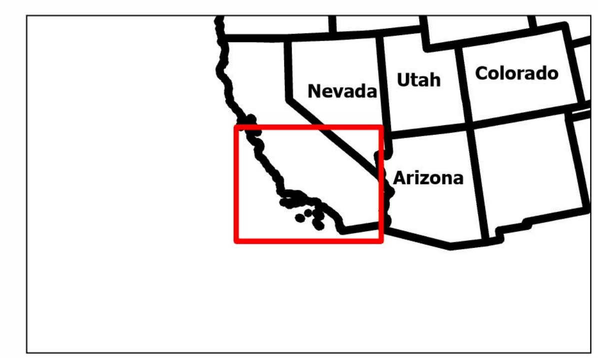
Prepared by BS on 2024-07-19

N

0 20 40 Miles
(At original document size of 11x17)
1:2,534,400

Legend
- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1

Reduction in NOx Emissions Attributable to AL in 2045, Low Scenario
- 0.00 - 0.05 tons/year NOx
- 0.05 - 0.12 tons/year NOx
- 0.12 - 0.23 tons/year NOx
- 0.23 - 0.37 tons/year NOx
- 0.37 - 0.55 tons/year NOx
- 0.55 - 5.7 tons/year NOx
- >5.7 tons/year NOx



Notes
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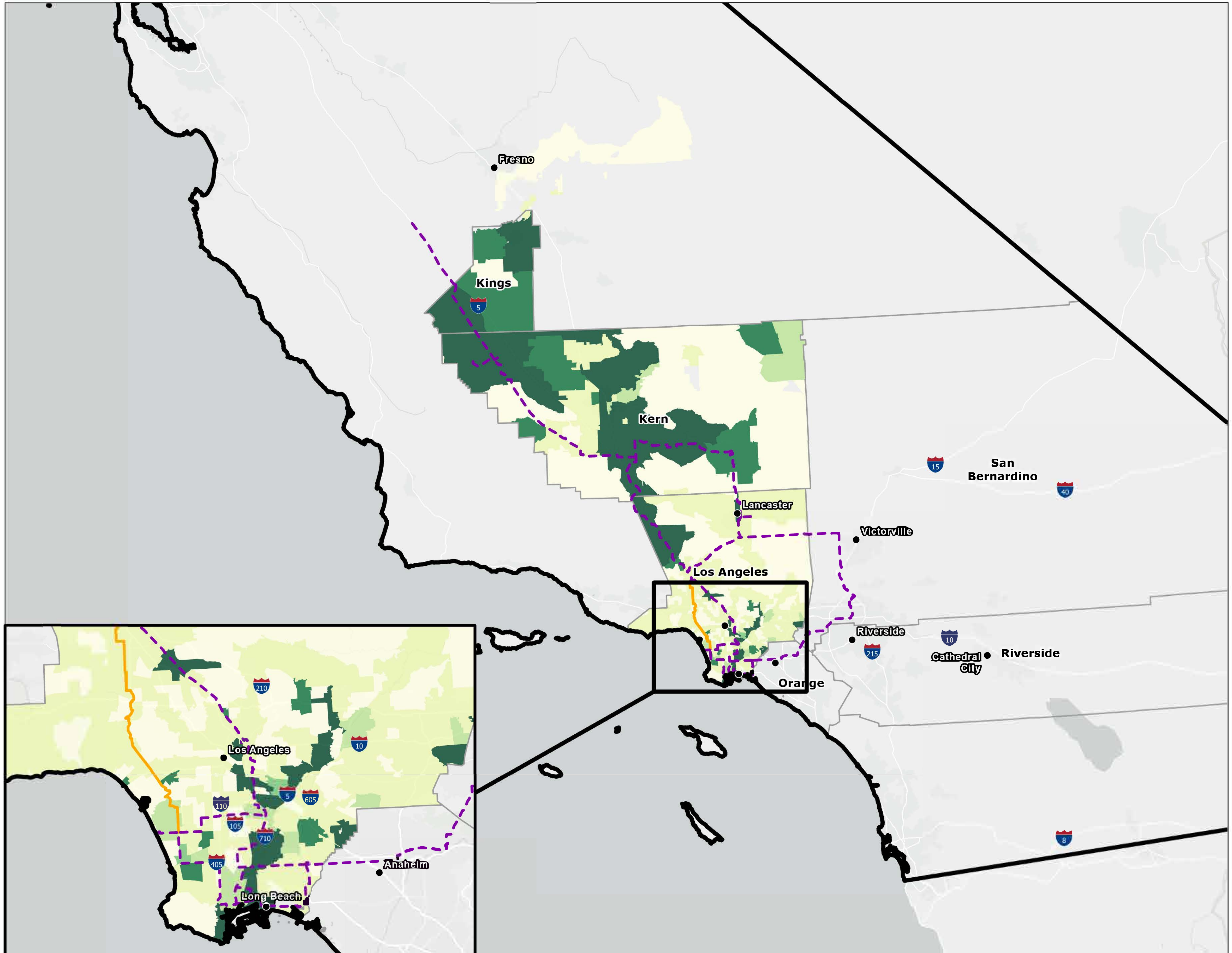
Figure No.
A-13

Title
NOx Emissions Reductions Associated With Angeles Link (AL) 2030 Total, High Throughput

Client/Project 203723235
Southern California Gas Company (SoCalGas)
Phase One NOx Study

Project Location
California

Prepared by BS on 2024-07-19

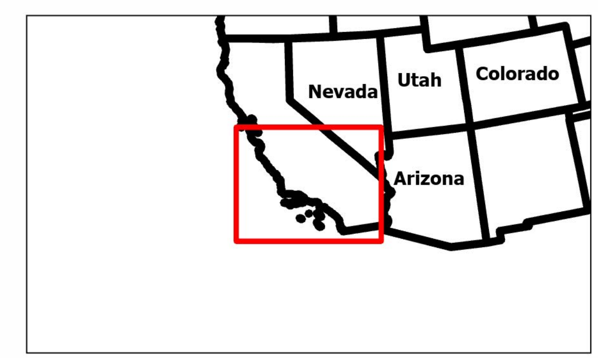


N

0 20 40 Miles
(At original document size of 11x17)
1:2,534,400

Legend
- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1

Reduction in NOx Emissions Attributable to AL in 2030, High Scenario
- 0.00 - 0.06 tons/year NOx
- 0.06 - 0.16 tons/year NOx
- 0.16 - 0.32 tons/year NOx
- 0.32 - 0.51 tons/year NOx
- 0.51 - 0.78 tons/year NOx
- 0.78 - 7.7 tons/year NOx
- >7.7 tons/year NOx



Notes
1. Coordinate System: NAD 1983 StatePlane California II FIPS 0402 Feet
2. Data Sources: USGS, OEHHA, CalEPA, CEQ
3. Background: ESRI Basemap
4. Figure depicts overall NOx emission reductions allocated by zip code
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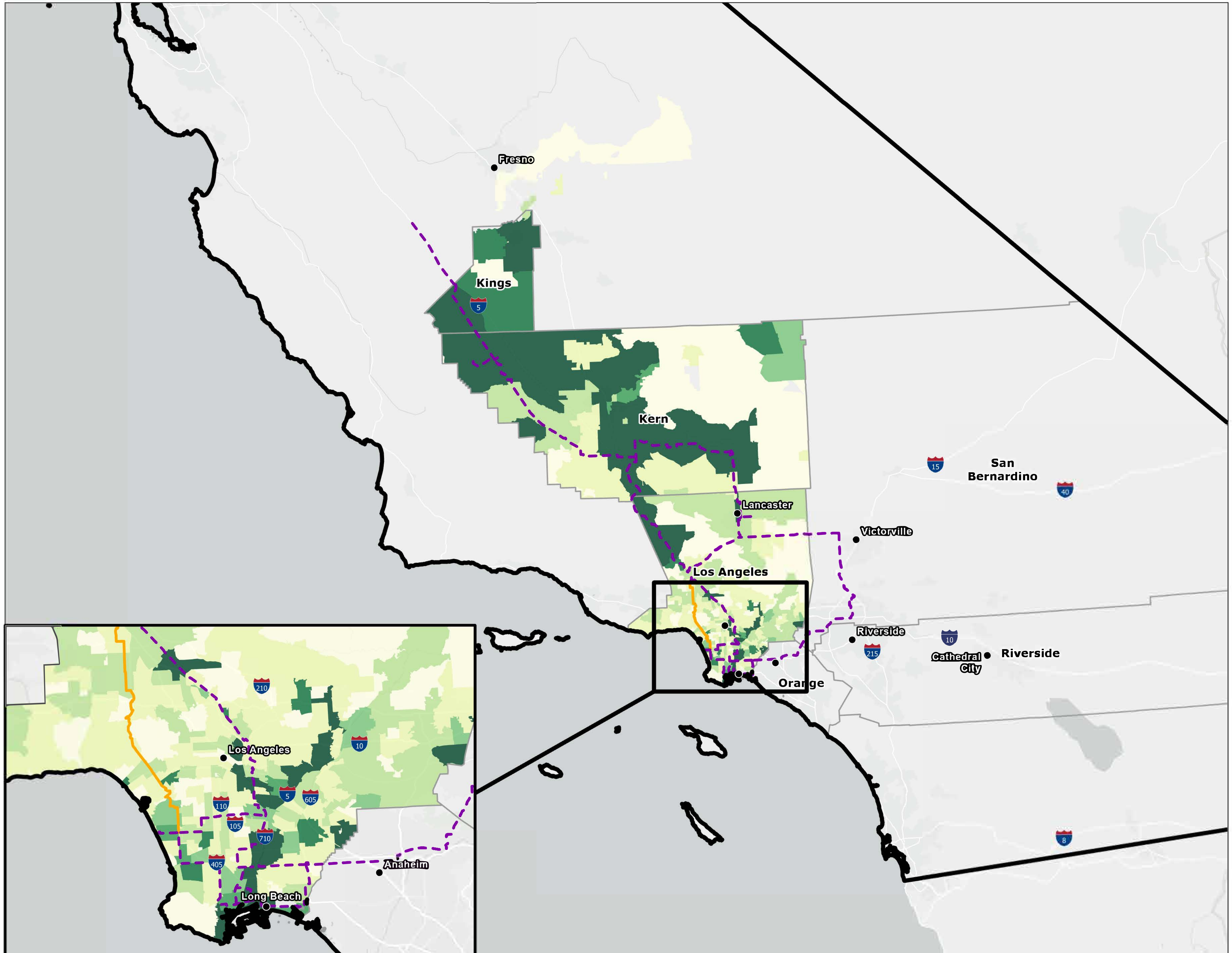


Figure No.
A-14

Title
NOx Emissions Reductions Associated With Angeles Link (AL) 2035 Total, High Throughput

Client/Project 203723235
Southern California Gas Company (SoCalGas)
Phase One NOx Study

Project Location
California

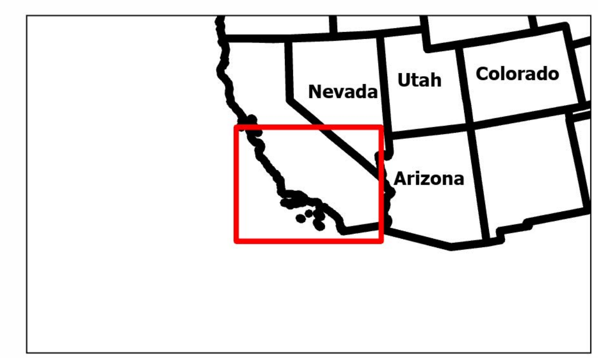
Prepared by BS on 2024-07-19

N

0 20 40 Miles
(At original document size of 11x17)
1:2,534,400

Legend
- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1

Reduction in NOx Emissions Attributable to AL in 2035, High Scenario
- 0.00 - 0.06 tons/year NOx
- 0.06 - 0.16 tons/year NOx
- 0.16 - 0.32 tons/year NOx
- 0.32 - 0.51 tons/year NOx
- 0.51 - 0.78 tons/year NOx
- 0.78 - 7.7 tons/year NOx
- >7.7 tons/year NOx



Notes
1. Coordinate System: NAD 1983 StatePlane California II FIPS 0402 Feet
2. Data Sources: USGS, OEHHA, CalEPA, CEQ
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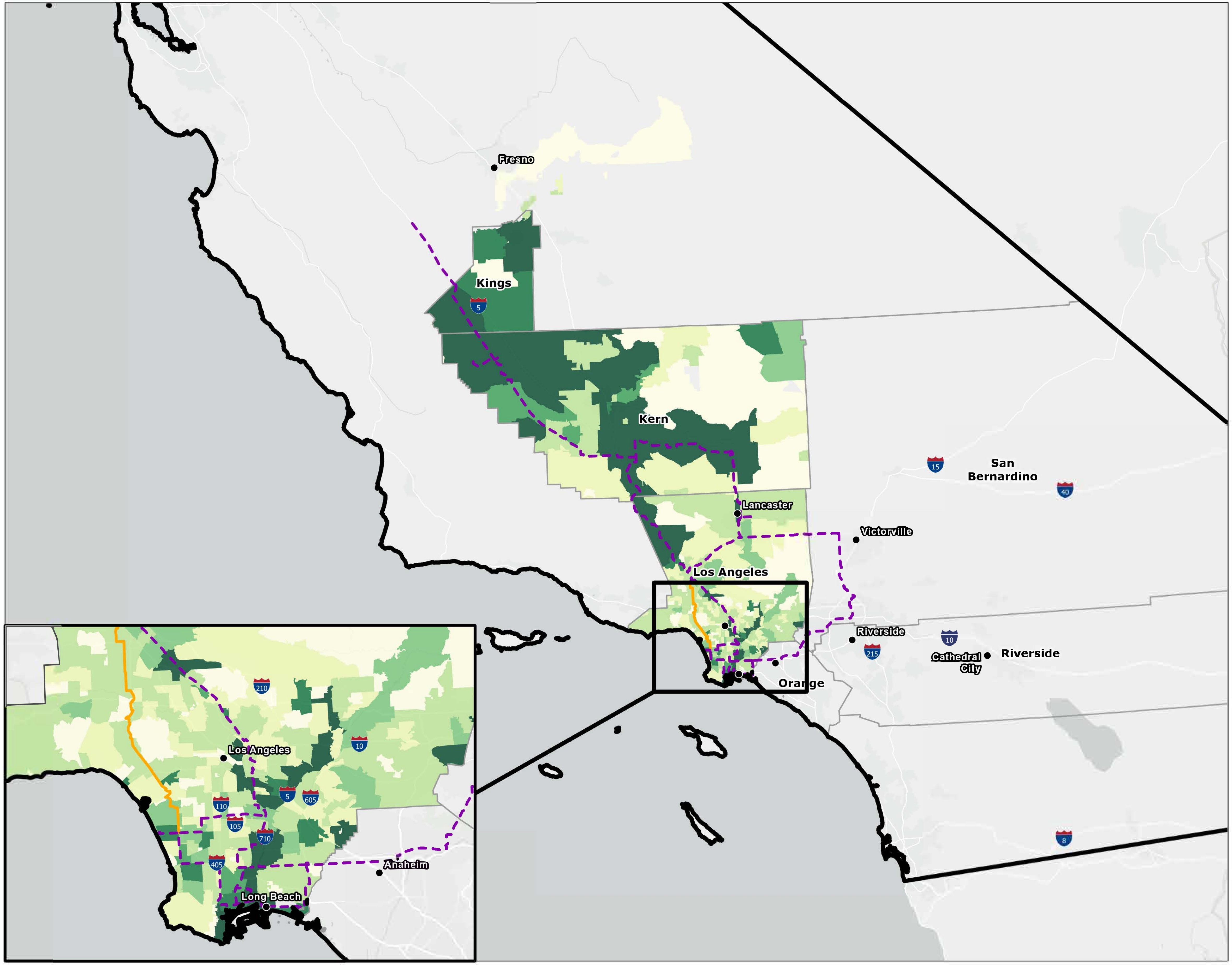
Figure No.
A-15

Title
NOx Emissions Reductions Associated With Angeles Link (AL) 2040: Total, High Throughput

Client/Project 203723235
Southern California Gas Company (SoCalGas)
Phase One NOx Study

Project Location
California

Prepared by BS on 2024-07-19



N

0 20 40 Miles
(At original document size of 11x17)
1:2,534,400

Legend
- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1

Reduction in NOx Emissions Attributable to AL in 2040, High Scenario
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- >7.7 tons/year NOx

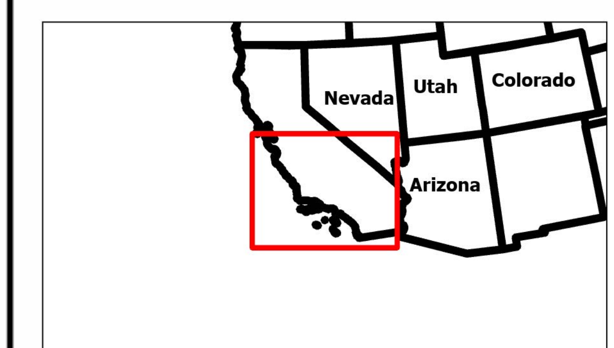

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Figure No.

A-16

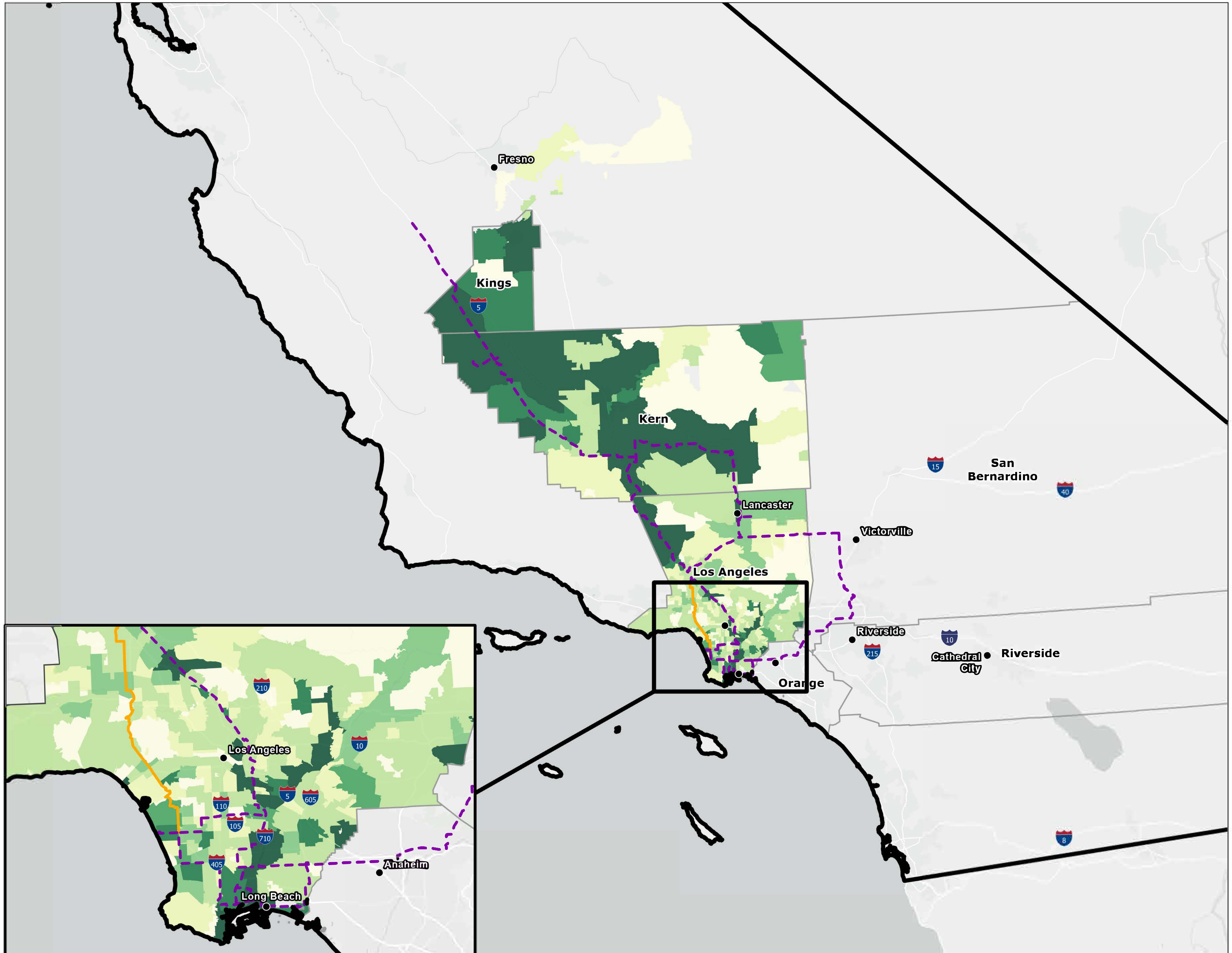
Title

NOx Emissions Reductions Associated With Angeles Link (AL) 2045: Total, High Throughput

Client/Project 203723235

Southern California Gas Company (SoCalGas)
Phase One NOx Study

Project Location Prepared by BS on 2024-07-19
California



N

0 20 40 Miles
(At original document size of 11x17)
1:2,534,400

Legend

- Major Cities
- State Boundary
- Counties
- Interstate/Highway
- Preferred Routes (combined)
- Route Variation 1

Reduction in NOx Emissions Attributable to AL in 2045, High Scenario

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- 0.32 - 0.51 tons/year NOx
- 0.51 - 0.78 tons/year NOx
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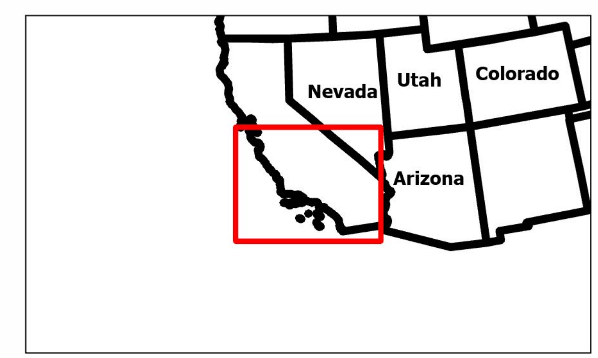
- >7.7 tons/year NOx



Notes

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Appendix B: EJ Map

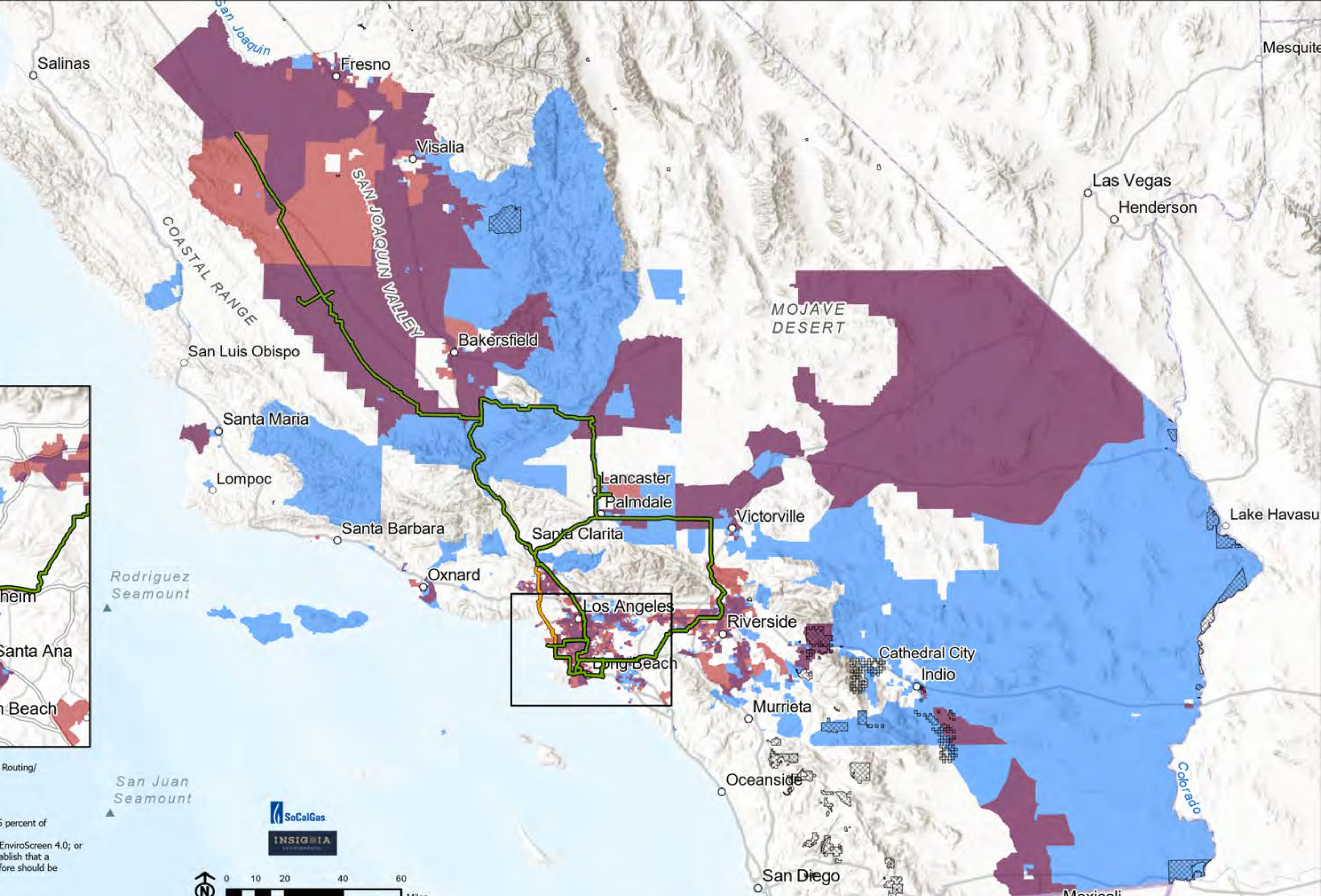
Angeles Link Project Phase 1
Potential Pipeline Corridors Under Evaluation

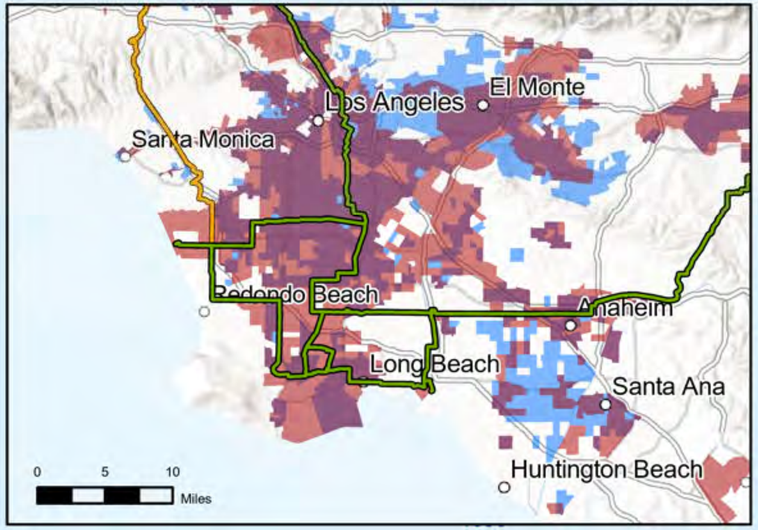
Disadvantaged Communities (DACs)

- Preferred Pipeline Corridor Route Under Evaluation^
- Route Variation 1

Disadvantaged Community

- CalEnviroScreen 4.0 (CES4) SB 535 DAC*
- Climate and Economic Justice Screening Tool (CEJST) DAC**
- CES4 and CEJST Overlapping DACs
- Federally Recognized Tribal Land





^Preferred pipeline corridor route based upon the alignment identified in May 2024 during the Preliminary Routing/Configuration Analysis.

*CalEnviroScreen 4.0 (CES4) SB 535 DAC identified as:
1) Census tracts receiving the highest 25 percent of overall scores in CalEnviroScreen 4.0;
2) Census tracts lacking overall scores in CalEnviroScreen 4.0 due to data gaps, but receiving the highest 5 percent of CalEnviroScreen 4.0 cumulative pollution burden scores;
3) Census tracts identified in the 2017 DAC designation as disadvantaged, regardless of their scores in CalEnviroScreen 4.0; or
4) Lands under the control of federally recognized tribes. For purposes of this designation, a tribe may establish that a particular area of land is under its control even if not represented as such on CalEPA's DAC map and therefore should be considered a DAC.

**Climate and Economic Justice Screening Tool (CEJST) DAC identified as:
1) Census tracts that meet the thresholds for at least one of the tool's categories of burden (climate change, energy, health,