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A Holistic Analysis of Energy and Environmental Impacts from Hydrogen as an Alternative Fuel in 2050

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Mechanical and Aerospace Engineering

by

Peter Willette

Thesis Committee:
Professor Scott Samuelsen, Chair
Professor Jack Brouwer
Professor Yun Wang

2014

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List of Terminology

Acronym	Meaning
GHG	Greenhouse Gas
ARB	Air Resources Board
CEC	California Energy Commission
SoCAB	South Coast Air Basin
SJVAB	San Joaquin Valley Air Basin
SFBAAB	San Francisco Bay Area Air Basin
APEP	Advanced Power and Energy Program
ZEV	Zero Emission Vehicle
LCFS	Low Carbon Fuel Standards
ARFVTP	Alternative and Renewable Fuel and Vehicle Technology Program
HFCEV or FCV	Hydrogen Fuel Cell Electric Vehicle
BEV	Battery Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
NREL	National Renewable Energy Laboratory
HSC	Hydrogen Supply Chain

MILP	Mixed Integer Linear Programming
DP	Dynamic Programming
GIS	Geographic Information System
MSM	Macro Systems Model
SNL	Sandia National Laboratory
SERA	Scenario Evaluation, Regionalization & Analysis
EMFAC	EMission FACtor
PCA	Preferred Combination Assessment
STREET	Spatially and Temporally Resolved Energy and Environment Tool
AHP	Analytical Hierarchy Process
LCA	Life Cycle Analysis
HFit	Hydrogen Fueling Infrastructure Tool
HiGRID	Holistic Grid Resource Integration and Deployment
VMT	Vehicle Miles Traveled
CR	Consistency Ratio
GREET	The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
H2A	The Hydrogen Analysis Project

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Abstract of the Thesis

A Holistic Analysis of Energy and Environmental Impacts from Hydrogen as an Alternative Fuel in 2050

By

Peter Willette

Master of Science in Mechanical and Aerospace Engineering

University of California, Irvine, 2014

Professor Scott Samuelsen Irvine, Chair

The driving factors for pursuing alternative fuels stem from energy issues associated with fossil based sources. In particular, such sources are finite in quantity, foreign sourced, and directly emit both greenhouse gasses (GHGs) and criteria pollutants during their utilization. In California, the transportation sector is in the lead for the consumption of overall energy by sector, with passenger vehicles emitting the most GHGs out of the entire transportation sector. Motivated by the large body of legislation and the complex nature of the potential alternative fuel supply chains, the goal of this work is to examine hydrogen as an alternative transportation fuel. To this end, a computer model was developed that allows for the systematic selection of preferred hydrogen supply chains. The goals of this thesis are to: 1) Establish spatially and temporally resolved generation, distribution, dispensing, and utilization scenarios for fueling the hydrogen transportation sector based on a systematic selection technique, and 2) Quantify the environmental impacts, and energy requirements in comparison to the current supply of petroleum fuels. The modeling approach developed herein, the Hydrogen Fueling infrastructure tool (HFit), takes a global decision-making approach to the creation and evolution of a future hydrogen infrastructure. In order to exercise the HFit, several case studies were conducted with different decision-making datasets. The outputs allowed for the simulation and quantification of a future hydrogen economy within the state of California on a spatial and temporal basis.

1. Introduction

1.1 Current Energy Issues

1.1.1 Finite Resources

Energy consumption is slated to rise steadily in the coming decades, clearly seen in Figure 1. One reason for this growing demand is that energy utilization is taken for granted. It is expected that we will be able to flip a switch and receive light, or turn a key and drive away. However, the dominant energy sources are not only finite, but continue to place an ever increasing burden on our environment. These two key factors drive the search for technologies and methodologies that will provide a greater fraction of energy demand from renewable resources.

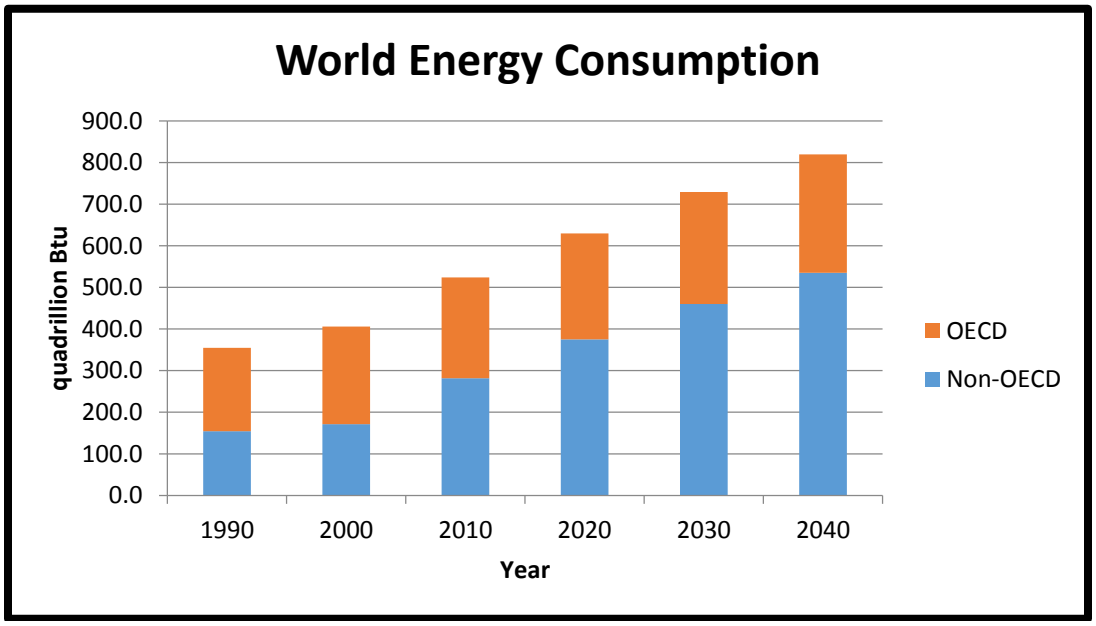


Figure 1 World Energy Consumption: Data Source [1]

1.1.2 Energy Security

Over the past two decades California has been steadily increasing its percentage of foreign crude oil import, as seen in Figure 2. According to the California Energy Commission in 2012, an all-time high of almost 51% of crude oil supplied to California refineries was placed into the “Foreign” category

[2]. A breakdown of the definition of "Foreign" can be seen in Figure 3. By relying on these sources for energy, it leaves the door open for complex geopolitical situations to occur, which could lead to energy shortages or extreme price hikes [3].

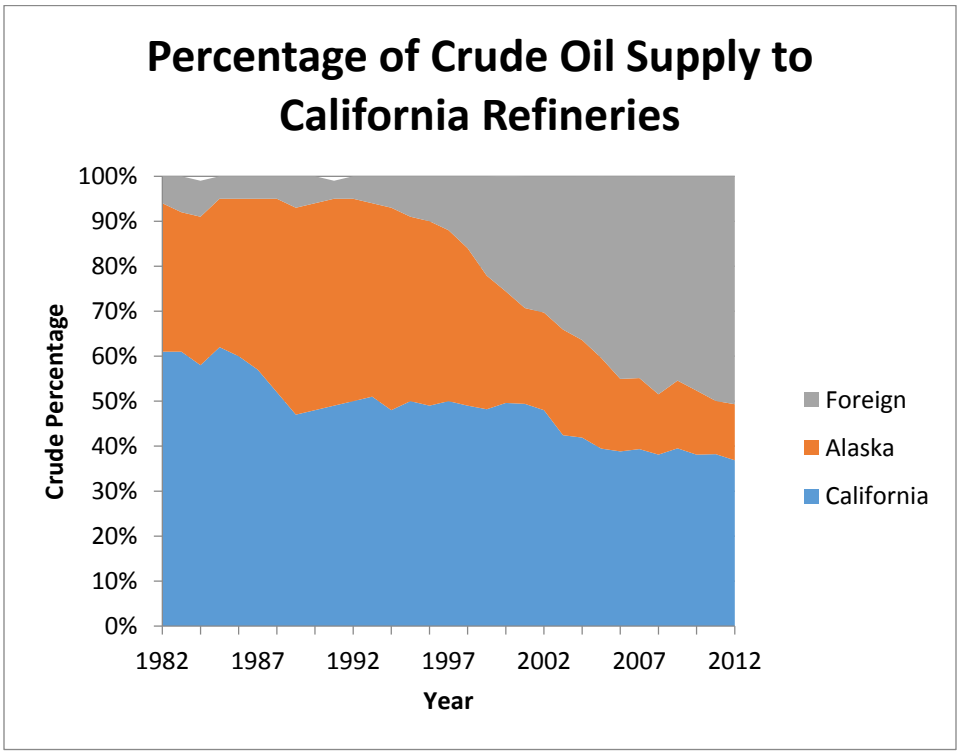


Figure 2 Source percentage breakdown for CA refinery crude receipts: Data Source [2]

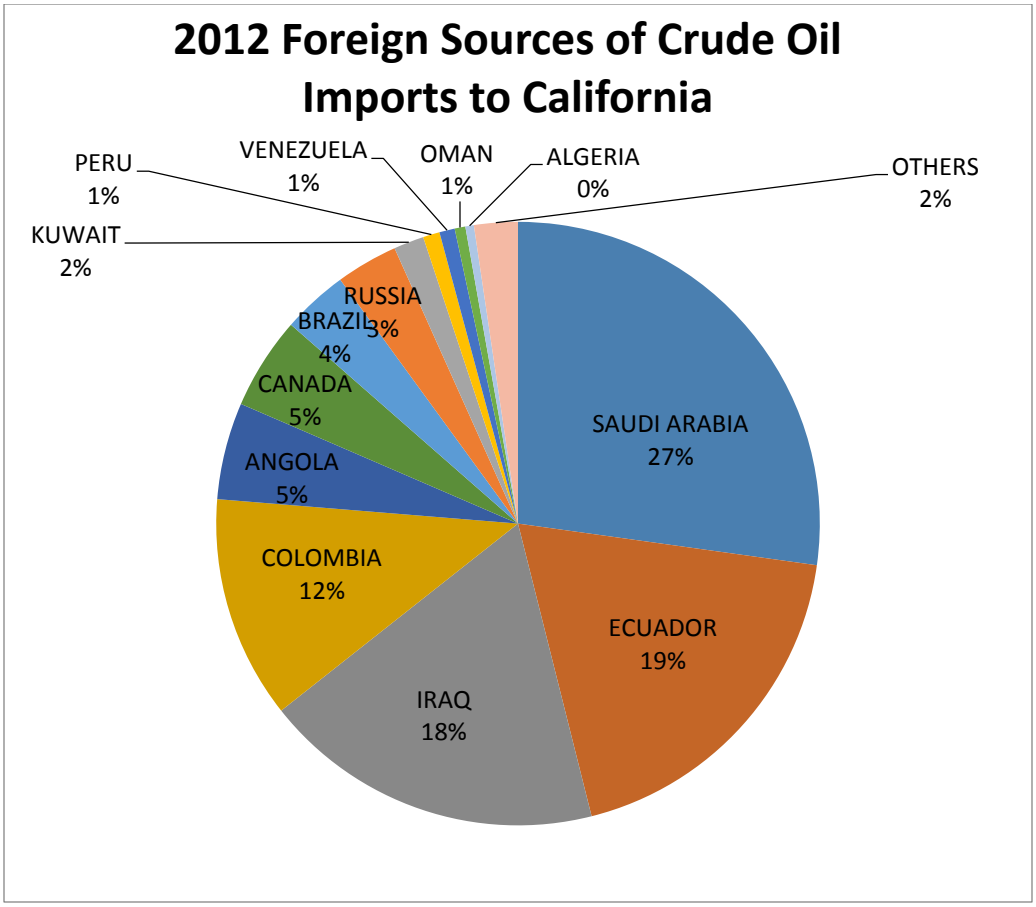


Figure 3 Breakdown of foreign crude oil sources: Data Source [4]

1.1.3 California's Emissions

California has a particularly unique challenge when focusing on reducing its current energy use and emission levels, due to its large transportation sector. It can be seen from Figure 4 that when comparing California's Greenhouse Gas (GHG) equivalent emissions to the national average, the transportation sector has a significantly larger percentage contribution. The California Environmental Protection Agency, Air Resources Board (ARB) has shown that about 33% of Greenhouse Gasses emitted in California come from on road sources, with a full breakdown exemplified in Figure 5. A more detailed view of emissions from the transportation sector in California, in particular, can be seen in Figure 6. By observing this figure it should be noted that about 25% of total industry wide and 76% of transportation

based emissions come from passenger vehicles. Noticing the emissions intensity of transportation in California becomes a primary driving factor for this work.

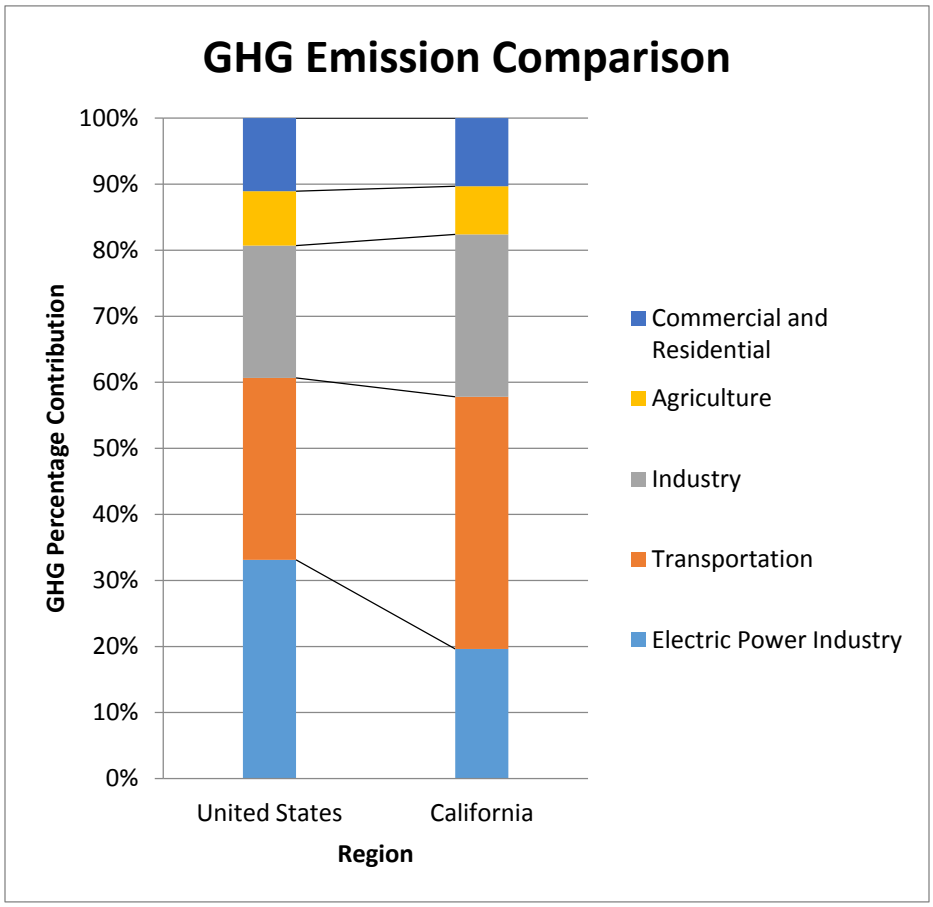


Figure 4 Comparison of National and California GHG Emission Inventories: Data Sources [5], [6]

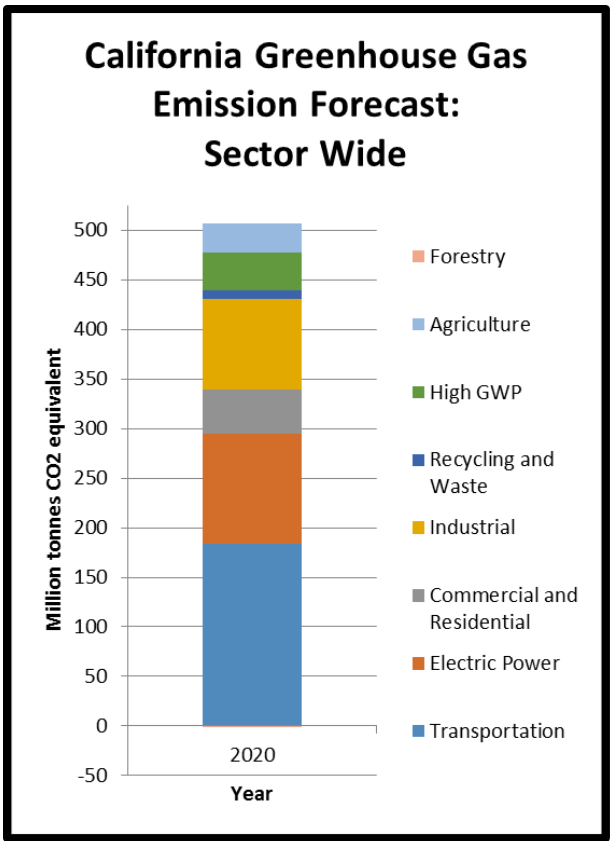


Figure 5 CARB GHG Sector Wide Emissions Projections 2020: Data Source [7]

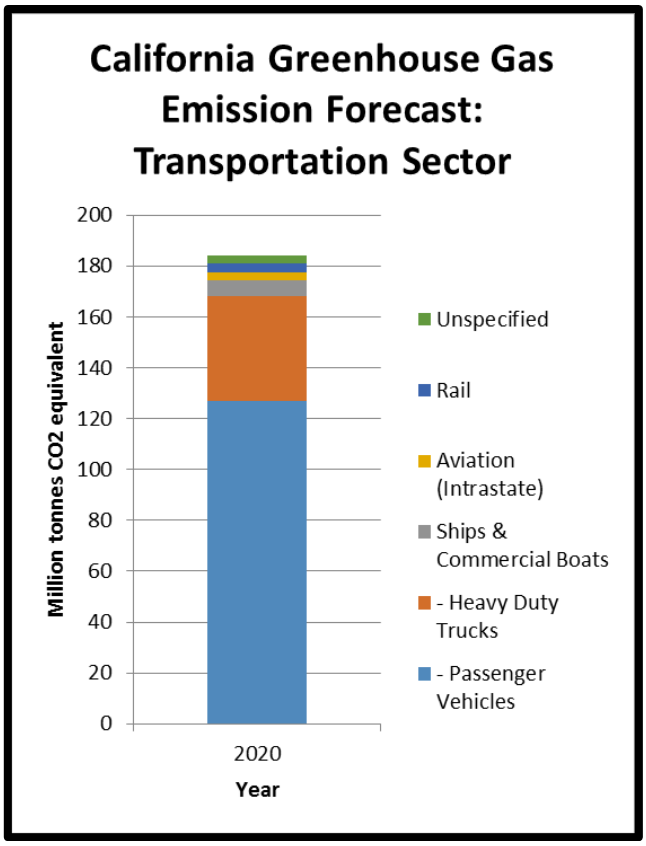


Figure 6 CARB GHG Transportation Sector Emissions Projections 2020: Data Source [7]

1.1.4 Transportation Sector Energy Demands

Exemplification of the large amount of energy used by the transportation sector in California can be seen through the steady increase in consumption of motor gasoline from the 1960's until about 2008. This increasing consumption trend is made apparent in Figure 7. Another key point that can be taken from Figure 7 is that in 2007 California reached peak consumption. The change in consumption trajectory is most likely due to the price of gasoline crossing the three dollar per gallon mark, alongside the legislation that California set into motion in order to reduce this dependence [8]. Even with this slight reduction in gasoline use, consumption and likewise emissions, pollutants, and dependence on foreign oil imports need to be reduced in the coming decades.

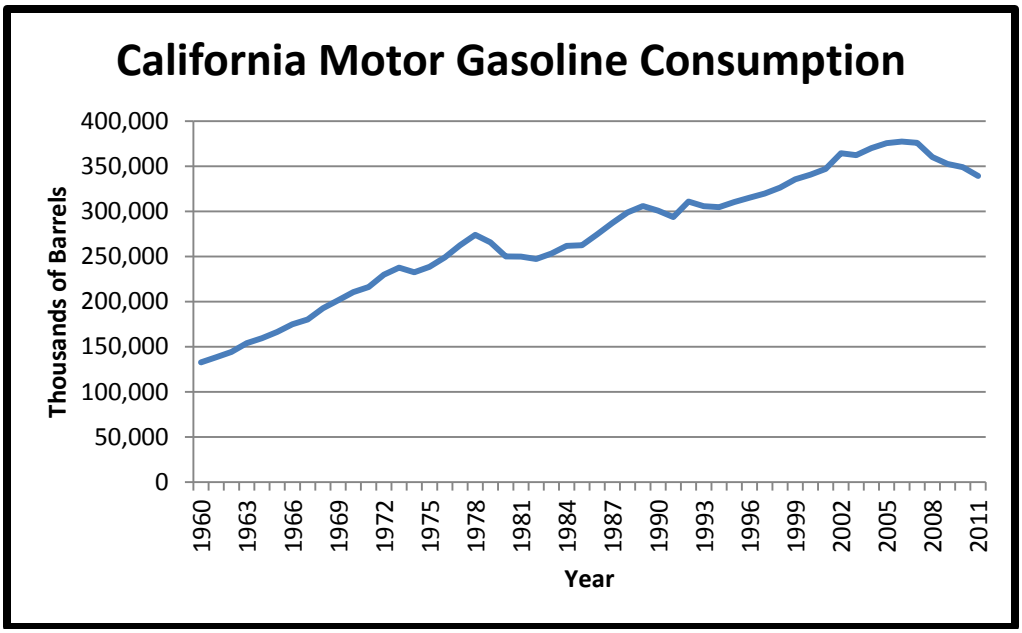


Figure 7 EIA Data for Motor Gasoline Consumption in California: Data Source [9]

In addition to the GHG emissions, more importantly for air quality, passenger vehicles emit a large amount of criteria pollutants. Persistent poor air quality in three primary air basins within the state of California underpins the motivation for a range of legislation. The three main air basins of concern are the South Coast Air Basin (SoCAB), San Joaquin Valley Air Basin (SJVAB), and the San Francisco Bay Area Air Basin (SFBAAB), which all are in non-attainment of either primary or secondary air quality standards [10].

Air pollutants lead to poor air quality across a large part of California [11]. One of the major contributors to poor air quality is Ozone. Figure 8 is a graph of the annual number of noncompliance days for 8-hr Ozone concentration levels in air shed areas across California, from this graph, two key points should be noted: 1) No regions had zero days of non-compliance to National 8-hr Ozone standards for more than one consecutive year and 2) The South Coast Air Basin, San Joaquin Valley Air Basin and Antelope Valley and West Mojave Desert were ranked the top three regions for non-compliance. Ozone is not emitted by automobiles directly; however, they do emit reactive organic gases (ROG), nitrogen oxides (NOx) and carbon monoxide (CO). These three emitted compounds play key roles

in the formation of ozone and can be directly tied back to mobile sources with 53% and 37% of NOx and ROG respectively being attributed to on road sources [12]. This evidence focuses on only three out of a large number of emission components from vehicle tailpipes, further supporting the need for the reduction of emissions from on road vehicle sources in urban areas.

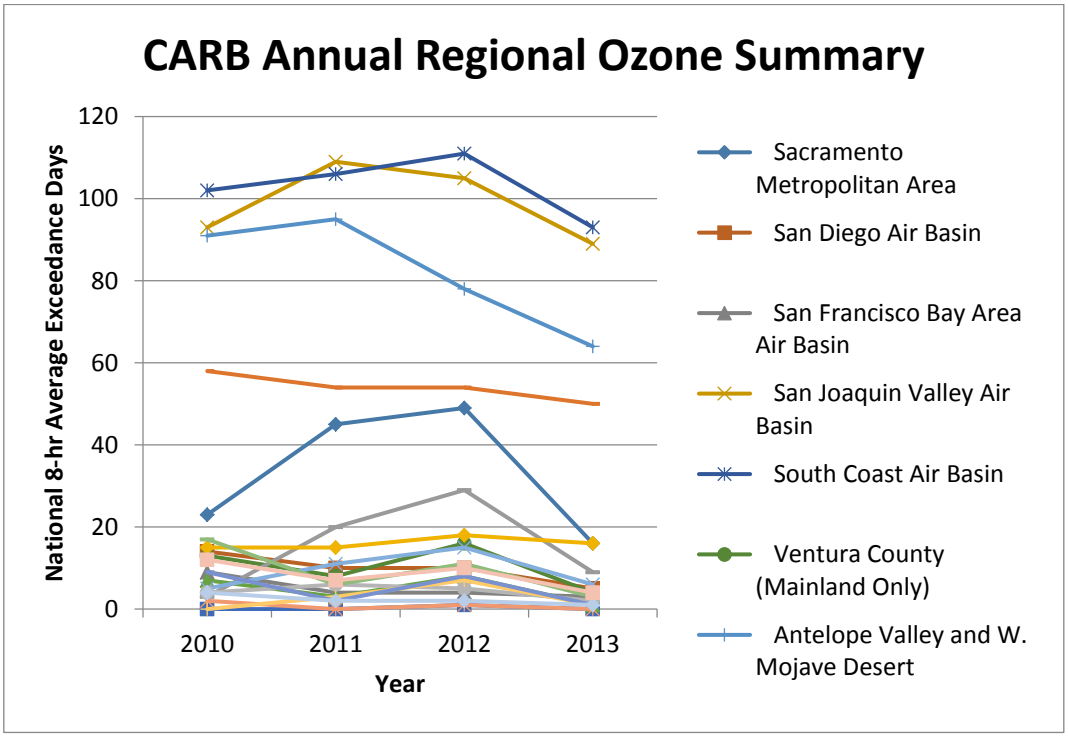


Figure 8 CARB Annual Regional Ozone Summary: Data Source: [13]

In order to combat demand concerns, energy security issues and environmental degradation, California has organized and implemented a series of novel and germane legislation. A summary of the relevant legislation is covered in the next section with a greater detailed analysis being conducted in the body of this document.

1.2 An Introduction to California's Legislative Backbone

California is unique in its area of progressive climate change legislation. As can be seen in Table 1 California has a wide range of legislation and programs dedicated to mitigating climate change and improving air quality. The main areas of focus with regard to legislation in this study have to do with the

production of hydrogen, its potential as a transportation fuel and the corresponding effects on symbiotic infrastructure. Therefore, the study herein leaves out the ongoing effort to reduce end use energy consumption in buildings, appliances and novel technologies within the state. This is due to as shown in Figure 4, Figure 6, and Figure 8 the main contribution to climate change and air pollution in California is the transportation sector.

Table 1 Summary of California's Climate Change Legislation with a focus on the Energy Sector and Transportation

Roadmap review of California's environmentally conscious legislation
Climate Change
i. **AB 32: Global warming solutions act:** Reduce GHG emissions 80% below 1990 levels by 2050 [14] ii. **SB 2: Energy: renewable energy sources:** 33% renewable energy portfolio by the year 2020 [15] iii. **SB 375: Sustainable Communities:** requires regional action plans for the reduction of GHGs due to transportation and sustainable land use [16]
Transportation Fuels
i. **Low Carbon Fuel Standards (LCFS):** is intended to ensure that the life cycle carbon intensity of a fuel meets certain goals. By meeting these goals, resulting GHGs will be lowered [17]. ii. **AB 1007: State Alternative Fuels Plan:** Created in 2005 in order to set in place a plan to further the utilization of alternative fuels within the state of California. The plan concludes that hydrogen is a viable alternative fuel and outlines what must be done in order to bring it to market with an emphasis in the need for hydrogen fueling stations and generation infrastructure. [18] iii. **The Zero Emissions (ZEV) Action Plan:** categorizes hydrogen fuel cell vehicles as zero emission in nature. The overall goal of the ZEV action plan is to expedite the market penetration of zero-emission vehicles to 1.5 million by the year 2025 [19]. iv. **AB 118: California Alternative and Renewable Fuel, Vehicle Technology, Clean Air, and Carbon Reduction Act of 2007:** This program looks to fund the improvement and implementation of technologies that will combat poor local air quality [20].
Hydrogen Specific
i. **AB 8: Alternative Fuel and Vehicle Technologies:** Funding Program which allocates $20 million in funding per year for the construction of hydrogen dispensing stations until 100 are operational [21]. ii. **SB 1505: Environmental and Energy Standards for Hydrogen Production:** Ensures that at least 33% of hydrogen will be produced from renewable resources, along with at least a 30% decrease in well-to-wheel GHG emissions, and strict reductions in criteria pollutant emissions as compared to the conventional gasoline pathway [22].

The primary concern of this research is to explore the utilization of hydrogen as a transportation fuel in the state of California, and how it will aid in meeting GHG reduction goals compared to the current petroleum supply chain. The methodology herein allows for a systematic approach in the selection and siting of all infrastructure required for generating, transporting, storing and dispensing hydrogen. This technique leverages all currently installed energy infrastructure locations and supply channels. The investigation takes a combined decision-making and energy systems approach to how a hydrogen economy will interact with the interrelated energy infrastructures. This methodology looks to allow key industry partners and legislators critically examine their preferences and quantify how they will impact the future build out of a hydrogen economy. This approach will allow for the minimization of the global GHG emissions and energy consumption of any given hydrogen generation configuration. Finally, once a pathway mixture is determined, emission factors will be applied for exploration into the effect a hydrogen economy will have on the local air quality and environment as a whole.

1.3 Goals

1. Establish spatially and temporally resolved generation, distribution, dispensing, and utilization scenarios for fueling the hydrogen transportation sector based on a systematic selection technique, and

2. Quantify the environmental impacts, and energy requirements in comparison to the current supply of petroleum fuels.

1.4 Objectives

1. Implement a spatially and temporally resolved hydrogen demand module.
2. Systematically select the overall spatially allocated mix of hydrogen generation technologies.
3. Fully leverage statewide renewable energy sources.
4. Calculate statewide emission profiles due to a future hydrogen economy.
5. Select and outline hydrogen distribution methodologies.

6. Analyze spatially allocated energy resource demand profiles for an hourly hydrogen demand.
7. Quantify emission reductions due to reduced gasoline consumption in a future hydrogen economy.

2 Background

As introduced earlier, California has an extensive and complex groundwork of legislation in place with the aim of reducing the environmental impacts of the energy sector within the state. Therefore, this section will examine in more detail, the legislative steps taken and how they relate to this work. Then, an introduction to hydrogen energy technology is carried out. Next, a thorough review of the current literature pertaining to hydrogen as a transportation fuel is conducted. Finally, the energy system modeling methodology developed at the Advanced Power and Energy Program (APEP) is introduced and the applicable part to this work is introduced in conjunction with the most recent and germane work being conducted in the literature.

2.1 Renewable Penetration and Energy Sector Emission Goals

In 2005 Governor Schwarzenegger enacted Executive order S-3-05 which set into motion three GHG emission goals for the state of California in the near and long term. These goals are to 1) By the year 2010 bring GHG emission back to 2000 levels, 2) By the year 2020 achieve 1990 levels and 3) by year 2050 establish levels of GHG emissions equivalent to an 80% reduction below those recorded in 1990. These goals have been extended by Assembly Bill 32 (AB 32) (Núñez/Pavley), the Global Warming Solutions Act. This bill focuses on the second objective of reducing GHG emissions to 1990 levels by 2020. [23]

In order to meet these ambitious targets, California will need to take a holistic[1] multi-sector approach. Therefore, other legislation such as Senate Bill 1078 has been put into place which establishes Renewable Portfolio Standard (RPS), or renewable energy penetration goals for the state. These goals are delineated specifically by Bill 1078 and are updated by Bill 2, with an aim to have a penetration of 20% by 2013, 25% by 2016 and 33% by 2020. [24] These high penetration objectives, along with future increased load from the electrification of the transportation sector will have complex and dynamic interactions with the electrical grid. These complex interactions and concurrent complimentary technology utilization strategies play a key role in optimal energy utilization and price regulation [25], [26]. Therefore, in order to fully leverage these high renewable penetration rates, a sector wide, California specific approach must be taken when analyzing the future of California's energy system and build out of complimentary infrastructure.

2.2 Transportation Specific Goals and Legislation

In 2002, California initiated its journey toward reducing overall GHGs from the transportation sector via Assembly Bill 1493 (Pavley), which set standards to reduce GHGs from passenger vehicles starting in the year 2004. However, due to a great deal of litigation against these standards by automakers, these original standards were not implemented. It was not until 2009 that an updated agreement was met and this legislation was enacted [27].

A plan was set into place in 2007 by Assembly Bill 1007 (Pavley) in order to spearhead an approach to expand the use of alternative fuels in California. Incorporated into this plan was powerful legislation introduced by Executive Order S-1-07, and is now known as the Low Carbon Fuel Standards (LCFS)(January 18, 2007) [18]. The purpose of these standards is to obtain a 10% reduction in the carbon intensity of transportation sector fuels by the year 2020 [18]. These standards focus on the

[1] "Holistic: relating to or concerned with complete systems rather than with individual parts [111]"

transportation sector as an integral part of California's overall global warming reduction strategy known as AB 32 (Núñez/Pavley) mentioned earlier [23].

Studies have shown that even with these forcing functions, in order to reduce fuel consumption and GHGs from passenger vehicles, more must be done in order to meet California's emission reduction goals by the year 2050 [23], [28]. In order to assist with this endeavor, California has enacted the Sustainable Communities and Climate Protection Act of 2008 (SB 375, Chapter 728, Statutes of 2008) [16]. This legislation forces regional action plans for a holistic approach toward transportation, housing and land use that must result in the region meeting California's overall AB 32 goals [16].

California has since taken additional steps toward fulfilling its environmentally conscious targets by continually ensuring the funding of alternative fueled transportation vehicles through the Alternative and Renewable Fuel and Vehicle Technology Program (ARFVTP), set into place by Assembly Bill 118 (Núñez) [29]. The ARFVTP has come to be known as the single largest public funding source of hydrogen stations in the country [29].

The most recent alternatively fueled vehicle planning and support was under taken by Governor Brown through the enactment of Executive Order B-16-2012. From this Executive Order stemmed the *2013 ZEV Action Plan* [19]. This plan cultivates an integrated approach to increasing the number of Zero Emission Vehicles (ZEVs) on the road through education, funding and the setting of targets [19]. In this context, the definition of ZEV incorporates the following vehicle types: hydrogen fuel cell electric vehicles (HFCEVs), battery electric vehicles (BEVs), and plug-in hybrid electric vehicles (PHEVs) [19]. This Executive order proposes to have 1.5 million ZEVs on the road by 2025 and solidifies the mandate of reducing carbon emissions by 80% below 1990 levels by 2050 [19].

2.2.1 Hydrogen Specific Goals and Legislation

In order to encourage a nurturing environment for alternative fuels in California, with special emphasis on hydrogen, legislation was established in 2004 by Executive Order (EO) S-07-04 [30]. This Executive Order is known as "The California Hydrogen Highway Network" (CaH2Net). This program was initiated with the goals of producing a hydrogen fueling network for the transportation sector that both advances a business environment, but also assists the state in meeting its environmental goals [31]. This program has been continued and further developed through AB 8, by making $20 million in annual funding available for the construction of hydrogen stations within the state until 100 dispensing locations have been deployed [21].

Finally, California has implemented goals that focus on the production of hydrogen. SB 1505 was signed into law in 2006 and was designed to focus on ensuring that California could reap the large potential benefits hydrogen has as a clean energy carrier [22], [32]. This law has set forth five key points for parameters that must be met in the future production of hydrogen as a transportation fuel, they are as follow:

1) 33.3% of hydrogen must be produced from eligible renewable sources [22], [32], [33].
2) On a well-to-wheel, per-mile basis, GHG emissions must be reduced by 30% as compared to a standard new gasoline fueled vehicle [22], [32], [33].
3) On a well-to-tank, energy equivalent basis, nitrogen oxides and reactive organic gases must be reduced by 50% as compared to the average gasoline dispensed [22], [32], [33].
4) On a well-to-tank, energy equivalent basis, air toxic contaminants at a hydrogen dispensing location must not increase as compared to motor gasoline [22], [32], [33].
5) Annual hydrogen dispensing and mass quantities must be reported to the ARB [22], [32], [33].

These laws motivate the drive to develop a strategy for the planning and development of a future hydrogen fueling infrastructure, with a special emphasis on sources of renewable generation and likewise serve as a cornerstone for the motivation of this project.

2.3 Hydrogen as a Transportation Fuel

Aside from the many forcing functions currently in place to foster a hydrogen economy, it exhibits many desirable characteristics as an alternative transportation fuel. The hydrogen cycle is closed, regenerative and when coupled with carbon free generation sources, has the potential to generate zero emissions during its synthesis and utilization [34]. Intermittent energy storage is another symbiosis that can be achieved when hydrogen and renewable energy sources are coupled. Finally, hydrogen's ability to be generated from a plethora of primary sources leads to a wide range of generation possibilities and will facilitate a transition toward its mainstream utilization [34]. Looking at hydrogen from a broader energy perspective, as a method for abandoning the current petroleum supply chain, will potentially allow for an enormous reduction in criteria pollutant and GHG emissions, along with a heightened sense of energy security [35].

2.3.1 Hydrogen Vehicle Fueling Supply Chains

As previously mentioned hydrogen has the potential to be generated from a wide range of primary energy sources, with the supply chains visualized in Figure 9. This figure displays the inherent flexibility that hydrogen has as an energy carrier. It can also be seen that the complexity of hydrogen generation is multilevel.

The feedstock must first be harvested as a primary energy source and then, dictated by source type, a conversion process to hydrogen must be undertaken. Each of these conversion technologies inherently has a different input energy requirement and as a result has a varied efficiency as can be seen in Table 2. An additional take away from this table is the option of renewable or sustainable primary

energy sources for the generation of hydrogen. This is a key point in pursuing a hydrogen economy in California, in the hopes of meeting future emission reduction goals.

After generation, hydrogen must then be purified and compressed to an acceptable distribution or storage pressure. Storage and distribution can be undertaken in gaseous or liquefied form. Gaseous delivery is nominally undertaken at either 2,500 or 7,500psi. Once the hydrogen has been delivered to the dispensing location, it must either be further compressed, or expanded in order to meet the specific delivery needs of the station, depending on the form of its arrival. There is also the option of generating hydrogen at the site of dispensing. This option thus eliminates the need to transport the hydrogen, usually with a tradeoff of lower conversion efficiencies and greater capital cost per kilogram, due to the lack in economies of scale. These tradeoffs were detailed in a study conducted by the National Renewable Energy Land (NREL) and are summarized for two cases in Table 3. Decentralized methods are still appealing in the near term, due to a low initial hydrogen demand. Lower capacity allows for a smaller initial investment cost and the elimination of any hydrogen delivery costs [36]. The aforementioned procedures and methodologies of producing, storing, distributing and dispensing hydrogen consist of what is often referred to as a Hydrogen Supply Chain or HSC.

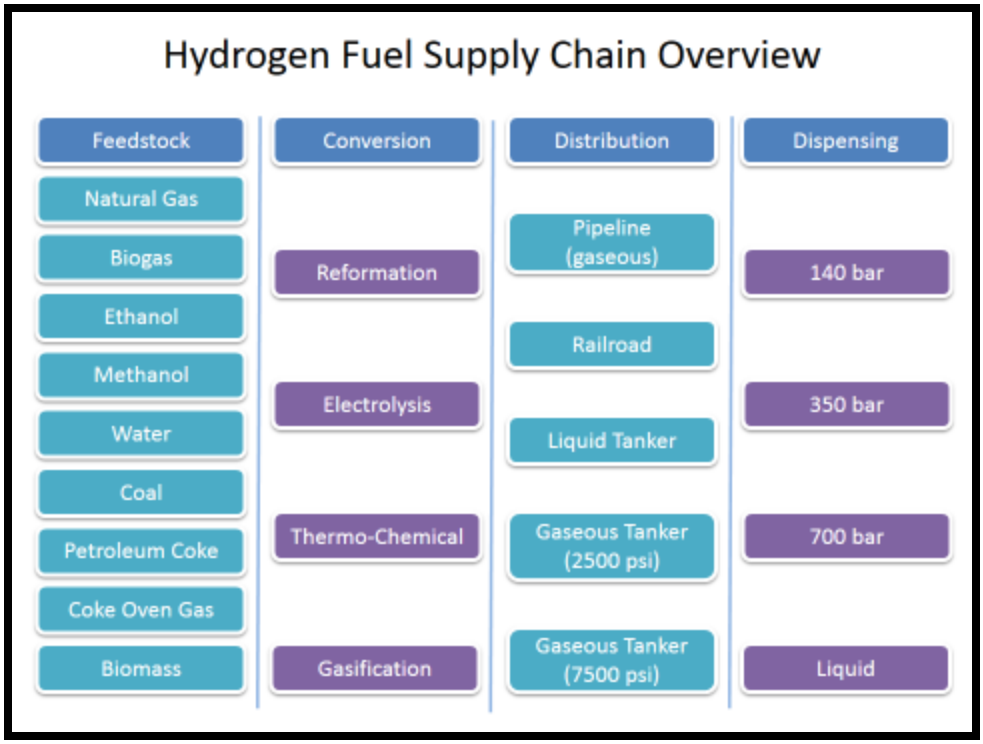


Figure 9 Potential Hydrogen Supply Chains: Data Source [37]

Table 2 Amount of Renewable and Non-renewable Resources Required To Produce 1 kg of Hydrogen and Production Efficiencies: Table Reproduced From Source: [38]

Amount of Renewable and Non-renewable Resources Required to Produce 1 kg of Hydrogen and Production Efficiencies				
Resource	**Conversion Pathway**	**Amount to Produce 1 kg Hydrogen[a]**		**Production Efficiency[b] (Eout/Ein, LHV)**
Natural gas	Steam Methane Reforming	167.5 scf	165 MJ	73.10%
Coal	Coal Gasification with CCS	9.8 kg	271 MJ	44.30%
Nuclear (uranium)	High-Temperature Electrolysis	6.72×10-5 kg U	260 MJ	46.00%
Nuclear (uranium)	Thermochemical	7.03×10-5 kg U	273 MJ	44.00%
Biomass	Biomass Gasification	13.0 kg bone dry biomass	242 MJ	48.30%
Wind power	Electrolysis	46 kWh	166 MJ	72.60%
Solar power	Electrolysis	46 kWh	166 MJ	72.60%

[a] Values are derived from H2A Future Central Case Studies for each resource type and from the central electrolysis case study for wind and solar. Efficiencies indicated are for "hydrogen energy out" divided by "resource energy in," and do not account for any additional input feedstock consumption or electricity byproduct credits. Efficiency definitions are distinct in that resource "energy in" is in different forms, as noted in the column indicating MJ of resource required. The 167.5 scf per kg for steam methane reforming is derived from the future central steam methane reforming case study, 9.8 kg of coal is from the future central coal gasification case study (coal use is equivalent between the with and without CCS case studies), and 13.0 kg bone dry biomass is from the future central biomass gasification case study. Heat content of coal is 27.685 MJ/kg coal, and it is associated with natural gas with an LHV of 930 BTU/scf. Uranium consumption for the nuclear high-temperature electrolysis and thermochemical production pathways are described above. The H2A case studies are available from the DOE H2A website: http://www.hydrogen.energy.gov/h2a_prod_studies.html.

[b] Production efficiency is defined as the energy of the hydrogen out of the production process (on a LHV basis) divided by the sum of the energy into the process from the feedstock. Production efficiencies indicated for wind and solar are based on electrical energy input (46 kWh) and nuclear efficiencies are on a heat input basis.

Table 3 Centralized Versus Distributed Generation of Hydrogen: Data Source [39]

Technology	**Centralized Process Energy Efficiency (LHV, W.O. CO2 Capture)**	**Total Delivered Hydrogen Cost**	**Distributed Process Energy Efficiency (LHV)**	**Total Delivered Hydrogen Cost**
Natural Gas Reformation	71.9% (Current) 71.8% (Future)	1.32 $/kg (Current) 1.40 $/kg (Future)	68.4% (Current) 71.0% (Future)	3.50 $/kg (Current) 1.47 $/kg (Future)
Electrolysis	62.4% (Current) 74.6% (Future)	4.50 $/kg (Current) 3.24 $/kg (Future)	60.5% (Current) 71.9% (Future)	6.05 $/kg (Current) 4.92 $/kg (Future)

2.3.2 Imminent Hydrogen Fuel Cell Vehicle Roll-Out

Automakers have invested a substantial amount into creating a robust HFCEV with many of these vehicles set to debut within the next two years [40]. A main issue that is currently barring a more rapid adoption rate of these vehicles is the lack of a well-established refueling infrastructure. Developing a hydrogen infrastructure, especially in the near term due to high initial investment costs, will be a delicate process. In order to foster both the near and long term infrastructure evolution, a well-planned roll-out sequence must be constructed for each specific geographic region that minimizes cost and environmental impacts via a multidimensional comparison of various HSCs. Choosing an appropriate deployment strategy leading to a desirable outcome is only complicated by the number of stake holders involved, processing complexity, and an expansive array of primary sources of feedstock that have the ability to be converted into hydrogen transportation fuel [35].

2.4 Traditional Fossil Based Transportation Fuel

2.4.1 Transportation Sector Fossil Fuel Supply Chains

The transportation sector fossil fuel supply chain is nearly as complex as a hydrogen supply chain. The many components of this energy pathway are illustrated by Figure 10, and include extraction, refining, distribution, dispensing and utilization of the fuel. A key difference between hydrogen and gasoline is the various physical states hydrogen is dealt with in, as compared to the primarily single liquid state of petroleum based fuels.

There has been prior analysis conducted on the petroleum supply chain in California and the potential impacts the reduction in its use might have. However, this study was limited to post refinery and post electricity transmission emissions [41]. This study was also limited to the Sacramento area and the timescale of 2005 and 2025. In order to compliment the work here in, a state wide analysis of the

impacts on the environment based on reduced gasoline production will be conducted through the year 2050.

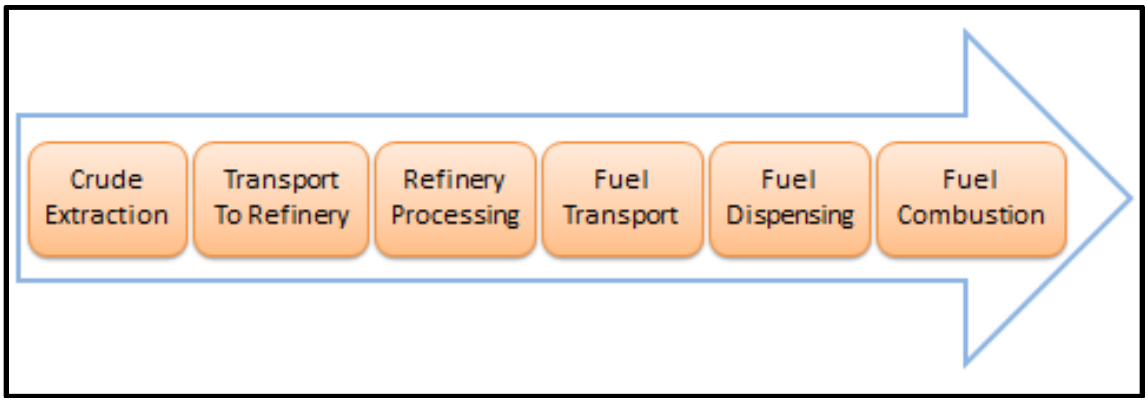


Figure 10 Petroleum Based Fuel Pathway

2.5 Previous Hydrogen Infrastructure Models, Methods and Approaches

Due to the breadth of methods available for producing and distributing hydrogen to the end user, a large number of models have been generated and are reviewed in detail below. The primary objective of these models is to predict the paramount roll-out strategy for a hydrogen supply chain, catering to the transportation sector. Each of the models has an individual and varied focus, ranging from differing geographic regions, to maximizing such things as safety, minimizing environmental impacts or associated investment costs. These models have been separated into three main categories by Dagdougui (2012), consisting of mathematical optimization, geographic information systems and assessment for the planning of a HSC. The work herein considers the aforementioned and several additional categories for the separation of these models.

2.5.1 Mathematical Optimization

Within the section of mathematical optimization problems there exists a large amount of variance between individual authors. One of the main separating factors in this category has been deemed to be the spatial scale and was suggested by Agnolucci (2013). These models can also be categorized by the fundamental optimization methodologies that are implemented.

2.5.2 Energy Systems Methods

A primary and well established subset of these optimization strategies is that of energy systems models. There exists a wide variety of these, which have been utilized in the literature and are named as follows: MARKAL, MESSAGE, GET, GRAPE, and REDGEM70. These software packages focus on energy from a systems wide level, usually spanning very large geographic regions. This type of optimization stands alone in that the hydrogen supply and demand are determined internally through optimization of the system, both spatially and temporally. However, these models typically and most importantly for this work, do not take into account spatial resolution finer than the national level. These models also do not take into account real world consumer or investor adoption of novel technologies. Another downfall of many of these works is that a "consumer-as-optimizer" approach is taken [42]. Finally, in most cases these studies neglect "returns-to-scale", or in other words, such things as economies of scale, bulk production, and variance in consumer familiarity with a product [42].

An additional energy systems model that has been built specifically for the exploration of the hydrogen energy network is MOREHyS [43]. This model was created for the Baltic Sea region and takes into account externally specified electricity and hydrogen demands. This modeling approach focuses on a global cost minimization only, and is limited by large scale clustered geographical regions [43].

2.5.3 Traditional Optimization Methods

Traditional mathematical optimizations come in several forms with Mixed Integer Linear Programming (MILP) being the most widely utilized in the design of hydrogen infrastructure literature. Dynamic Programming (DP), Multi-Objective Programming, Stochastic Programming, and Multi-Period Programming have also been utilized.

The strengths of MILP lay in the fact that this type of problem is able to calculate the infrastructure cost, cost of hydrogen, or environmental factors from a formal optimization methodology [42]. The approach is also general and applicable to varying spatial and limited temporal scenarios [36].

There is an extensive library of literature that utilizes the MILP approach. One concept employs TIMES, which is also an energy systems model that the study caters to focus on several regions and their hydrogen infrastructure build outs [44]. This approach falls short in that it is only quasi-spatial, dividing California into several clustered subsections. It also does not model the interaction of other energy sectors with the hydrogen economy. This model also concentrates on a minimal discounted total system cost and does not focus on the environmental impacts directly [44]. Other models that do not take into account interactions between energy sectors and solely focus on a cost minimization are presented in [45]–[47]. There are studies that take into account interactions of the hydrogen and electric energy sectors that are not explicitly energy systems models, but are limited in their scope by the narrow focus of hydrogen generation technologies [48]. Often times studies not only focus on cost minimization, but have a deterministic hydrogen demand, neglect siting of refueling locations and completely overlook any sort of emission analysis [47], [49].

Other applications of the MILP only capture a portion of the complex nature of a full hydrogen economy [50]–[52]. For example, Johnson (2012) only focuses on the build out of a hydrogen pipeline network and Kim (2012) concentrate solely on hydrogen fueling station siting via a flow maximization problem. This optimization method has again been applied to a limited region of California, with only a single hydrogen pathway consisting of biomass to hydrogen being considered [52].

Current studies using a formal optimization approach have overlooked spatial hydrogen demand gradients, making the assumption that they remain constant across a given region [42]. It has also been denoted that these studies largely neglect life cycle costs of the systems installed (e.g., Value of installed infrastructure or decommissioning costs) [42].

DP is a simplified approach to traditional and formal optimization problems. This methodology was utilized in the planning of hydrogen infrastructure in Southern California with the lowest possible

cost [53]. This approach was also developed in order to optimize roll out scenario decisions on a spatial and temporal level and was coined The Hydrogen Infrastructure Transition Model or HIT [54]. At a first glance, the simplicity of this approach may seem like a positive attribute, but the need for large assumptions in order to produce a solution set has been suggested to be a restriction on the potential breadth of the given results, when compared to traditional MILP [42]. An example of an over simplification in HIT is that an aggregation of stations and production site types is carried out. A post processing approximation methodology is then applied in order to determine the mix of generation locations [54]. Other studies such as the one conducted by Qadrdan (2008), focus on several aggregated geographic regions, with an exogenous hydrogen demand set as a percentage factor, but does take into account the possibility of electricity production from hydrogen. However, this study does not consider the dispensing of hydrogen to fuel cell vehicles portion of the supply chain [55].

Multi-Objective Programming is an alternative form of the MILP problem that is able to simultaneously minimize several factors [36], [56]–[60]. An example of one of these approaches is the design of a hydrogen supply chain, with economic minimization and a component considered for uncertainties involved in economic performance of the system. This particular MILP with uncertainty accommodation is applied in a case study to Spain [60]. Sabio (2012) aims to minimize multiple life cycle assessment and economic impact criteria which lead to large complex data sets and topologies.

A slightly modified approach to the standard Multi-Objective and MILP approaches incorporate stochastic and or Multi-Period Programming. These approaches attempt to predict the future of a hydrogen economy without utilizing a pre-determined hydrogen demand. These methodologies cover the complexity of hydrogen supply chains in their interactions, many components, and large uncertainty in the future of a hydrogen demand over several time “periods” [36], [43], [46], [59]. A specific approach is applied to the overall cost and safety minimization, with stochastic demand capability and a case

study applied to Korea [59]. Following the closely related MILP approach, the Multi-Objective, Multi-period and Stochastic approaches are all limited primarily by the lack of interaction with other energy sectors, along with a spatial capacity constrained to larger aggregate regions due to computational capacity.

2.5.4 Geographic Information Systems (GIS)

GIS acclimated approaches give a strong correlation to regional data such as population, delivery network, availability of primary sources and local legislation [36]. These methods also allow for adaptation and the growing of regional coverage over time [36]. The methodologies main strong points also become its shortcomings when modularity is a focal point of the approach. There are GIS approaches that take into account regional factors and optimize the infrastructure roll out. However, for example, in Johnson (2008), only a single pathway is considered, temporal resolution and thorough analysis of tradeoffs between centralized and distributed methodologies are all lacking.

MARKAL, the energy systems model and GIS have been united in order to explore future policy impacts. One study focuses on the exploration of emission constraints and energy prices based on future proposed energy policy scenarios for Norway [61]. This methodology is limited in that it incorporates a deterministic list of generation facility locations, along with and external number of fueling sites being delegated. Another combination of the two software packages explored the UK and potential effects of future scenarios [62]. This approach greatly simplified the spatial aspect limiting the entire UK to only 6 supply and 12 demand areas [62]. In the future, this study suggests further expansion of the number and detail of the hydrogen fueling pathways along with increased spatial resolution [62].

2.5.5 Hydrogen Economy Simulations

The Macro Systems Model (MSM) was collaboratively created between NREL and Sandia National Laboratory (SNL) in order to integrate the suite of models already created by the United States Department of Energy, for the analysis of various hydrogen supply chains [63]. The models that are

linked can be viewed in Figure 11. With the integration of these models, full Well-to-Wheels analyses can be carried out for various hydrogen supply chains, with a limited spatial and temporal capacity. This global systems model focuses on the hydrogen supply system and leaves out possible interactions with other infrastructure such as electrical or natural gas [63], [64].

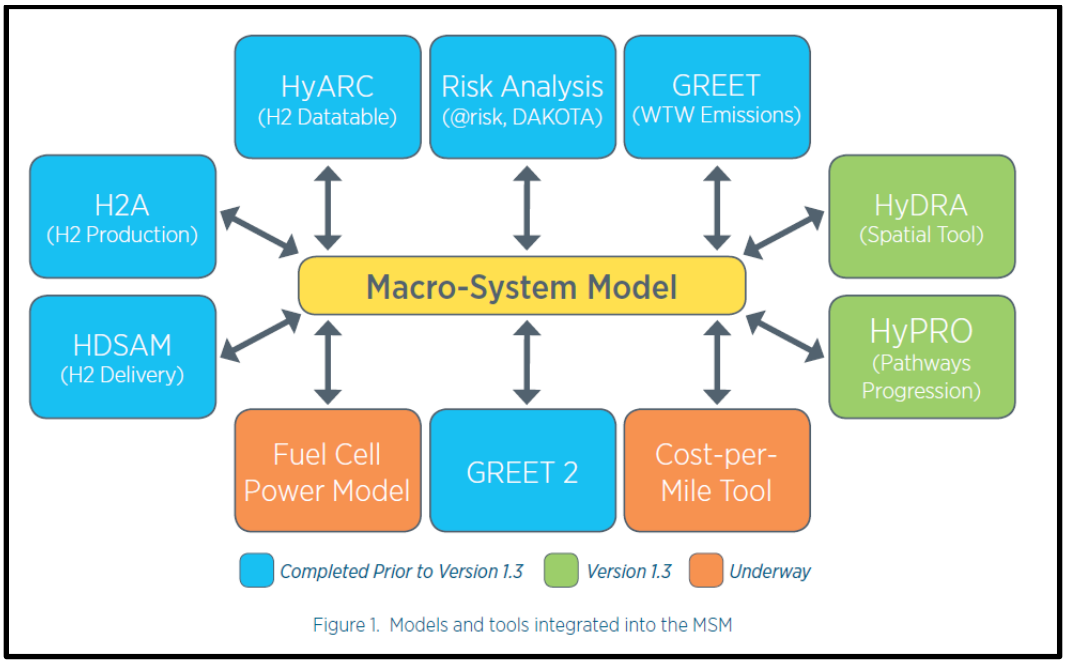


Figure 11 Illustration of the MSM model: Figure Source: [64]

Another model that has been developed at the NREL is known as the Scenario Evaluation, Regionalization & Analysis or SERA. This model takes an exogenously specified regional hydrogen demand, an array of transport and production methods and projected future cost of various hydrogen feedstocks. From these inputs, the model suggests generation locations and pipeline distribution on a spatial level with rail and truck delivery methods being aggregated [65]. This methodology employs a "geospatial statistical model" in order to establish hydrogen dispensing locations which aggregates and then statistically distributes city population densities [65].

2.5.6 Assessment for the planning of a HSC

Exploration into an optimal HSC with regards to emissions and energy consumption has been initiated previously at the APEP, within the category of assessment for the planning of a HSC. This model has been coined the Preferred Combination Assessment (PCA) [66]. The purpose of this model is to determine the emission levels, both criteria and GHG emitted and the associated resources consumed (e.g., water, electricity, natural gas, and diesel fuel), from various HSCs. This model has played a key role in a much larger organizational effort coined Spatially and Temporally Resolved Energy and Environment Tool or STREET [35]. The overall layout and flow of STREET can be visualized in Figure 12.

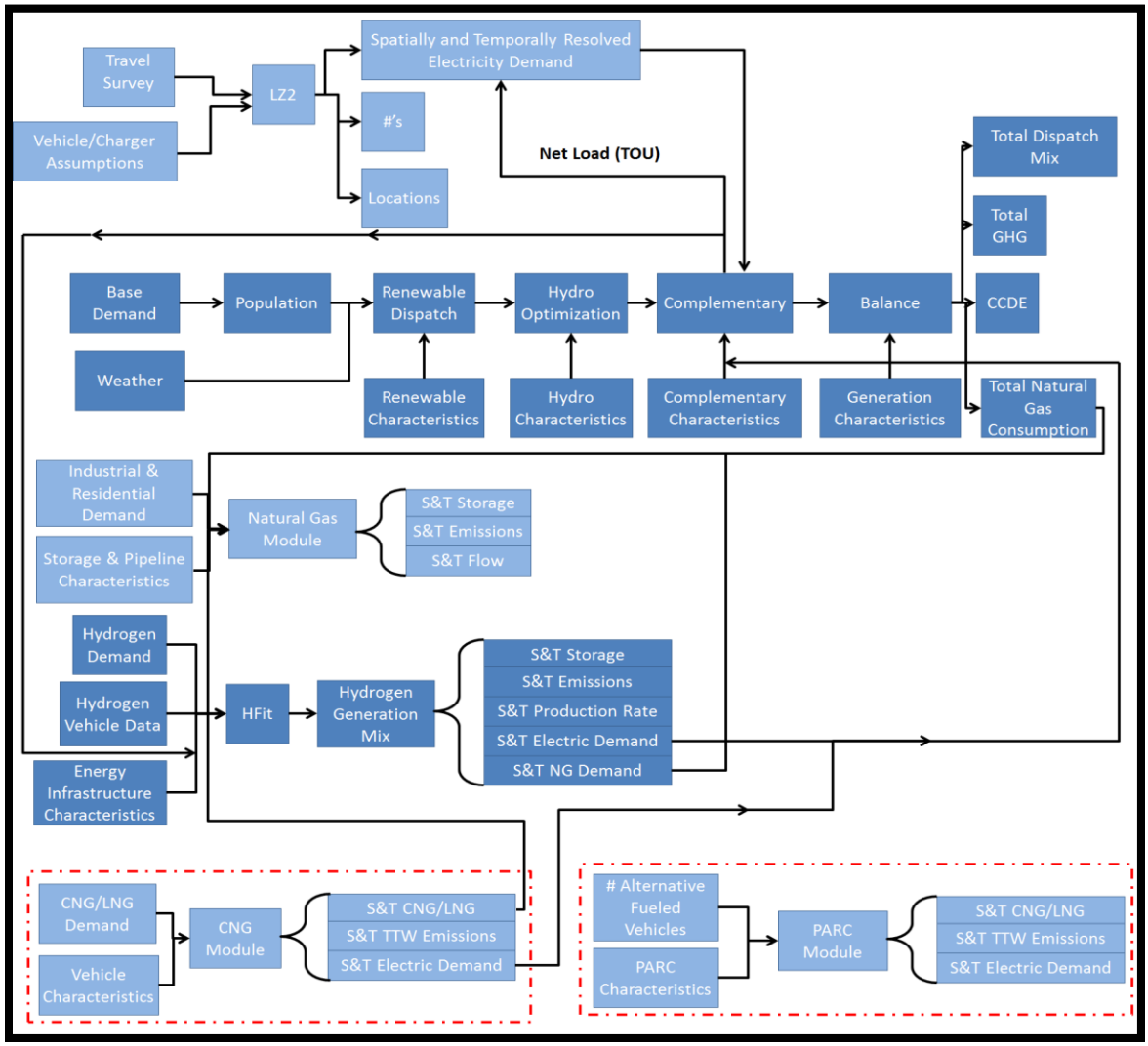


Figure 12 Schematic of modeling platform known as STREET

STREET is a suit of models that are capable of interacting, in order to explore on an energy systems level, the impacts various changes will have on the overall energy system. STREET places a great deal of emphasis on optimal hydrogen refueling station placement from a spatially and temporally resolved perspective for the near term. Based on the station placement, STREET has been utilized in order to determine the emissions and air quality effects meeting this hydrogen demand would have in localized geographic regions in Southern California [67]. Both the STREET and PCA models have been decisive tools in the preliminary stages of a HSC roll-out strategy, centered on Southern California. These methodologies are designed to explore various comprehensive planning and implementation strategies for the early adoption of hydrogen as a transportation fuel [67].

2.5.7 Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) is a tactical decision-making process able to facilitate the decomposition of complex problems that consist of multiple criterion and often times have multiple level decisions to overcome in order to obtain an optimal conclusion. This process is used across many sectors (e.g., government, business and energy sectors [68]). The

The AHP has been utilized in several studies that address hydrogen infrastructure. In Andalusia, the AHP was implemented in order to provide a preferential sequence for the build out of hydrogen dispensing locations [69]. This study supports the power of making a multi-criterion based decision, along with the flexibility of the AHP in that it ranks all of the locations and does not solely provide an "optimal" solution [69]. This outputted set of ranking allows for decision makers to utilize the results as guidance, along with other exogenous information in order to come to a final conclusion. Another study examined the tradeoffs between several conversion technologies with the criteria being: cost of hydrogen, capital cost, feedstock cost, operations and maintenance cost, and carbon dioxide emissions [70]. This methodology has also been applied to not only current hydrogen conversion technologies, but to future projections, along with scenario analysis tools [71]. This study accredits the AHP with showing

facility in discerning weighting criterion from an inventory of expert inputs in addition to being able to utilize both quantitative and qualitative criterion [71]. A hybrid AHP approach study combines a fuzzy decision-making methodology with the AHP in order to take into account varied human perceptions and uncertainties [72]. This study evaluated six of the most industry ready hydrogen production methods for a region in Korea [72].

In addition to pure hydrogen related implementations, others that are worth noting are those that optimally site central manufacturing facilities. An improved, integrated, AHP methodology has been recently utilized to solve the multi criteria decision-making problems consisting of production facility siting that businesses often encounter when trying to expand production [73]–[75]. The AHP was utilized in these studies in order to develop the relative importance of the weighting criterion for each of the decisions. Other methods were then utilized in conjunction to determine the best set of alternatives. The selection of plant locations is a pivotal decision as it heavily effects the overall supply chains efficiency [73]. This approach holds potential in siting future hydrogen generation facilities.

In summary the AHP has several defining attributes that make it ideal for this study and are as follows: 1) Capable of comparing multiple criterion that may vary greatly in unit and magnitude, 2) Decomposes complex multi-criterion and multi-level decisions, 3) Collects and aggregates expert inputs on an equivalent basis, 4) Implements a Consistency Ratio in order to ensure results are meaningful, 5) Ranks results so as to provide guidance to decision makers and 6) The relevance and symbiotic nature this approach has with the prior PCA methodology applied at the APEP.

2.5.8 Life Cycle Analysis

One last approach to the analysis of hydrogen supply chains is noteworthy in the area of energy and emissions analyses. Life Cycle Analyses or LCAs are undertaken in order to examine a products lifetime spanning energy consumption and impacts on the environment. LCAs are important in the exploration of hydrogen as a transportation fuel because they allow for examination of the

environmental impacts on a lifetime spanning basis. The LCA incorporates the raw materials extraction processes, all delivery and manufacturing activities, along with the products impacts during use and disposal [76]. This study considers only the LCA of the vehicle fuel supply chain in that extraction, delivery, conversion, dispensing and utilization energy and emissions are encompassed. The main components of the LCA that should be considered in future work, is that of the energy required and emissions produced during the construction of HFCEVs and hydrogen production facilities, along with the decommissioning and recycling of these products and facilities.

2.5.9 Summary of Modeling Methodologies

In order to obtain a firm grasp on the various methodologies often implemented in the literature, this section summarizes modeling activities being conducted within the Department of Energy, along with a comparison of four of the most germane models alongside the Hydrogen Fueling Infrastructure Analysis Tool (HFit) model. In Figure 13 the overall structural hierarchy of the suit of modeling tools developed in the collaborative effort to examine a future hydrogen economy can be seen. From this figure it is apparent where the work herein was at, seen as STREET and where it has evolved to being a part of the Environmental and Life Cycle, Vehicle Penetration and to even some extent Component, Infrastructure and Vehicle Assessment sections of Figure 13. As far as the tabular model comparison in Table 4, the programs chosen are representative of the main types of approaches utilized in the planning of a future hydrogen infrastructure deployment. These models have also been chosen due to their spatial capacity that has targeted California in some way.

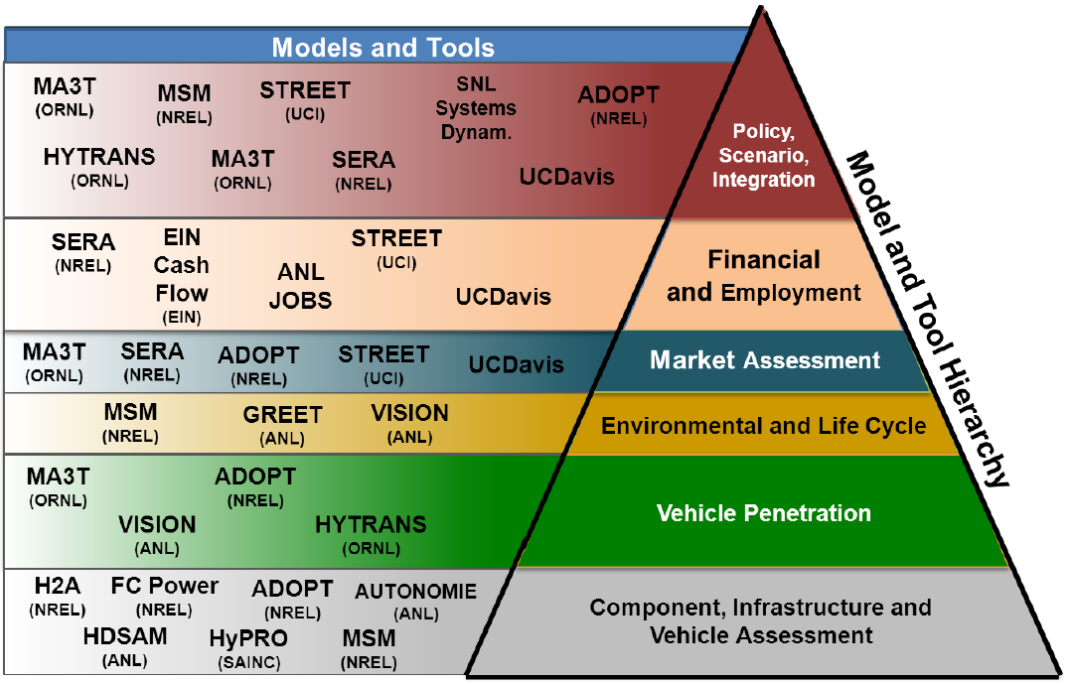


Figure 13 Hydrogen economy modeling efforts supported by the Department of Energy.

Table 4 Comparison of several hydrogen infrastructure deployment models

Aspects	MSM	PCA	Hfit	H2TIMES/MARKAL	SERA
Spatial	By County - Lacks Spatial Deployment Scenarios	No	Adjustable	Idealized City Model (8 independent demand clusters)	Urban Areas
Temporal - Build Out	Yearly Resolved	No	Yearly	5 year steps	5 year time steps
Temporal - Production	No	No	Hourly	No	No
Economic Consideration	Levelized Cost of Hydrogen	No	Costs Drive Decision but are not Calculated	Yes	Yes
# of Generation Pathways	10	10	Currently 4, but up to 23+	5	9+
Produce Emissions Data	yes	yes	yes	Carbon Intensity	Probable
Institution	NREL	UCI	UCI	UCD	NREL
Filling Pressures Considered	345 bar, 430 bar	350 bar, 700 bar, Liquid hydrogen, 140 bar	700 bar	Cryogenic Liquid Truck and Pipelines	Pipeline and Aggregate Truck Delivery and Dispensing Locations
Grid Representation	Single Electricity Price	Single Emission Factor	Integration with HiGRID	Hydrogen System Focus Only	Single Electricity Price
Data Sources	[58], [59]	[33], [61]		[40]	[60], [72]

2.6 Previous Methods and Future Applications

For successful deployment of hydrogen as a vehicular fuel, a holistic approach must be applied in order to facilitate such an expansive and costly transition. This type of strategy can be carried out by creating a sound plan to produce hydrogen and transport it to dispensing locations on a statewide level. Due to a low market call currently for hydrogen and HFCVs, an optimal and therefore cost effective approach must be developed. During Preliminary stages, the creation of a bare-bones infrastructure will lead to an increased demand. In order to properly tailor the STREET model to initiate this first step, an emphasis must be placed on optimal systematic selection of hydrogen generation locations. These

locations will be based on currently implemented energy infrastructure, in order to reduce initial capital costs, along with the location of proposed hydrogen dispensing locations, to ensure hydrogen fueling needs are fulfilled [77]. As demand increases a well-developed and thoroughly mapped procedure must be in place for hydrogen infrastructure evolution [35] . Also, due to the initial generation of hydrogen most likely heavily utilizing fossil based resources, a buildup scheme that transitions to renewable energy sources should be considered. This type of analysis holds the potential to highlight how California can best leverage its renewable resources, especially with its ambitious renewable penetration goals, in order to holistically meet its environmental goals along with the fact that it has been shown there exists a void in the investigation of ”clean” HSCs in the literature [36].

In order to elevate the MATLAB based PCA model to the next stage of planning for the future of hydrogen as an energy carrier, the model must be modified to include a statewide spatial and temporal capacity.

The purpose of a spatial component has multiple levels. The primary concern is the current non-hydrogen energy infrastructure that is in place and its accompanying ability to be utilized to its full potential in the production of hydrogen. This energy infrastructure includes natural gas, electricity, wind, solar, biomass and biogas. Infrastructure designed to transport these energy providers will also serve as preferred hydrogen delivery corridors. The second aspect is the application of a novel air quality modeling tool to the hydrogen generation road map.

The necessity for a temporal resolution is twofold. The first will be to explore the effects of a dynamic energy demand throughout a 24 hour period at fueling stations on emission levels generated by the electrical grid. The second will be to develop a roll-out strategy that will focus on meeting the demand of hydrogen as it grows and develops over time. A focus on renewable based hydrogen

generation will be deployed as the call for hydrogen increases and California moves toward meeting its 2050 GHG reduction goals.

From Table 4, it can be seen the main attributes that will elevate this work above the rest are the spatial and temporal resolution and capacity with which the analyses will be applied. Also, this work focuses on utilizing previous hourly dynamic infrastructure models developed at the APEP. The first model is known as the Holistic Grid Resource Integration and Deployment model (HiGRID). This model focuses on the interaction of high levels of renewable power generation and the incurred effects on the electrical grid, such as level of curtailment, GHG emissions and electricity prices [25], [78]. This model will be utilized in order to best determine the utilization of curtailed energy from such renewable sources as wind and solar in the state of California [25], [78]. The second dynamic model that has the potential to be integrated with this work has come to be known as CANGAM, or the California Natural Gas Analysis Model. This model will be integrated and utilized in order to provide spatial and temporal information about emission and natural gas levels on a statewide basis. Finally, the implementation of EMission FACtor (EMFAC), developed by the Air Resources Board (ARB) will provide data on passenger vehicles in California that include vehicle miles traveled and associated emissions on a county level [79]. Along with data from the EMFAC model, data provided on the California Energy Commission (CEC) website will allow for refinery locations and capacities to be determined [80]. These two previously mentioned data sets along with refining emission factors from GREET will allow for the spatial analysis of the petroleum based fueling pathway for the production of California Reformulated Gasoline utilized in passenger vehicles in California. With the combination of the above models and the proposed work, a holistic approach to the design and analysis of a future hydrogen infrastructure in California will be under taken.

The work herein aims to examine and further several areas in the current field that have not been focused on. First, this work will spatially disaggregate hydrogen demand based on a geographically distributed population dataset. The next facet of this work is the focus on the entire state of California and its appeal to the siting of hydrogen infrastructure. The modeling strategy also takes an alternative approach as compared to the traditional optimization problems for the solution of the hydrogen energy system design. The overall theory and application of this problem solving process is not novel, but the specifics of this models formulation and design are. By deploying a decision-making strategy that allows input from industry members and legislators, the paradigm of a gap between university research and real world application can be fully bridged. Finally, considering the interaction of the hydrogen energy system with others, such as the electricity supply system is not well characterized in the literature. The approach that is taken in order to accomplish all of the said facets of this study will now be presented.

3 Approach

Task 1. Implement a spatially and temporally resolved hydrogen demand module.

Utilize population, Vehicle Miles Traveled, hydrogen penetration levels and fuel use characteristics in order to determine the overall hydrogen demand for a given region. The purpose of this module will be to analyze current and future hydrogen demand scenarios with a spatially varying component. The divide between distributed and centralized generation technologies will be captured by this component.

Task 2. Systematically select the overall spatially allocated mix of hydrogen generation technologies.

This segment will provide the optimal number of hydrogen generation sources based upon current and projected hydrogen fueling station demands. This will be accomplished by first, generating a set of candidate generation locations. Each of these sites will then be ranked based on technology independent factors, followed by hydrogen conversion technology dependent factors.

These two rankings will then be combined in order to generate a spatially allocated hydrogen generation infrastructure.

Task 3. Fully leverage statewide renewable energy sources.

This will be accomplished by integrating the previously established HiGRID tool in conjunction with spatial and temporal energy source information. The aim of this segment will be to symbiotically work with the electrical grid in order to assist in balancing the intermittent renewable energy sources.

Task 4. Calculate statewide emission profiles due to a future hydrogen fueling infrastructure.

Apply the PCA module to each generation site in order to correlate an emissions profile for that site. This will be conducted as a post processing step, once the number and locations of all of the facilities in the state have been chosen.

Task 5. Select and outline hydrogen distribution methodologies.

This module will explore the various hydrogen delivery choices and their particular limitations depending on characteristics specific to the region (e.g., Distance to nearest hydrogen station). This module will examine the energy and emissions required to transport hydrogen from production to dispensing locations.

Task 6. Analyze spatially allocated energy resource demand profiles for an hourly hydrogen demand.

Electricity and natural gas demand will depend on the number and type of generation and dispensing locations. Demand for electricity and natural gas are generated by the PCA. The electricity profile for each station will be based on a gasoline dispending profile. These profiles will then be related back to emissions profiles based on the electrical grid performance.

Task 7. Quantify emission reductions due to reduced gasoline consumption in the presence of a future hydrogen economy.

This pathway will be created by utilizing data on current petroleum refinery locations and capacities, emission factors for generating California Reformulated Gasoline and an emissions module for passenger vehicles in California. This baseline will allow for the comparison of energy and emissions of various hydrogen fueling pathways to the petroleum based supply chain.

4 Hydrogen Fueling infrastructure tool (HFit)

4.1 General Modeling Methodology Overview

The Hydrogen Fueling infrastructure tool (HFit) takes a global decision-making approach to the creation and evolution of a future hydrogen infrastructure. The general overview of the model can be viewed in Figure 14. In order to better illustrate the flow and logical progress of the model, Figure 14 has numbers to the right of corresponding modules. Later in this text, those numbers correspond to figures that are explained in greater detail.

As an introduction, the methodology and flow of the model is considered in the next couple of paragraphs and delved into in much greater depth in sections to come. The model first starts out by generating a mesh grid of candidate hydrogen generation locations for the state of California. Each of these candidate locations is then ranked on two separate accounts, once for their overall land use desirability and once corresponding to the locations capacity to accommodate a certain hydrogen generation technology. These two decisions are made in order to give every location a global ranking and a preferred generation technology. The model then moves onto siting hydrogen dispensing facilities at pre-established gasoline stations. The highest ranked candidate generation locations are then utilized in order to meet the overall aggregate state hydrogen demand. As a result of meeting this demand a list of generation facilities and their locations is known. Returning to this list, the nearest hydrogen dispensing locations demands are met via a systematic process. This approach then moves onto deciding the best possible hydrogen delivery strategy given the scenario that has been constructed this far. Three

delivery methodologies have been considered and are: 1) gaseous hydrogen via a pipeline to a centralized terminal in combination with gaseous truck distribution, 2) gaseous truck distribution from the central plant and 3) liquid hydrogen truck distribution from the centralized plant. Once the generation mixture, delivery method and dispensing profiles are known, the spatial and temporal emission results can be simulated. These spatial and temporal results can be compared with an additional module that was created in order to simulate the current gasoline economy.

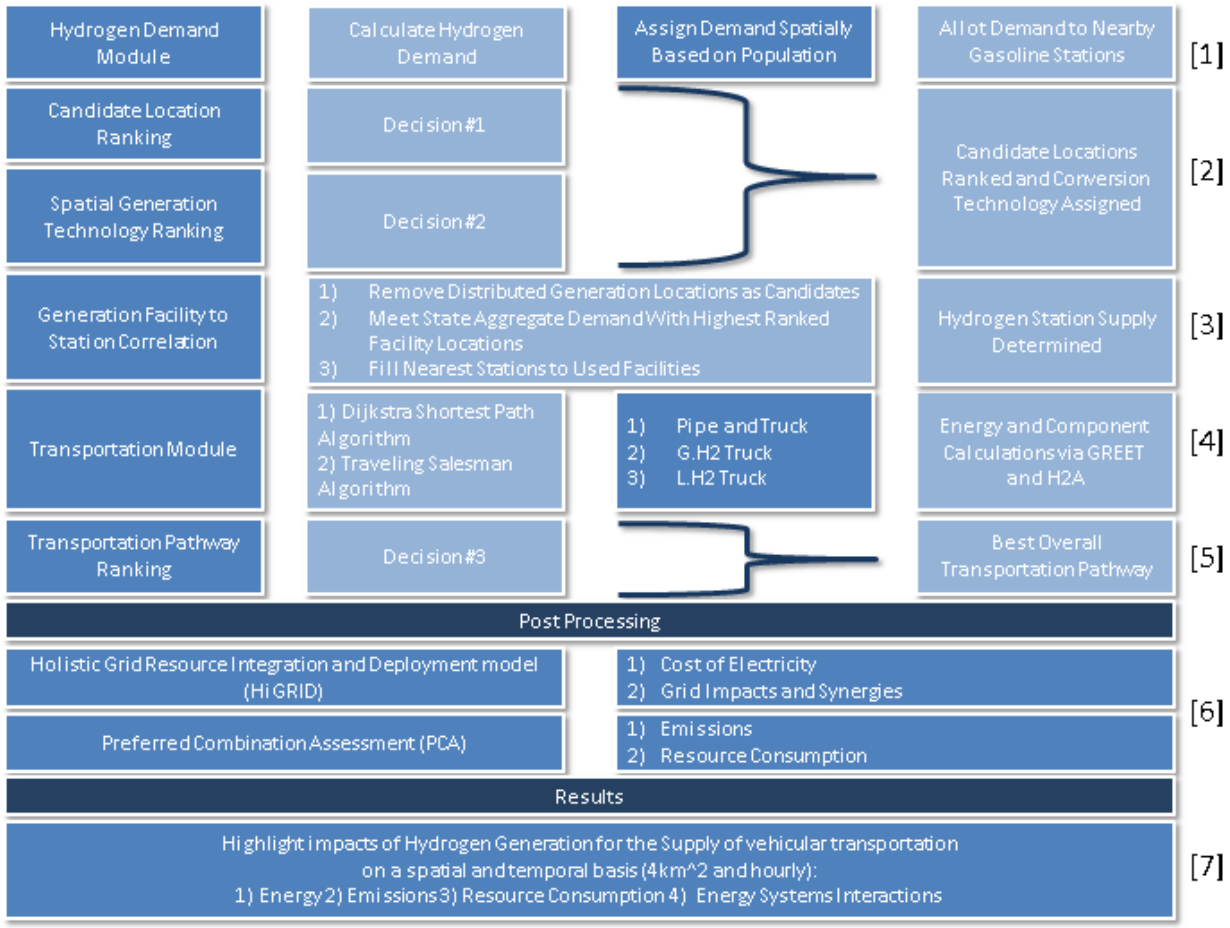


Figure 14 Overall HFit modeling methodology, process flow, and associated models

4.2 Hydrogen Demand and Dispensing Module

The hydrogen demand module consists of three primary steps; this procedure is depicted in Figure 15. The first stage of the calculation is to project a future aggregate hydrogen demand based on a

penetration level of FCVs, along with the utilization of these vehicles, and an efficiency that serves as a fuel utilization factor. This aggregate demand is then dissociated spatially by utilizing highly resolved (1km^2) population data. The spatially allocated demand can then be used to find the nearest candidate hydrogen dispensing locations. Additional data such as spatially allocated VMT, and gasoline demand can be coupled with the population data in order to better preferentially rank the candidate hydrogen dispensing locations. Finally, the hourly demand can be calculated by again employing vehicle utilization data, the overall hydrogen demand and an hourly gasoline demand profile for a representative week.

Figure 15 Overall flow of the hydrogen demand module, where the number to the right indicates the figures flow in the overall schematic seen in Figure 14.

4.2.1 Hydrogen Fuel Cell Electric Vehicle Adoption Rate:

Studies show that hydrogen demand will most likely follow a logistic substitution curve [42]. By utilizing such an adoption curve, several parameters must be specified. These necessary parameters are the saturation level of the vehicle penetration, an "anchoring" date for projecting the adoption rate, and a growth or transition pace [42]. For this particular study the traditional population growth curve was chosen as the logistical substitution curve from Moeler (2011) [81]. The formal mathematical expression is as follows:

$$\dot{y} = k\left(1 - \frac{y}{\mu}\right)y \qquad \text{Equation 1}$$

Where μ is the carrying capacity (HFCV penetration percentage), k is a proportionality constant, $y(t)$ is the populations size and $\dot{y}(t)$ is the populations growth rate [82]. This equation was solved numerically by utilizing the function "ode45" in MATLAB. The parameters that were utilized in order to solve this equation were $k = 1/3$, $\mu = 25\ to\ 75$ and an initial condition of $\eta = 1/25$. The ode45 function was

integrated over the time period of 2010 to 2060, with a time step of 5 years. The curves that were generated by this section for the adoption rate of HFCEVs can be viewed in Figure 16. For this particular case it is assumed that the HFCEV penetration percentage will be 75% in the year 2050 and will be the focus from here on out.

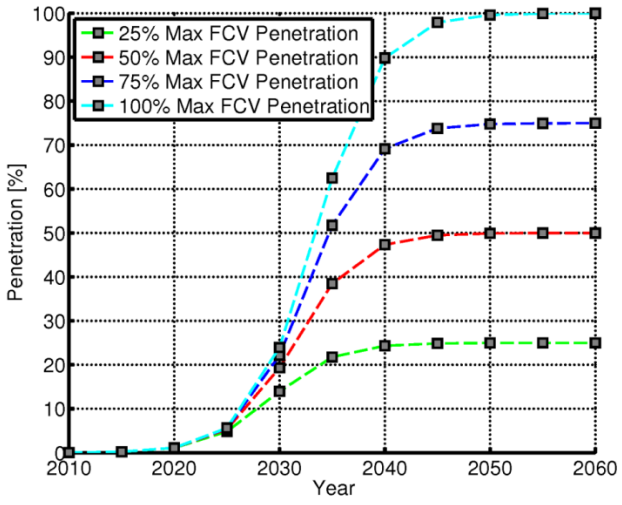


Figure 16 Projected HFCEV Adoption Rate

4.2.2 Spatial Hydrogen Demand

Based on the vehicle adoption rate as a HFCV penetration percentage, a normalized population distribution, vessel use in Vehicle Miles Traveled (VMT) and fuel use as a vehicle efficiency rating, a projected hydrogen demand is produced. A similar methodology was suggested by [42] and adopted for this application, the demand is formally written as:

$$\mathrm{H2D} = \mathrm{NP} \times \mathrm{VU}\left[\frac{\mathrm{miles}}{\mathrm{car}}\right] \times \mathrm{VP}\,[\%] \times \mathrm{VFU}\left[\frac{\mathrm{kg\ H2}}{\mathrm{mile}}\right] \qquad \text{Equation 2}$$

H2D: Hydrogen Demand
NP: Normalized Population Distribution
VU: Vehicle Utilization
VP: Vehicle Penetration
VFU: Vehicle Fuel Use

The VMT data were obtained from the EMFAC model that was mentioned in the Previous Methods and Future Applications section of this document [79]. Data for years spanning from 2010 to

2035 was gathered and then extrapolated to the year 2050. The results of this methodology can be seen in Figure 17.

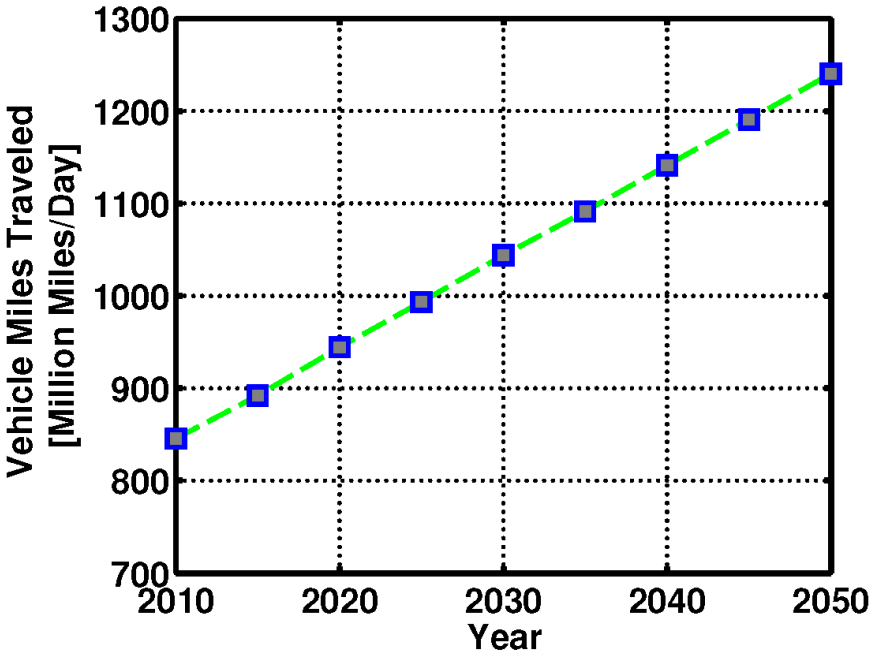


Figure 17 Extrapolated VMT Data from EMFAC

In order to obtain an estimation of the spatial distribution of the population, a data set generated by Oak Ridge National Laboratory entitled LandScan™ was implemented [83]. This data set consists of population data resolved into 1km squares. These spatially distributed population statistics were combined with Equation 2, in order to distribute the hydrogen demand projections regionally.

The distribution process in Equation 2 for the allocation of a future hydrogen demand was improved upon by integrating two other datasets and correlating the resulting demand to current gasoline stations. LandScan™ values, spatially allocated VMT, (obtained from the "2012 California Public Road Data" report), and gasoline demand survey results, (obtained from the "Retail Gasoline Sales by County" page on the CEC website) were assigned to each of the currently considered gasoline stations [84], [85]. The values assigned to these stations were then normalized. The normalized results were then combined via a geometric mean in order to come up with an overall weighting for each gasoline station in the state. Hydrogen demand intensity maps were then created by multiplying this normalized

weighting parameter by the overall statewide hydrogen demand calculated via Equation 2. These intensity maps can be found later in this document as Figure 52 through Figure 58.

In order to make it economical to install a hydrogen dispensing location, all of the hydrogen demand points need to be systematically aggregated in order to ensure the maximum utilization of all installed hydrogen dispensing locations. Due to this need, the next step in this modeling effort is to agglomerate and install dispensing locations, beginning with the highest ranked gasoline stations in order to serve the greatest number of customers possible, with the fewest installed stations.

4.2.3 Hydrogen Station Siting

After the hydrogen demand has been extrapolated and spatially allocated, candidate dispensing locations were taken to be previously installed gasoline fueling stations. This conclusion was reached due to the fact these stations already receive commercial tanker deliveries, are sanctioned to sell transportation fuel, along with the existence of a pre-established business [37]. The data for this segment consists of 9816 current gasoline stations.

In order to choose the appropriate gasoline stations to utilize for the dispensing of hydrogen, a demand fulfillment methodology was implemented. Based on the chosen station size for installation, the algorithm performs a nearest neighbor search by utilizing the “knnsearch” function that was developed by Yi Cao [86]. The developed algorithm finds the nearest fueling station to each demand point, starting with the largest demand point magnitude. The number of fueling stations that are found starts with one, the magnitude of this station is subtracted from the demand point quantity that was found. This process is repeated with gradually further fueling stations until the demand point is satiated. For every new station that is added, a value equivalent to the station capacity is placed into a bin labeled “H2 Dem Met” and is compared to the statewide demand that is suggested in order to ensure it has been met at the completion of the code segment.

Each of the demand points can be thought of as a glass of water, with varying amounts due to the spatially allocated hydrogen need calculated earlier. Each of these glasses of water has a closest proposed fueling station capacity removed, until the demand is less than the full value of another station installation. Once all demand points are less than the value of adding another full dispensing location, another algorithm is implemented in order to group the remaining demand. This algorithm again sorts the data in order to start with the greatest magnitude demand point remaining. It then utilizes the nearest neighbor search in order to find the next nearest demand point and adds the two, checks to see if the magnitude is now greater than the addition of a new station and if so adds another fueling station location. If the magnitude remains below the necessary amount in order to add another station, then the search is expanded and more demand points are included until another station is able to be added. This process is repeated until the total aggregate state demand is met. The resulting dispensing locations are shown and examined in the "Hydrogen Dispensing Location" in the results section.

In summary, the hydrogen demand module takes geographically allocated population and other demographic data and calculates a spatially disaggregated hydrogen demand. From this spatially allocated demand, the nearest gasoline stations which are taken to be prime candidate locations for hydrogen dispensing are located. These candidate locations are tracked as being utilized until all of the hydrogen demand within the state is satiated. This is the first step of HFit and is illustrated in Figure 15. Now that a hydrogen demand is determined and spatially allocated to certain dispensing locations an hourly demand profile at the dispensing site can be created.

4.2.4 Temporally Resolved Hydrogen Demand

The final step in the analysis of a future hydrogen demand is to resolve it temporally. In order to carry out such an endeavor, variations in monthly VMT, along with diurnal changes in demands were taken into account. The diurnal profile of the dispensing locations was taken to be similar to a gasoline

fueling stations. The gasoline profile data was extracted from "Final Report Hydrogen Delivery Infrastructure Options Analysis" [87]. This assumption was made after analysis was done on the hydrogen fueling station located at the University of California at Irvine, internally to the APEP with key results published as Brown (2012) [88]. It was observed that the peak demand occurred on Friday (15.4% of weekly demand dispensed) with about 1.2% of weekly demand being dispensed between 4-5pm. Therefore, the monthly variation in VMT and diurnal demand are taken into account. The resulting profiles can be seen in the "Hydrogen Demand and Dispensing Module Exercise" section.

The overall methodology utilized in this hydrogen demand module section aims to project a future hydrogen demand that is both spatially and temporally resolved. The study herein aims to fill the gap within the literature of considering a spatially disaggregated hydrogen demand [42]. It is the purpose of this modeling endeavor to be flexible and modular in its approach and projections analyses, in order to accommodate any new information gained in the coming years about the trajectory of the hydrogen economy. This module serves as a basis upon which further modeling endeavors can be built in order to simulate the entire build out of a hydrogen energy system for the supply of HFCEVs. The spatial and temporal resolution will allow for a correspondingly resolved generation, distribution and storage systems to be modeled and in the end, the application of a novel air quality model. The next step in the systematic selection process is to apply a decision-making methodology, which is explained in the next section.

4.3 Decision-Making Methodology

4.3.1 Candidate Generation Sites

This modeling endeavor seeks to examine all of California for candidate fuel production locations. In order to carry out such a task, the model first generates a mesh grid of candidate hydrogen generation locations for the state. Each of these candidate locations is then ranked based overall land use desirability for transportation fuel production using the AHP.

Several metrics are utilized in order to create a mesh grid of potential hydrogen generation locations over the entire state. The first step is to generate a rectangular mesh grid of a desired spatial resolution that covers the state. Two metrics are then utilized in combination with a filtering function. The two metrics determine if the point lays within the border of the state and then if the point falls within the boundaries of California's many parks, preserves or large water bodies. A map of candidate locations with a spatial grid of 4km^2 can be viewed in Figure 18. This detailed spatial resolution comes as a result of the resolution necessary for the inputs to the air quality modeling tool. The exact spacing of the candidate locations is adjustable. For the case study explored herein, 10 square kilometers is used due to the resolution versus modeling time trade off. The grid areas generated in this step are then passed off to the decision-making portion of the code in order to analyze geographical metrics for each individual point of interest.

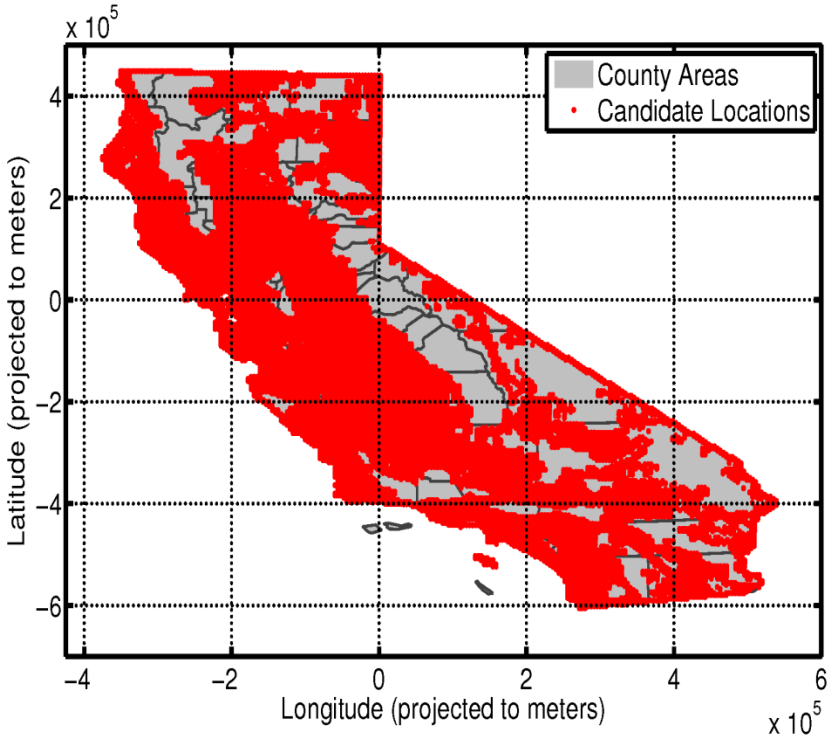


Figure 18 Candidate Fuel Generation Locations shown in red at a 4km^2 resolution. The light brown areas are not considered in the study because they have been deemed protected (i.e. parks, preserves and water bodies).

4.3.2 AHP Decision-Making Theory

The following generalized AHP approach is a methodology adapted from Bushan (2004) [68]:

Step 1: Decouple the problem “into a hierarchy of goal, criteria, sub-criteria and alternatives” [68]. A general overview of a hierarchical structure used in this type of decision-making can be seen in Figure 19.

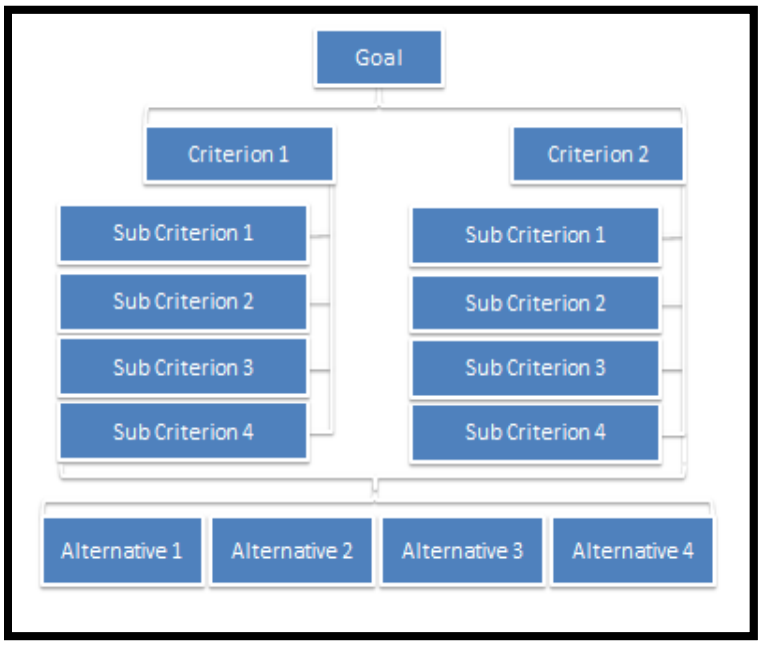


Figure 19 General AHP Hierarchy: Adapted From [68]

Step 2: Pairwise comparisons are made based on quantitative data gathered on the importance of each criterion. The comparisons are made on a scale from 1 to 9, where even numbers represent transitional rankings and the odd numbers are firm values. The rankings and corresponding values can be found in Table 5.

Table 5 Definition of Pairwise Rating Criteria for AHP: Adapted from source [68]

Importance	Equal	Fuzzy Element	Marginally Strong	Fuzzy Element	Strong
Value	1	2	3	4	5
Importance	Fuzzy Element	Very Strong	Fuzzy Element	Extremely Strong	
Value	6	7	8	9	

Step 3: The pairwise comparisons are organized into matrices in order to display all criteria of each decision. The matrix diagonal values are all unity, signifying that equal criteria have equal importance.

Values above and below the diagonal are both mirrored and inverted, or $a_{ij} = 1/a_{ji}$. Values in the matrix vary from 1/9 to 9 due to the rating system. Therefore, when there is a value of less than one in any particular cell, the criteria represented by the corresponding column has more weight than the criteria in the row. If the value is greater than one, the row criterion is deemed to be more important than the column.

Step 4: Each of the matrices must be checked for consistency in order to ensure a meaningful solution will be reached. In the case of small matrices a standard Consistency Ratio (CR) is generated as in Equation 3.

$$CR = CI/RI \qquad \text{Equation 3}$$

In order to obtain such a ratio, first a Consistency Index (CI) must be derived for each particular matrix. This index is obtained via Equation 4, by utilizing λ_{max} or the maximum eigenvalue along with n, the order of the matrix.

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \qquad \text{Equation 4}$$

The next step is to look at the Random Index (RI), or the consistency of a set of random matrices with the same order as the considered matrix. There are well known values for matrices up to the order of 15. With orders of greater than 15, Alonseo et al. (2006) suggest a method for estimating the CR as seen in Equation 5. [89]

$$CR = \frac{(\lambda_{max} - n)}{(\bar{\lambda}_{max} - n)} < 0.1 \qquad \text{Equation 5}$$

Where they calculate a least square fit for the mean maximum eigenvalue as shown in Equation 6.

$$\bar{\lambda}_{max} = 2.7699n - 4.3513 \qquad \text{Equation 6}$$

The combination of Equation 5 and Equation 6 yields an expression that is a good estimate for determining the consistency of the matrix under examination, and is presented in Equation 7. This

expression is utilized in this study for the estimation of the CR for all of the matrices corresponding to the input datasets.

$$CR = \frac{(\lambda_{max} - n)}{(1.7699n - 4.3513)} \qquad \text{Equation 7}$$

Step 5: Weighting values for each criterion are calculated by finding the principal eigenvalue and normalized right eigenvector of the matrix. In other words, for every criterion there is a comparative dataset. There is also a matrix of weighting values from the pairwise criteria comparison step performed earlier. The geometric mean is taken across the columns for each of the dataset rows. Each of these datasets is then normalized. These average normalized comparative datasets are then placed into another matrix, with the same number of columns as the weighting matrix has rows.

Step 6: The previously calculated weighting values are multiplied by the new average normalized matrix. This step is first carried out on the sub-criteria and then repeated with weights of the overall criteria in order to obtain a global solution.

4.3.3 Hydrogen Infrastructure AHP Decision-Making Tool

Due to the complexity of selecting the optimal primary feedstock, conversion technologies, locations, transportation methods and dispensing locations, the AHP has been divided into three primary decisions. Table 6 serves as both an outline to this section and a guide to the overall flow of the decision-making process in the HFit model. It should be noted that a short detailed description of each of the decision criterion mentioned in each of the three decisions are organized in Appendix A.

Table 6 HFit model flow and Hydrogen Infrastructure AHP Decision-Making Tool Section outline.

HFit Application – Facility Siting, Type and Transport:
1. Rank Candidate Generation Locations ○ LandScan™ [83] ▪ Least Populous ○ Zillow™ Home Values [90] ▪ Least land cost (Real-estate data) ○ California Energy Commission Datasets [91] ▪ Energy Generation Facilities ▪ Transportation Infrastructure ▪ Water Infrastructure
1. Rank Technology Type for each location ○ The Hydrogen Analysis (H2A) Project [92] ▪ Capital Cost ▪ Operations and Maintenance Cost ▪ Energy Conversion Efficiency ▪ Feedstock Cost ○ California Energy Commission Datasets [91] ▪ Feedstock Infrastructure ○ GREET Data [93] ▪ Least Carbon Intensive Technology
2. Combine Location and Technology Rankings
3. Select highest ranked locations to meet full CA demand
4. Transportation and Storage Selection ○ H2A Delivery Scenarios Analysis Model [92] ▪ Capital Cost ▪ Operations and Maintenance Cost ○ GREET Data [93] ▪ Energy Consumption ▪ Carbon Intensive Method

The first two decisions made via the AHP methodology deal with site and conversion technology selection for the generation of hydrogen fuel. The overall goal of this decision is to rank each location for its overall appeal to siting a hydrogen generation facility, along with the particular conversion technology to be utilized there. These two decisions are divided into two different spatially resolved problems, one that is independent (Figure 20) and one that is dependent (Figure 21) on the conversion technology type.

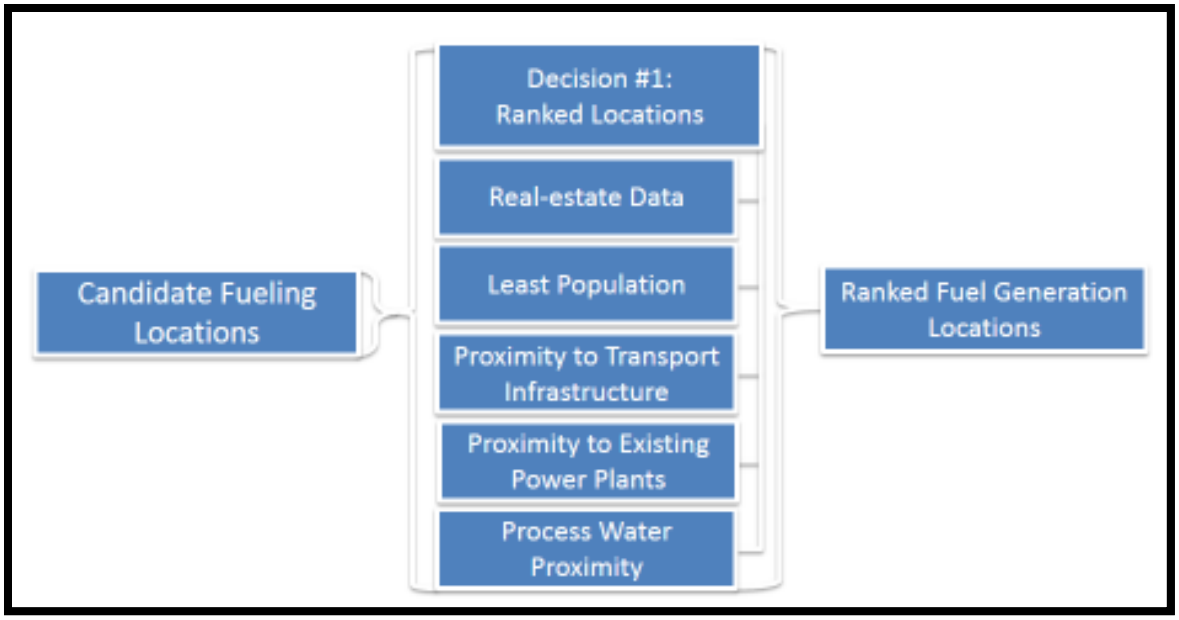


Figure 20 Technology Independent Land Ranking Process

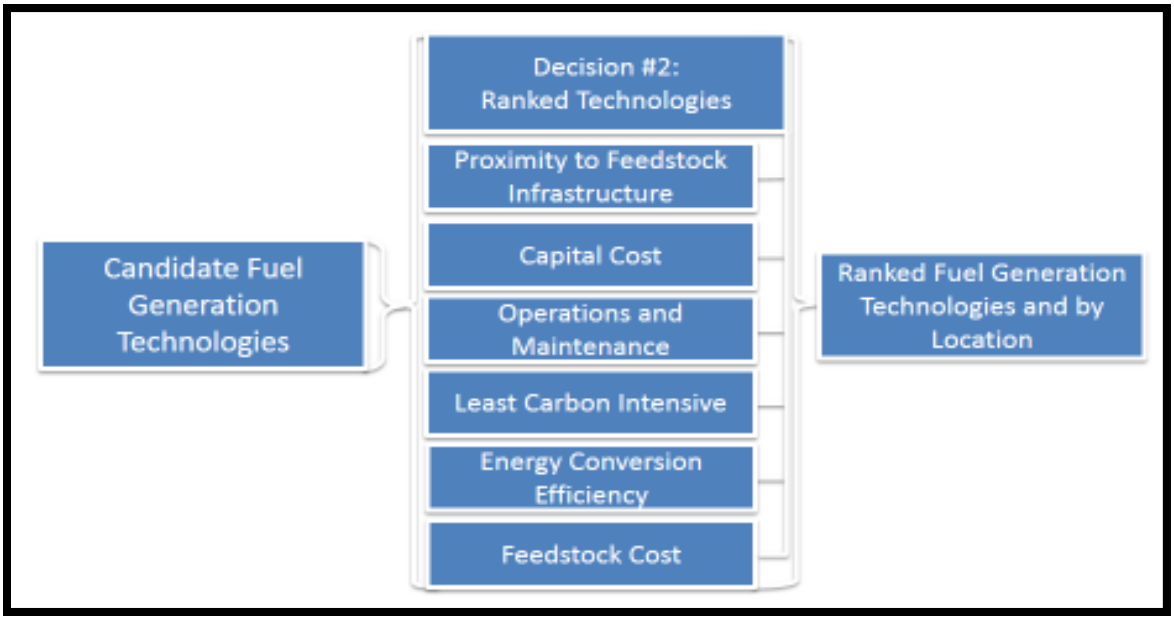


Figure 21 Hydrogen Conversion Technology Dependent Land Ranking Process

A visual outline of the overall decision-making process is displayed in Figure 22 and Figure **23**. The corresponding pairwise comparisons for these two decisions can be seen in Table 7 and Table 8. These matrices were left blank in this section because during the modeling runs these values were changed based on different groups of experts who were surveyed. The combination of Decision #1 and Decision

#2 is carried out by normalizing the results obtained by these two decisions as seen in Figure **23**, and combining them by applying an equivalent weighting of 50% to each.

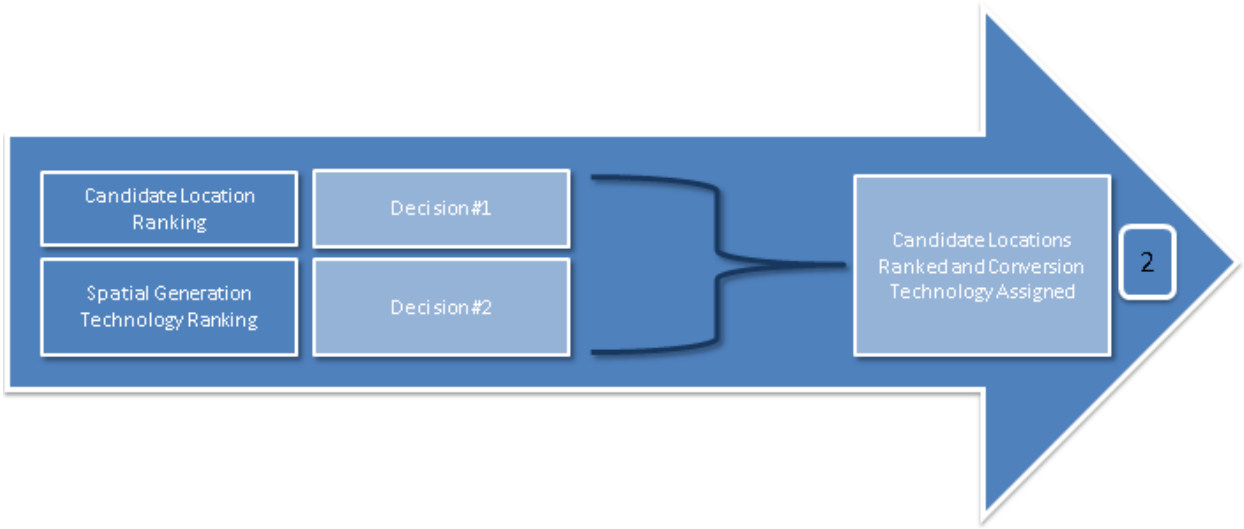


Figure 22 Overall candidate location decision-making flow, where the number to the right indicates the figures flow in the overall schematic seen in Figure 14.

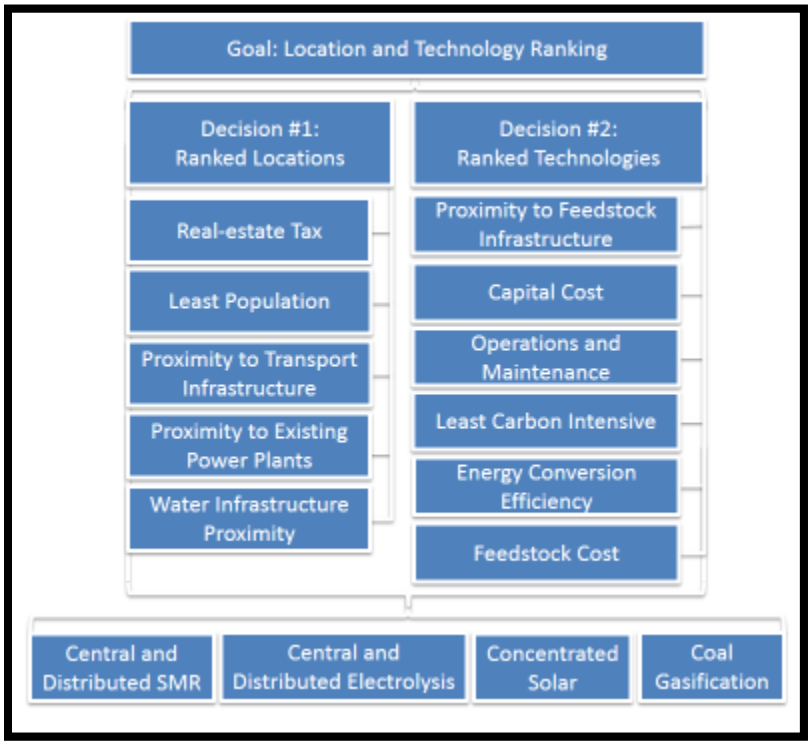


Figure 23 Spatial AHP Decision Making Process with included decision-making criteria and technologies considered.

4.3.4 Technology Independent Criterion Justification

For the technology independent decision, the five metrics used in the AHP decision-making process were Power Plant Proximity (PPP), Least Land Cost (LLC), Least Populous (LP), Energy Infrastructure Proximity (EIP) and Water Infrastructure Proximity (WIP). PPP is the distance to the closest electricity generation locations (e.g., Solar Farms, Wind Farms, Natural Gas Power Plants). LLC are current median dollars per square foot values extracted from Zillow™ [90], LP is the lowest population based on LandScan™ data, EIP is the distance to current energy infrastructure (Highways, Railroads, Natural Gas Pipelines and Electrical Transmission Lines) and WIP is the distance to the nearest major lakes, rivers and water ways in California. The data sets utilized for this and any other geographically allocated decisions can be viewed in Figure 24 through Figure 29.

Table 7 Spatial Candidate Location Pairwise Comparison Matrix

Spatial Candidate Location Weighting Matrix					
	Least Land Cost (LLC)	Least Populous (LP)	Infrastructure Proximity (IP)	Power Plant Proximity (PPP)	Water Infrastructure Proximity (WIP)
Least Land Cost (LLC)					
Least Populous (LP)					
Infrastructure Proximity (IP)					
Power Plant Proximity (PPP)					
Water Infrastructure Proximity (WIP)					

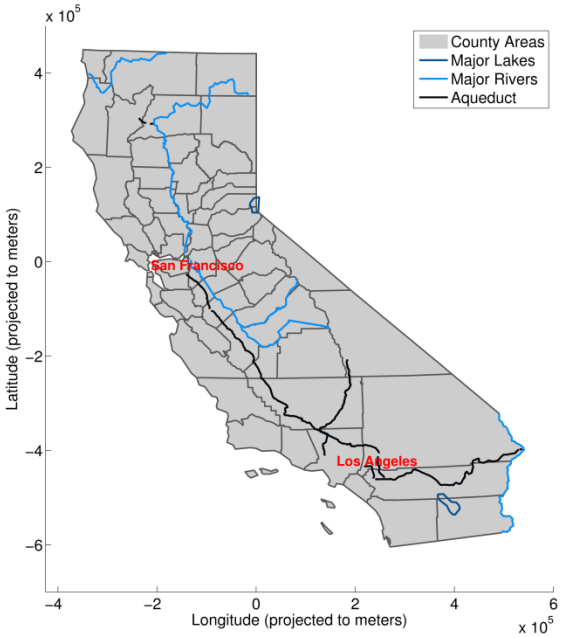


Figure 24 California Major Water Infrastructure [94]

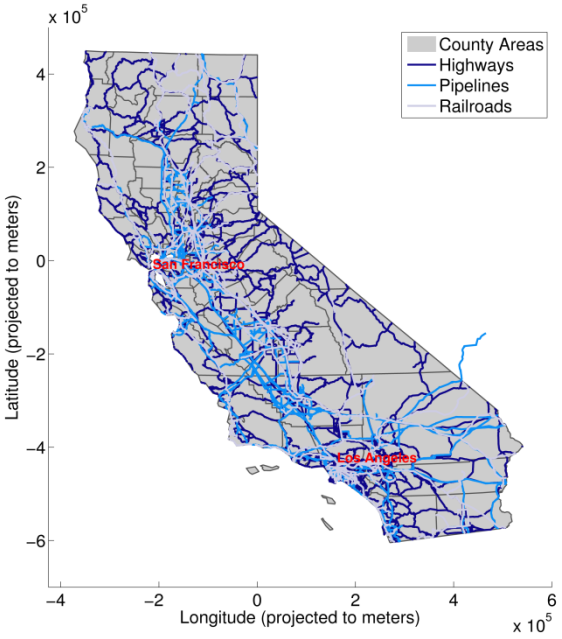


Figure25 Major Transportation Infrastructure [95], [96]

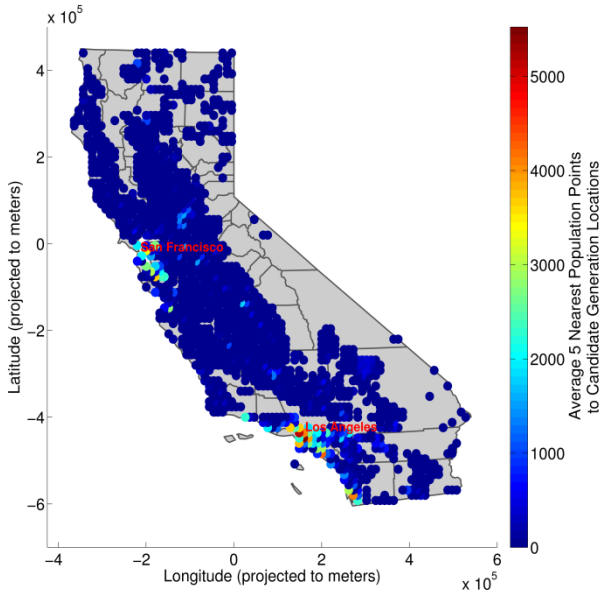


Figure 26 LandScan™ Spatial Population Data [83]

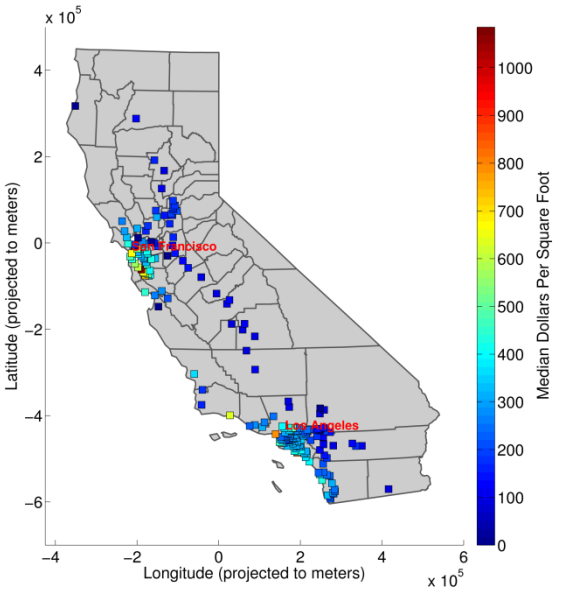


Figure 27 Zillow™ Median Dollars Per Square Foot Values [90]

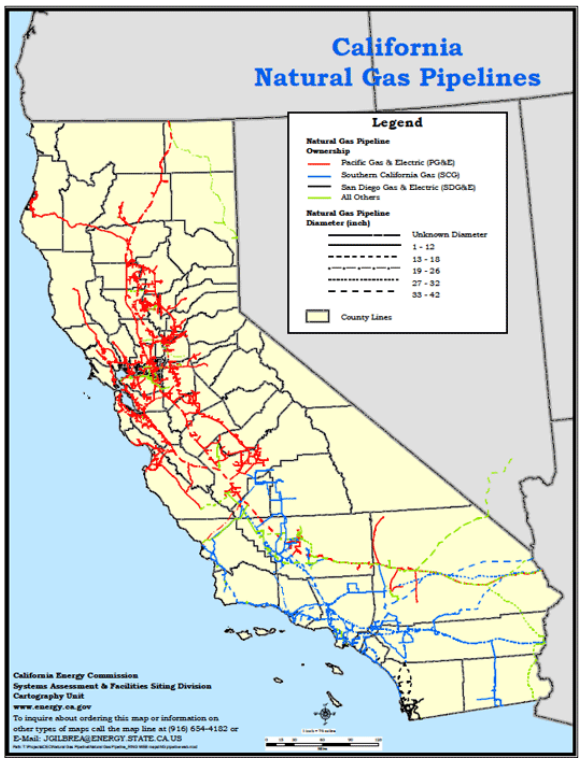


Figure 28 CEC NG Pipeline Infrastructure [91]

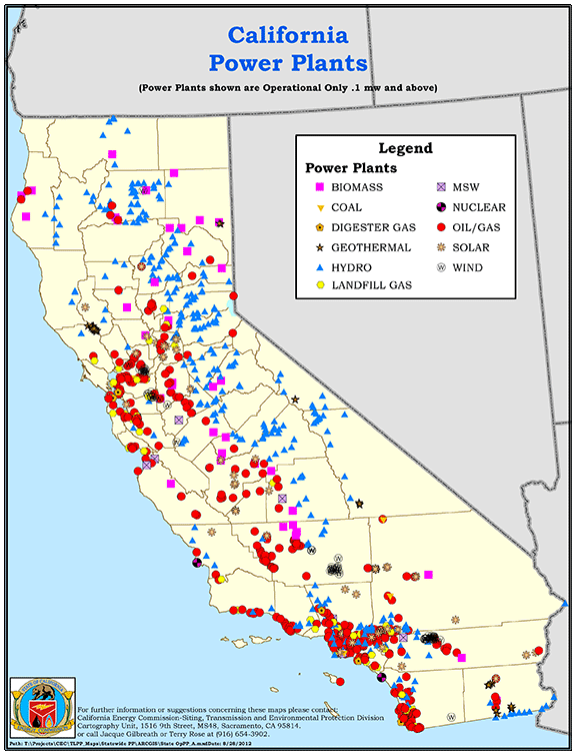


Figure 29 CEC Power Plant Data [91]

These metrics were chosen based on their relevance to the generation of transportation fuels in general and correspondingly the selection of optimal generation sites. Near distance to electrical generation facilities was selected in order to give a priority to the co-location of fuel and electrical generation. By co-locating these facilities, much of the commercial permitting process would not need to be undertaken due to the previously zoned land. Additional benefits from co-location exist, such as utilizing a portion of the generation facilities feedstock for fuel production (e.g., wind or solar for the production of hydrogen). The average housing value was utilized as an estimate of land cost in the area. Preference should be given to areas with low land cost in order to reduce the initial capital investment for the facility. The lowest population metric was utilized for two reasons: 1) an area with fewer people is more likely to have open space available for development and 2) an area with fewer residents is less likely to receive resistance from an aesthetic point of view. The next metric is the least distance to eligible transportation infrastructure. This is a key metric for two reasons. The first is that many times

previously installed infrastructure can become the primary energy supplier for fuel production. Secondly, once the fuel is created; it needs to be transported to the dispensing location. All of the considered infrastructure will allow for previously zoned energy transmission corridors to be utilized in conjunction with new pipelines or trucking routes for the delivery of transportation fuels. The final metric considered is water infrastructure proximity. Water is an important resource to consider as it has become a scarce and greatly underestimated energy utilization component. Demand has rapidly been increasing, while supply has fallen. This water metric adds a great deal of value when siting fuel production locations, due to the inherent need of process water. This parameter becomes even more germane when considering the generation of hydrogen, due to the fact many of the process to generate such a fuel require a large magnitude of water, for example, hydrogen via steam methane reformation requires about 0.06gallon/mile [97].

4.3.5 Technology dependent Criterion Justification

For the technology dependent decision, the six metrics used in the AHP decision-making process were Greenhouse Gas Emissions (GHG), Capital Cost (CC), Fixed Operations and Maintenance Costs (FOM), Energy Conversion Efficiency (ECE), Feedstock Cost (FC), and Proximity to Feedstock Infrastructure (PFI). These criteria are organized in a pairwise manner in Table 8.

GHG are the emissions generated by the conversion of the primary energy source into to hydrogen fuel and are estimated by utilizing values from a model developed by the Argonne National Labs, known as The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) [93], [98]. This tool was developed in order to explore the life cycle energy and emissions impacts that various transportation fueling supply chains have on a Well-to-Wheel basis. This modeling tool now encompasses over 100 fueling pathways and considers many alternative fueling pathways such as biomass, natural gas and hydrogen [93], [98]. Values were extracted from it for each conversion

technology considered and converted to a GHG equivalent emission factor. This criterion will ensure that the future hydrogen generation facilities will have the lowest carbon impact possible.

Table 8 Spatial Candidate Technology Rating Pairwise Comparison Matrix

Spatial Candidate Technology Weighting Matrix						
	Greenhouse Gas Emissions (GHG)	Capital Cost (CC)	Fixed Operations and Maintenance Costs (FOM)	Energy Conversion Efficiency (ECE)	Feedstock Cost (FC)	Proximity to Feedstock Infrastructure (PFI)
Greenhouse Gas Emissions (GHG)						
Capital Cost (CC)						
Fixed Operations and Maintenance Costs (FOM)						
Energy Conversion Efficiency (ECE)						
Feedstock Cost (FC)						
Proximity to Feedstock Infrastructure (PFI)						

The remaining datasets were utilized from the Hydrogen Delivery Infrastructure Analysis Models or H2A that was developed by the United States Department of Energy for analysis of various production and delivery methods for hydrogen as a transportation fuel [92], [99]. The overall dataset utilized in this section of the decision-making process can be viewed in Table 9.

A brief summary and justification of the criteria that were implemented are as follows. Three cost parameters are considered and are CC, the capital cost of a given conversion technology, the FOM, Fixed Operations and Maintenance and finally FC is the primary energy source Feedstock Cost. These three criteria combine ensure that the conversion technology retains the lowest cost of installation and operation. The ECE is the Energy Conversion Efficiency, and this criterion ensures that the systems overall efficiency is maximized. Finally, PFI is the nearest distance to the primary energy source infrastructure for each corresponding technology considered. It is important to note that the considered infrastructure changes for each technology type (e.g., steam methane reformation processes consider

the natural gas pipeline infrastructure only). The last factor ensures that the least amount of exogenous infrastructure will be required in order to supply the generation facility with its primary energy source. It should be noted that the only geographically dependent variable in this decision is the location to the primary energy source infrastructure. This variable is different across each technology and for each considered generation location.

Table 9 Technology Data utilized from H2A [92], GHG Emissions from GREET [93], [98]

Technology Name	Plant Capacity [kg/day]	GHG Equivalent Emissions [kg/kg H2]	Capital Cost [$/kg H2]	Fixed O&M [$/kg H2]	Energy Efficiency [%]	Feedstock Costs [$/kg H2]
SMR	379,387.00	3.32	0.48	0.06	70.95	1.63
Solar-Thermal	100,000.00	0.00	2.88	0.49	5.00	0.00
Electrolysis	52,300.00	35.10	0.39	0.09	72.59	3.40
Coal Gasification	246,478.00	5.24	1.52	0.39	62.13	0.41
Distributed SMR	1,500.00	5.65	0.39	0.14	68.77	1.35
Distributed Electrolysis	1,500.00	37.82	0.43	0.18	67.37	3.27

The metrics for creating a spatially and technology dependent problem were chosen in order to encapsulate energy consumption, emissions and monetary costs. GHGs were chosen in order to focus on the minimization of a fleet wide carbon footprint which will assist in California meeting its reduction goals. The three cost factors were chosen in order to ensure that hydrogen would be produced via the least cost technology that is currently available. Lowest overall cost technologies ensure that the consumer will obtain the maximum benefit and will allow for the possibility for hydrogen to become competitive with gasoline prices in the near term. Table 3 illustrates that hydrogen is currently cost competitive at the pump when produced via steam methane reformation at either a centralized or even distributed location. Finally, the distance to the primary feedstock infrastructure is considered because of two factors. The nearer to a primary energy source (e.g., natural gas when steam methane reformation is considered), the lesser investment cost required to build infrastructure from the pipeline

to the generation facility along with a reduced energy requirement for the movement of the energy source (e.g., Pumping).

4.3.6 Generation Facility Selection and Dispensing Location Correlation

The model has now calculated the hydrogen demand and allotted it to finite dispensing locations throughout the state. At this point, the decision-making portion of the model has taken into account the expert inputs and generated an overall rank and technology type for each candidate generation location. The next step is to meet the overall state demand with the minimum number of generation locations and least delivery distance possible. A general overview of this process can be viewed in Figure 30. Each generation technology type has a corresponding hydrogen production capacity and is shown in Table 9. The list of ranked candidate generation locations is sorted in descending order. Next the location with the highest overall ranking is selected, its capacity is removed from the state demand and the process is repeated with the next highest ranked location, until the state demand has been met. A list of the necessary generation facility locations is now determined along with the generation technology at each site.

The next step is to correlate the hydrogen generation to the dispensing locations. The correlation is carried out by again starting with the highest overall ranked generation facility within the list generated by the previous step. The nearest dispensing location is found and attributed to this generation facility. The same process is repeated for the next highest ranked facility location, adding only a single station at a time. This process is repeated for all generation locations within the proposed list, until the end is reached. The process is then repeated, again starting at the highest ranked generation facility, adding only one dispensing location and moving down the list. This looping process is repeated until all of the dispensing locations demands are satisfied. This process of the single nearest dispensing location per iteration ensures that there will be an equal correlation of the nearest dispensing locations, instead of having one generation facility with a cluster of nearest dispensing

locations and the rest needing to supply a demand that will be much further away.

Figure 30 Generation facility to dispensing location correlation, where the number to the right indicates the figures flow in the overall schematic seen in Figure 14.

4.3.7 Delivery Mode Module

For hydrogen delivery scenarios in this analysis, three different potential solutions are considered. These three scenarios are: 1) gaseous hydrogen via a pipeline to a centralized terminal in combination with gaseous truck distribution, 2) gaseous truck distribution and 3) liquid hydrogen truck distribution. Each of these pathways will have a varied amount of energy consumed and resulting emissions due to the fact they each utilize a different technology and considered network. The flow of this sections analysis can be seen in Figure 31.

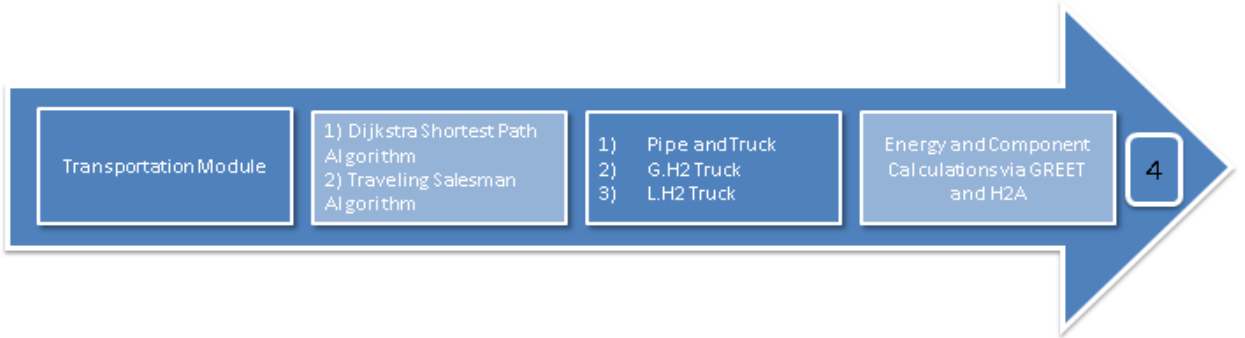


Figure 31 Overall flow of the Delivery Module for the calculation of energy and emissions, where the number to the right indicates the figures flow in the overall schematic seen in Figure 14.

In order to determine the best overall delivery method to deploy, the calculation of the energy and emissions related to each possible supply scenario must be tabulated. Two primary networks are

employed for this calculation, the major highways in California and the natural gas infrastructure. The highway network is utilized for calculating the truck delivery routes, where the natural gas pipeline network serves as a surrogate for the best routes by which to install a hydrogen pipelines.

Working with these datasets, the first step of this section is to determine all of the shortest paths from the centralized generation facilities, to their previously correlated dispensing locations. This shortest distance is tabulated via the Dijkstra methodology and is implemented for both pipeline and trucking routes. In the case of the pipeline delivery scenario, the centroid of the supplied stations is found, and the best possible route for the pipeline becomes the pathway from the centralized facility to this centralized terminal.

For the trucking routes however, once all of the different possible routings from each node to all other considered nodes (nodes here consist of the centralized generation facility and all correlated dispending locations that the particular facility supplies) are known, the Traveling Salesman Algorithm developed by Kirk (2011) is implemented [100]. This algorithm aims to find the HiGRID shortest distance a salesman can travel from the centralized facility and supply all of the necessary hydrogen dispensing locations through the implementation of a genetic algorithm. It should be noted that due to the nature of this genetic programming algorithm, the greater the iteration number and larger the initial population, the more optimal results will be, with the tradeoff of longer computational times. In the case of this application, the salesmen are the delivery trucks. This algorithm is applied to each generation facility, or in the case of pipeline delivery, centralized terminal, separately, as each facility has its own set of correlated dispensing locations which it will supply. In order to calculate the number of required trucks for the delivery process, the capacity of each truck must be calculated, and then the centralized facilities output capacity is divided by the trucking capacity. The calculation for the carrying and or storage capacity of the trucks is employed based in the H2A analysis and is as follows [92]:

- For gaseous truck delivery:

$$truckcapacity = numberoftubes * tubecapacity \quad \text{Equation 8}$$

Where $numberoftubes = 9$ and $tubecapacity$ = 74.4 kg.

- For liquid truck delivery:

$$truckcapacity = 4372\ kg/truck. \quad \text{Equation 9}$$

The previously described delivery methodology allows for the calculation of the miles traveled by truck or pipeline in order to supply the hydrogen fuel. Examples of one centralized generation facility and its correspondingly supplied dispending locations via the pipeline and trucking scenarios are shown in Figure 32 and Figure 33. It may be noted that the delivery routes do not go all the way to the generation facility or dispensing locations, this is due to the fact that a nearest neighbor search is conducted in order to correlate each point (generation facility or dispensing location) to the nearest infrastructure location for the initiation of a delivery route. Any distance between the points and the delivery pathway will have to be made up via installed infrastructure. Once this has been tabulated, factors for energy consumption and emissions can be applied, allowing the different methodologies to be compared.

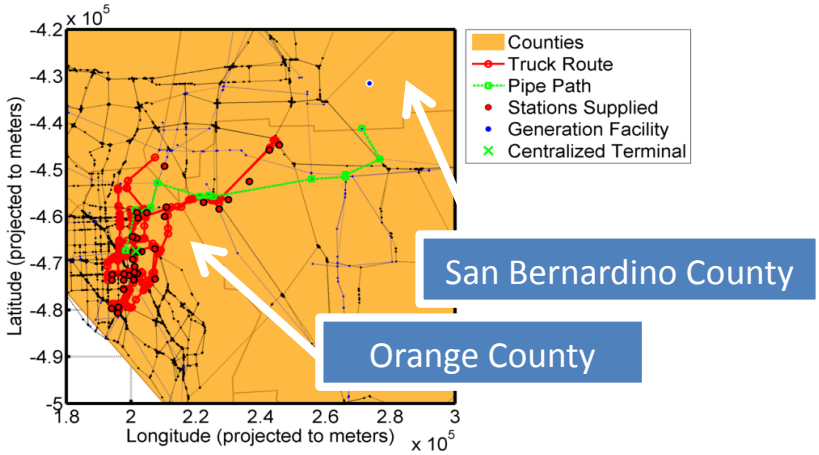


Figure 32 Example of gaseous hydrogen delivery via pipeline from central generation facility to a centralized terminal and corresponding truck delivery from the terminal to the supplied stations

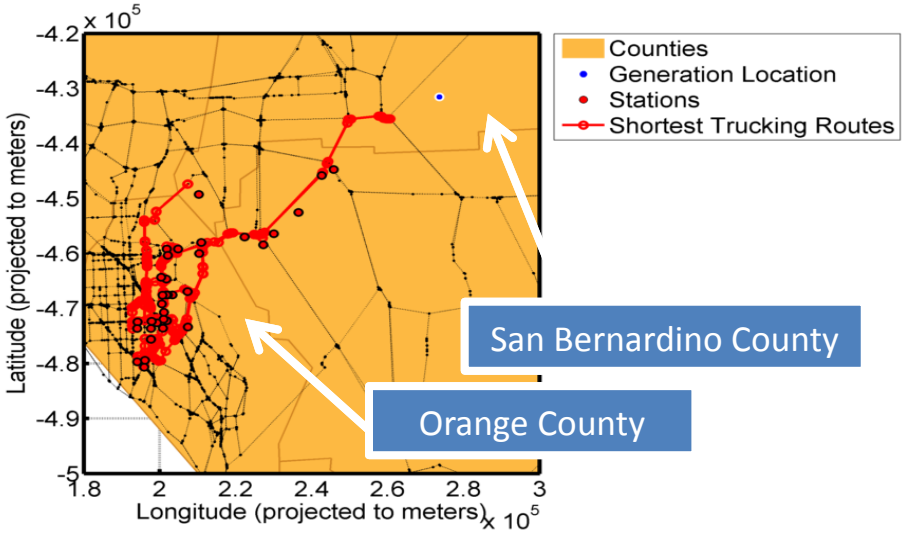


Figure 33 Example of gaseous hydrogen delivery via truck directly from a centralized generation facility to the dispensing locations.

4.3.8 AHP for Delivery Technology

Once the overall distance, resulting energy consumption and emissions generated from each delivery method has been established, the AHP is implemented. The overall process flow in this final decision can be seen in Figure 34. From this decision-making process the preferred delivery method and route will be known.

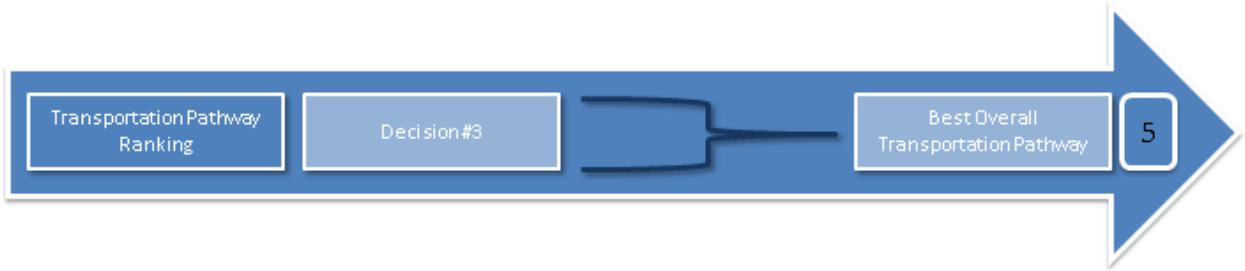


Figure 34 Selection of preferred delivery methodology flow diagram, where the number to the right indicates the figures flow in the overall schematic seen in Figure 14.

For the best overall delivery pathway decision, the four metrics used in the AHP were Greenhouse Gas Emissions (GHG), Least Energy Consumption (LEC), Capital Cost (CC), and Operations and Maintenance Cost (OM). These criteria are organized in a pairwise manner in Table 10.

Table 10 Delivery Methodology Criteria Rating Pairwise Comparison Matrix

Delivery Pathway Weighting Matrix				
	Least Energy Consumption (LEC)	Capital Cost (CC)	Operations & Maintenance Cost (OM)	GHG Emissions (GHG)
Least Energy Consumption (LEC)				
Capital Cost (CC)				
Operations & Maintenance Cost (OM)				
GHG Emissions (GHG)				

The criteria that were chosen for the delivery method selection were chosen on the basis of minimizing energy, emissions and cost. It should be noted that this decision is only applied to pathways that consider centralized hydrogen production methodologies. If the hydrogen is produced at the site of dispensing, this decision is disregarded. The GHG emissions are those generated by the delivery of hydrogen from the conversion facility to dispensing location, if the hydrogen is produced centrally. The LEC or energy required to deliver hydrogen from the conversion facility to dispensing location is sought to be minimized (e.g., Electricity required for pipeline pumping or diesel fuel use for trucking routes). The CC is the total capital cost involved in the installation of the delivery pathway. The OM or operations and maintenance cost is considered as the total cost of maintaining and operating the delivery pathway.

The criterion chosen for this decision were intended to keep the process in the track of energy, emissions and cost minimization. This can be clearly seen by the selection of least energy consumption, capital cost, operations and maintenance costs, and GHG emissions as the decision criteria. The overall decisional flow and criteria for this section can be viewed in Figure 35.

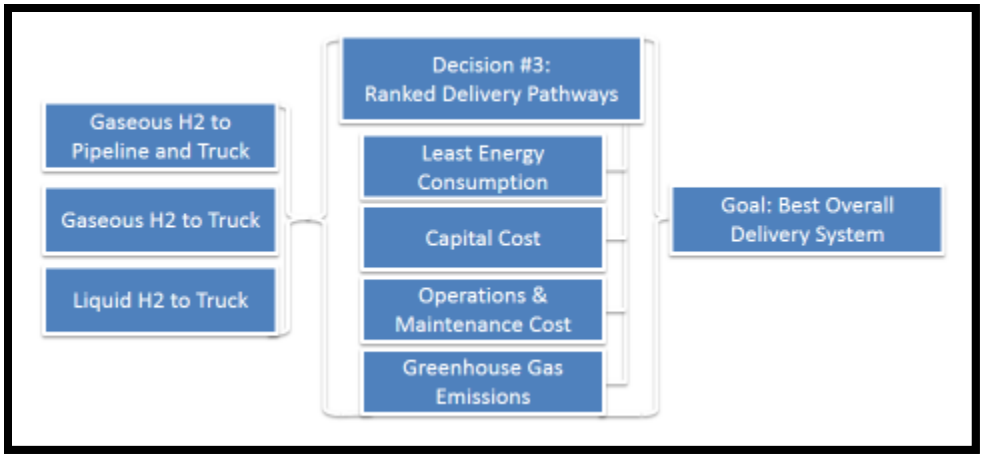


Figure 35 Delivery Pathway Ranking Process

At this point the HFit methodology, through systematic processing, has preferentially selected the most appealing generation sites, facility type, delivery routes and methods along with the dispensing locations. The next step in this process is to analyze the environmental and energy systems interactions that will occur from a future projected hydrogen infrastructure build out scheme.

4.3.9 Application of Hydrogen Fuel Cell Heavy Duty Trucks

In order to setup scenarios that would be realistic and most beneficial to a hydrogen economy, alternatively powered hydrogen delivery trucks were considered. Hydrogen was considered as an alternative fuel for liquid hydrogen delivery trucks. In order to model such delivery trucks, data from Vision Industries Corporation was utilized. Visions initial testing of an Organic Liquid Hydrogen Carrier allows for 110 kg of hydrogen to be stored on board for a 650 mile range at highway speeds for heavy duty trucks. This works out to be 5.9 miles per kilogram of hydrogen. The same delivery pathway calculations as outlined above are applied in order to obtain overall truck route distances. Then the Vision data is applied in order to determine how much overall hydrogen will be required to deploy 0, 50 or 100% of truck delivery powered by hydrogen. This hydrogen demand is then subtracted from the overall state demand in order to determine the hydrogen provided to passenger vehicles allowing for a final vehicle penetration to be tabulated.

4.4 Hydrogen Energy and Emissions Module (Post Processing)

The HFit produces spatially and temporally resolved outputs in the following forms: 1) hydrogen generation technology mixture, 2) hydrogen demand, 3) distribution distances and technologies. This section of the model is considered post processing because it takes in the outputs after the HFit has executed completely. This module consists of two other key energy infrastructure models developed within the APEP and fall within the boundary of STREET, as was introduced by Figure 12. The flow of this post processing and integration section is shown in Figure 36.

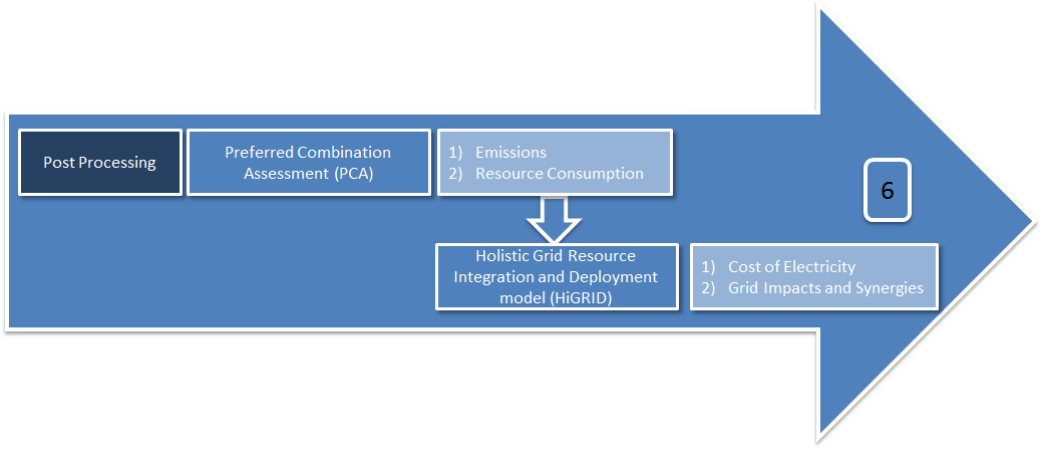


Figure 36 Integration of other energy systems analysis models with HFit outputs, where the number to the right indicates the figure's flow in the overall schematic seen in Figure 14.

The first model utilized in this portion is known as the Preferred Combination Assessment or PCA [35], [37], [67]. The methodology employed in this model was introduced in the "Assessment for the planning of an HSC" section of this document. The overall flow process of this model, along with its

integration with the HFit can be seen in

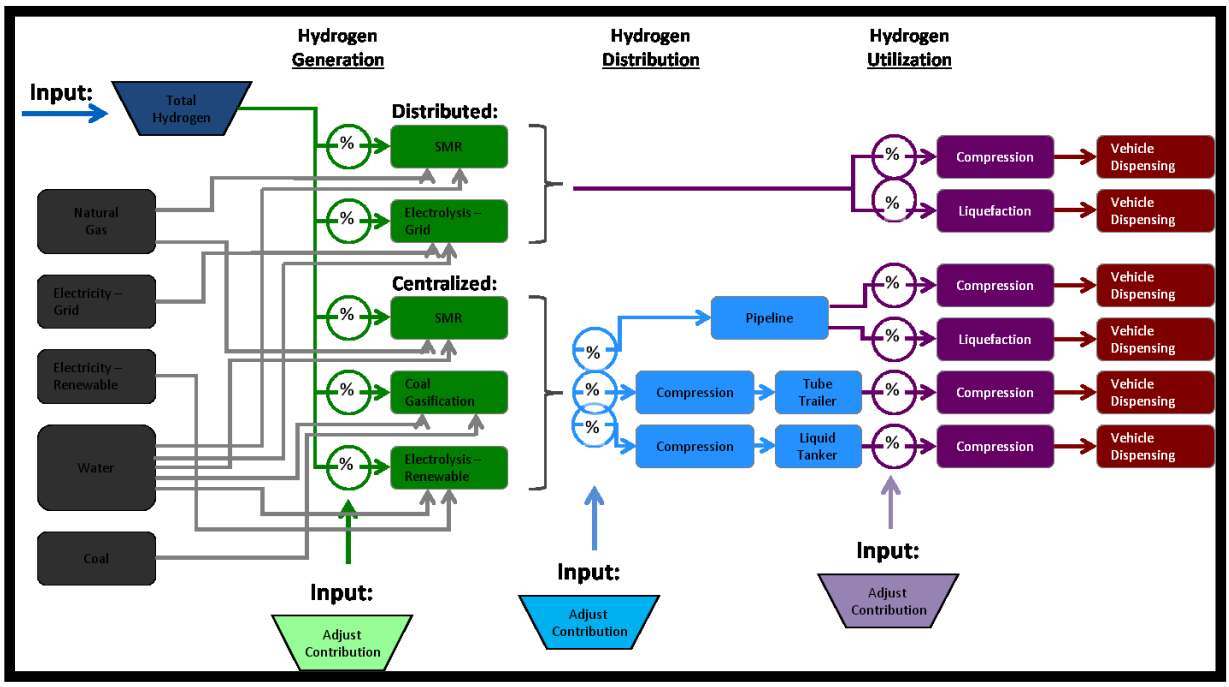


Figure 37. A more detailed view of the generation, distribution and dispensing technologies able to be considered are displayed in

Table 11. For this analysis, it is assumed that all centralized and distributed technologies are base-loaded with the exception of hydrogen electrolysis.

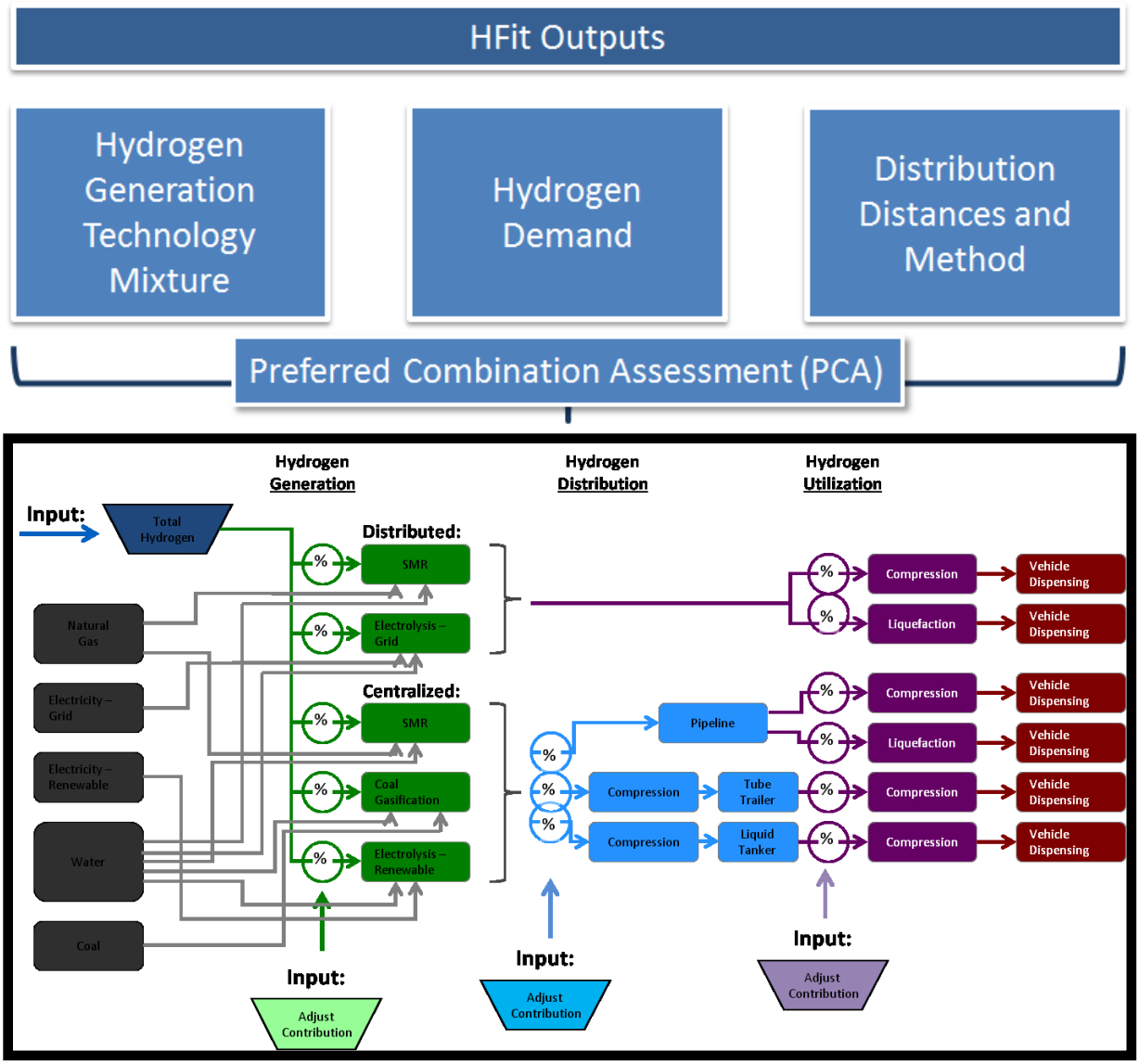


Figure 37 Integration of the HFit outputs as the PCA inputs

Table 11 Hydrogen supply chain methodologies considered by the PCA [33]

HYDROGEN GENERATION	
Feedstock extraction & transportation	
Natural gas	
Water	
Electricity	
Biomass	
Petroleum Coke	
Coal	
Uranium	
Conversion to hydrogen	
Centralized	*Distributed*
SMR	SMR
Electrolysis (renewable)	HTFC cogeneration with natural gas
Petroleum coke (cogeneration)	HTFC cogeneration with biogas
Coal gasification (cogeneration)	Electrolysis (grid)
Biomass	Electrolysis (renewable)
Nuclear	
HYDROGEN DISTRIBUTION	
Truck - Tube trailer	
Truck - Liquid tanker	
pipelines	
HYDROGEN UTILIZATION	
350 bar	
700 bar	
140 bar	

The outputs of the PCA are hourly resolved consumed resources, such as water, electricity, natural gas and diesel fuel, and corresponding supply chain emissions generated. The portions of the supply chain that are considered by the PCA are the hydrogen generation, distribution and dispensing. For this application of the PCA, the emission factor due to the electrical demand is removed. This factor is substituted later by the HiGRID as discussed in the “Previous Methods and Future Applications” section.

The next step in post processing is to employ the HiGRID tool. This model focuses on the interaction of high levels of renewable power generation and the incurred effects on the electrical grid, such as level of curtailment and electricity prices [25]. A special module within the HiGRID has been developed in order to determine the feasibility of dispatching hydrogen electrolyzers in order to store what would otherwise be curtailed renewable electricity. In order to undertake such an endeavor, the storage component of this analysis is considered within this module.

Each of the three different considered delivery pathways will have a different overall capacity for storage. The storage at the station is assumed to range from 410kg to 100,000kg, with an additional capacity of 68kg in the cascade system [92]. For the pipeline pathway, the overall pipeline packing capacity is taken into account via equations 3.34 and 1.36 from "Gas pipeline hydraulics" [101] and are recast as Equation 10 and Equation 11 respectively.

$$V_{pack}\,[scf] = 28.798\left(\frac{T_b}{P_b}\right)\left(\frac{P_{avg}}{Z_{avg}T_{avg}}\right)(D^2L) \qquad \text{Equation 10}$$

$$\mathrm{P_{avg}} = \left(\frac{2}{3}\right)\left[\frac{(\mathrm{P_{in}^3} - \mathrm{P_{out}^3})}{(\mathrm{P_{in}^2} - \mathrm{P_{out}^2})}\right] \qquad \text{Equation 11}$$

Where D is the inside pipe diameter (8 inches for this study), L is the pipeline length in miles. This calculation is then converted into kilograms of hydrogen with the ideal gas law and the Pavg. Next, the storage available in all of the trucks delivering hydrogen is tabulated by utilizing data and equations adapted from The Hydrogen Analysis (H2A) Project [92]. The calculations and assumptions are as follows:

$$truckstoragecapacity = tpd * truckcapacity * numberoftruck * 0.96 \qquad \text{Equation 12}$$

Where, 0.96 represents the assumed useable hydrogen in each truck and the truck capacity is calculated via Equation 8 for gaseous hydrogen and Equation 9 for liquid hydrogen.

4.5 Petroleum Pathway Module

The Petroleum Pathway Module leverages several data sets and an additional model developed under STREET at the APEP, in order to explore the potential reduction in emissions due to decreased gasoline consumption across the state. Emission factors are leveraged from GREET in combination with data from the CEC on the location and capacity of refineries to calculate emission profiles of each refinery location. These supply side emissions are utilized in combination with a demand side module that consists of data from the computational modeling tool known as EMission FACtor (EMFAC). This model was developed by the Air Resources Board (ARB) and provides data on passenger vehicles in

California including vehicle miles traveled and associated emissions on a county level [79]. This tool was queried in order to create a Matlab based model for predicting the emissions of on road passenger vehicles in a chosen year and county. This model was then modified to take into consideration the effect that introducing a given percentages of Alternative Fueled Vehicles (AFVs) would have on statewide emission profiles.

The primary data utilized for this section was extracted from GREET and consists of emissions and energy required for Reformulated Gasoline along with those related to crude oil extraction and transport to California. The ability for the removal of upstream energy and emissions for natural gas and electricity are built into this model order to be accounted for externally by CANGAM and HiGRID respectively.

With assistance from data provided on the CEC website, along with ArcGIS geocoding the refinery locations and capacities were determined [80]. With a conversion factor of an average gasoline production of 19 gallons for every barrel (42 gallons) of crude oil processed, an estimate of the amount of gasoline produced at each refinery was reached [102]. Once a gasoline production estimate was reached, this was converted to a million Btu basis from the factor of LHV of 113,927 Btu/gal, which is located within the GREET Fuel Specifications Sheet [93].

The model developed here has the capacity to take in different percentages of AFVs and to generate hourly and spatially resolved on a county level the emissions due to gasoline refining and utilization. The outputs of this model become key input parameters to the air quality modeling that is being conducted at the APEP. The outputs of this model also serve as a basis for comparison between the current trends in gasoline vehicles and the future potential benefits of deploying a hydrogen economy.

5 Summary of Results

The aim of this results section is to highlight the strengths and capabilities of the newly integrated HFit model into the STREET platform. This section corresponds to the last part of the overall flow figure presented in Figure 14 and is presented again in Figure 38. In order to best express the abilities of the HFit model, two analyses were conducted, thoroughly analyzed and are presented here in the results section. The first analysis aims to explore only the siting of fuel production facilities via the AHP and looks to highlight its strengths and weaknesses. The second analyses takes data from a different survey and conducts a full analysis by leveraging the HFit methodology that has now become an integral part of the STREET package.

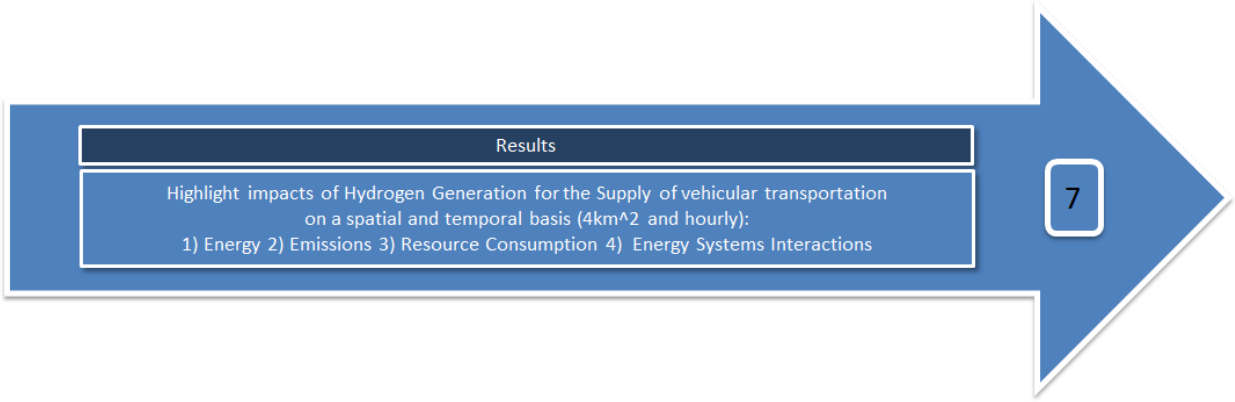


Figure 38 Overall results from the integration of the HFit into the STREET modeling platform, where the number to the right indicates the figures flow in the overall schematic seen in Figure 14.

5.1 AHP Evaluation: Hydrogen Generation Location Ranking

In this study, the AHP methodology is implemented as a site selection tool for the generation of hydrogen as a transportation fuel. The overall goal of this decision is to rank each location for its overall appeal to siting a hydrogen generation facility, which will inform government officials and other prominent leaders. This tool is intended to delegate suggestions over wide swaths of land. As will be pointed out, there are some limitations and anomalies due to dataset resolution when looking at highly focused results. This tool is intended to highlight areas of interest and not to be taken as absolute. A visual outline of this specific decision-making process is displayed in Figure **23**.

In order to gather data on the weighting parameters for each metric as applied to the case of hydrogen generation locations, a survey was performed that asked each participant to rank each metric. Several Hydrogen Fueling Supply Chain Experts were surveyed.

5.1.1 Surveyed Results

The survey contained the previously mentioned five criteria (PPP, LLC, LP, EIP, WIP). The experts were asked to rank each criterion in a pairwise fashion based on the previously described weighting scale, while maintaining a CR of 10% or less. Data was collected from 5 field experts with the results displayed in Table 12. These criteria maintained a CR of 9%, which satisfies the consistency constraint.

Table 12 Aggregate Expert Rankings

Spatial Candidate Location Weighting Matrix						
	Power Plant Proximity	Least Land Cost	Least Populous	Infrastructure Proximity	Process Water Proximity	Normalized Principle Eigenvector
Power Plant Proximity	1	5/4	1	3/8	3/2	16.50%
Least Land Cost	4/5	1	7/8	1/4	1	11.97%
Least Populous	1	8/7	1	2/7	8/7	14.30%
Infrastructure Proximity	8/3	17/4	31/9	1	17/7	43.84%
Process Water Proximity	2/3	1	7/8	2/5	1	13.39%

Observations should start with the results of the expert survey. Going back to Table 12 and taking the normalized principal eigenvector of each row, the general importance of the ranked criterion can be seen (displayed in the last column). At the conclusion of this step, it can be noted that the experts as a whole put a large amount of emphasis (43.8% more than the other criterion) on the importance of EIP relative to the fuel production locations. This shows that the location of existing energy infrastructure is critical in dictating future fuel production facility siting decisions. The other four criteria were ranked significantly less important. In order to explore how these criteria played into the ranking of generation locations, each one will be examined individually later in this paper.

Once the aggregate weighting criteria were obtained, the process as described in the AHP Decision-Making Methodology section was applied. This process allowed for a color intensity map corresponding to the rank of each site as a candidate fuel production location to be produced.

5.1.2 AHP Ranking Results

Statewide results generated from the AHP can be viewed in Figure 39. The first observation likely made from Figure 39 is to note the low ranking areas since many areas received a high priority ranking. Examining these low ranking areas can provide some insight. Focusing on the corners, it can be seen that the areas of low rank exist far from installed energy infrastructure locations. However, other areas that display low rankings (i.e., the San Francisco, Los Angeles, San Diego metropolitan areas) are very near much energy infrastructure and power plants. The low rankings in these areas results from the high populations in these areas, causing an intensification of the weight on population. The final, somewhat low scoring location is settled into the north-western corner of San Bernardino County. This low ranking is also correlated to its large distance from candidate energy infrastructure and power plant locations. These results are broad generalizations and are the aim of this study. These results are reasonable given the input weighting of the different criteria. These results can also be useful for decision makers interested in locating hydrogen generation sites in certain regions or areas. In order to further investigate how these results would affect calculations in a complete hydrogen supply chain planning tool, it is necessary to look at some of non-attainment areas in more detail to ensure that there are no pockets of high ranking within these areas.

To do this, the three main air districts that continually do not attain compliance with national standards are concentrated upon. Some general observations of these districts will be highlighted. The first noteworthy aspect is the high ranking of almost all points within the SJVAB. This could cause problems when considering the addition of hydrogen generation technologies that emit greenhouse gasses and criteria pollutants. Another overarching conclusion that can be drawn is the effect that

infrastructure proximity has on the overall decision. It can be seen that areas both in the Bay Area and the Port of Los Angeles, are ranked high mainly due to their proximity to energy infrastructure and oil refineries. The effect of other criterion is hard to judge at this scale. Therefore, two subsections of the state have been chosen for closer analysis.

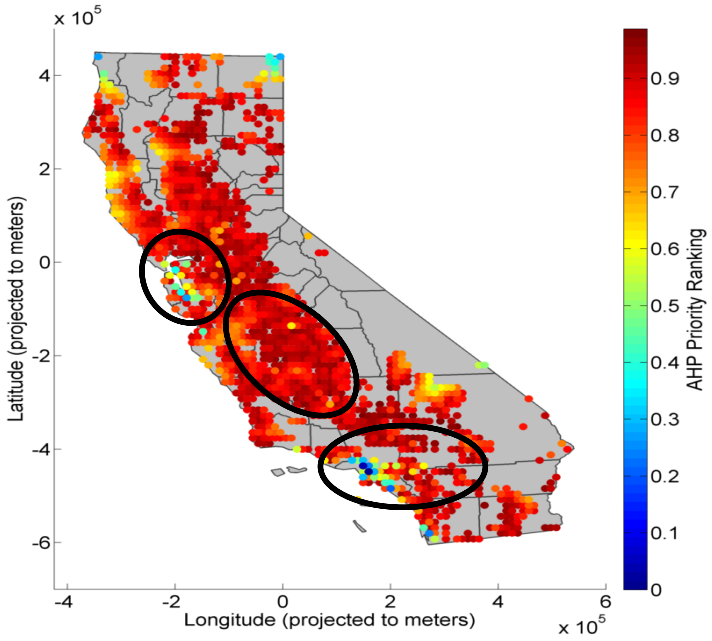


Figure 39 Candidate generation location rankings for the entire state of California

5.1.2.1 Southern California Focus

The AHP results for Southern California are displayed in Figure 40. The SoCAB region was chosen as a focus because this area has been noted for non-attainment of air quality standards [10] in addition to some interesting results. In this region, several locations have been ranked highly for the siting of hydrogen generation facilities. Of particular interest are the four highly ranked locations circled in red in Figure 40, as many of the locations surrounding them are ranked much lower overall. This becomes of particular interest when taking into account that large hydrogen generation facilities would not be sited there given the proximity to residential areas and that some hydrogen generation methodologies may still contribute to air quality problems. However, if the hydrogen technologies of interest were to be distributed in nature, environmentally sensitive, and acoustically benign, then these locations near

residential areas might be of interest, and it is necessary for the AHP designed here to resolve distributed as well as centralized generation possibilities.

To further evaluate why these sites scored high while sites near them scored low, it is important to consider the infrastructure criterion given its high weighting relative to all other criterion. The energy infrastructure is shown in Figure 40. On average almost every considered point in this region is near some sort of infrastructure as evident in Figure 40. This shows that a high weighting on proximity to infrastructure by the experts places a large, yet similar weighting on all candidate locations. The only difference between the locations is the distance they are located from the nearest infrastructure. Therefore, it is of interest to determine why some areas in the SoCAB are ranked markedly higher for the siting of a hydrogen generation facility.

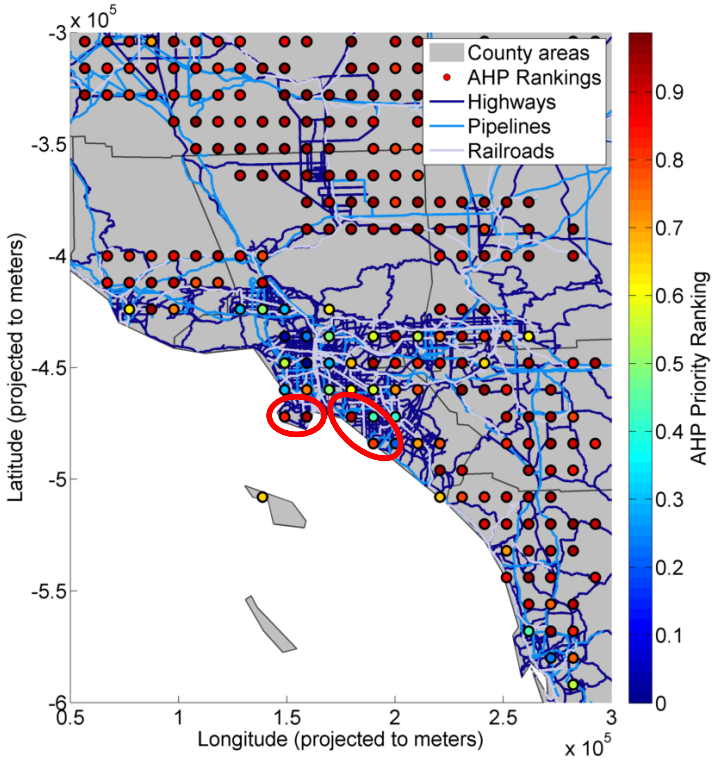


Figure 40 SoCAB AHP priority rankings for fuel production locations and Infrastructure map

In order to better understand where the locations of focus are geographically, Figure 41 is displayed and can be compared to Figure 40. These locations will be the concentration of the remainder of this section.

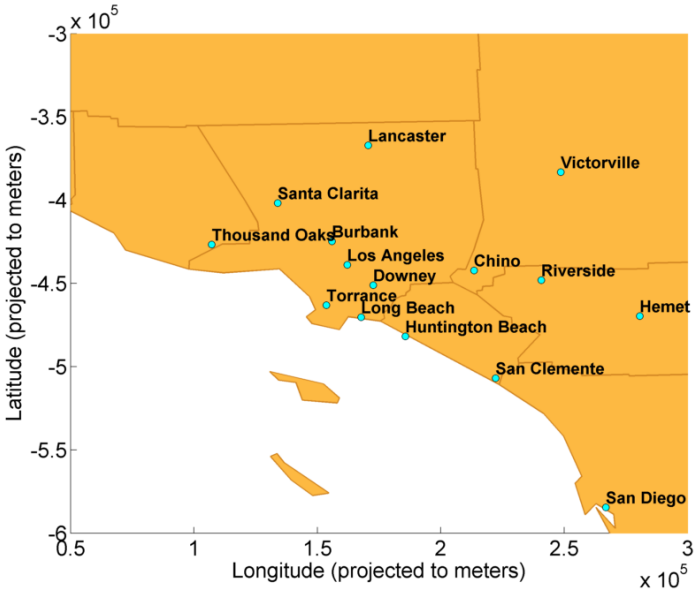


Figure 41 Detailed view of cities in the SoCAB area of study

In order to continue to unravel the complex rankings determined by the AHP, a map of the SoCAB with AHP results and power plant locations are overlaid in Figure 42. Power plants are chosen next due to their relative importance (See Table 12). The first thing to note about Figure 42 is the apparent power plants in the ocean near the Port of Long Beach. This aberration is most likely due to the resolution of the dataset incorporating the power plants and the lack of resolution utilized by the base map. From viewing this figure it can be seen that all of the candidate locations are relatively close to power plant locations. Therefore, it is assumed that the priority assigned due to this criterion is similar for the different points. The question still remains as to why some of the surrounding locations are ranked much lower, while being just as near if not closer to power plant locations.

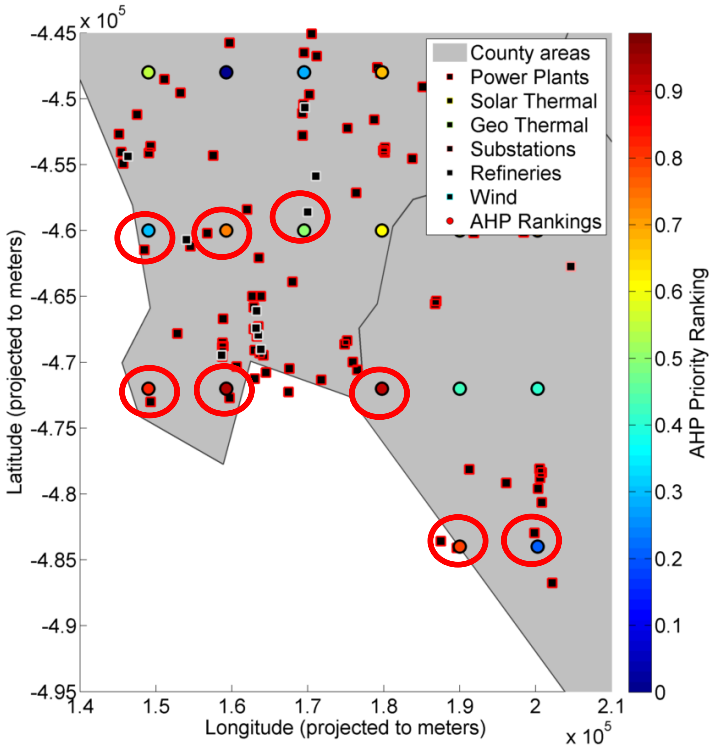


Figure 42 SoCAB AHP priority rankings for fuel production locations and power plants map.

The next step is to examine population data, which is next in the priority of the weighting criterion. After looking at Figure 43, it can clearly be seen there is a large amount of fluctuation in the data within the areas of consideration. Populations near the generation locations that were ranked highly overall, are clearly low. This is most likely not the sole reason for the high rankings of these four locations due to the low overall priority of the population criterion.

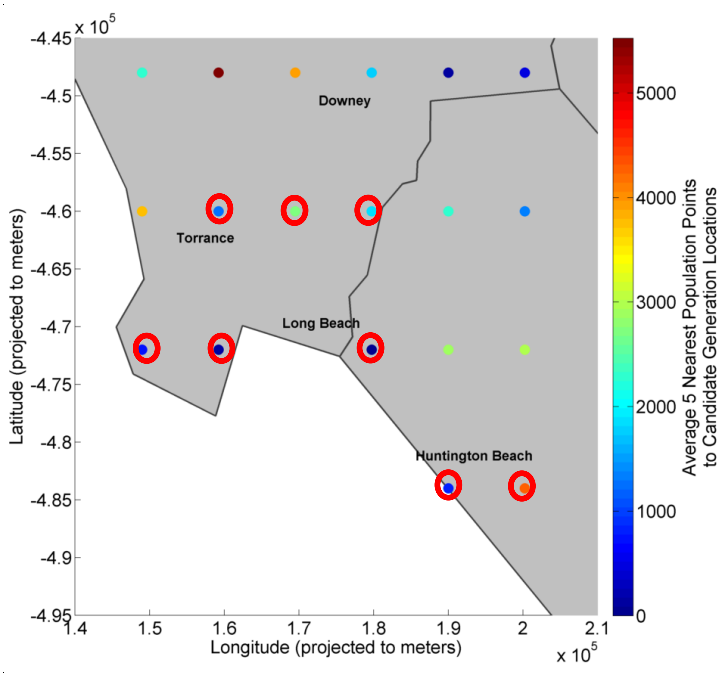


Figure 43 SoCAB Average 5 nearest population points from LandScan™ data relative to candidate fuel production locations

The next highest ranked criterion would be location of water infrastructure relative to the candidate generation site. This criterion is disregarded for this micro-study, because there are no major waterways in the SoCAB region.

The final criterion of consideration becomes the relative cost of land. It can be seen from Figure 44 that the land costs in the areas of consideration are very near in magnitude. This raises some concern when looking at the candidate sites circled in red in Figure 45, known as Rancho Palos Verdes or Palos Verdes Estates. It is well known that this area not only has costly homes built there, but would not be receptive to the construction of an industrial hydrogen production facility although distributed, environmentally sensitive and quiet systems would be possible. This anomaly shows two important facts. The first is that the tool is designed to provide guidance to industry and state officials in decision-making and is not intended to be a deterministic approach. Such instances of highly ranked generation locations would need to be manually removed by local authorities with a more detailed knowledge of the local land appraisals and zoning if centralized hydrogen generation strategies were the only ones

being considered by these decision makers. Secondly, this anomaly shows the critical nature of understanding the resolution of the datasets being utilized in such a study. Going back to Figure 45, it can be seen that there is a lack of data in the region circled in red, which is assumed to be a missing, yet large magnitude data point. This data point is non-existent in that location mainly because the data set was generated for all major cities in California and within the marked region exist no cities. Therefore, this tool would benefit greatly from acquiring land cost data with a greater spatial resolution.

This still leaves the question of why there are some candidate locations which are ranked higher overall than others in a relatively small proximity. The main reason for this variation is that of the spatial variation in the population and land cost datasets. This lack of a single parameter dictating the results showcases the simple yet strong attribute of being able to synthesize large datasets, multiple decision criterion and repositories of expert inputs in order to rank each candidate location for an overall solution space.

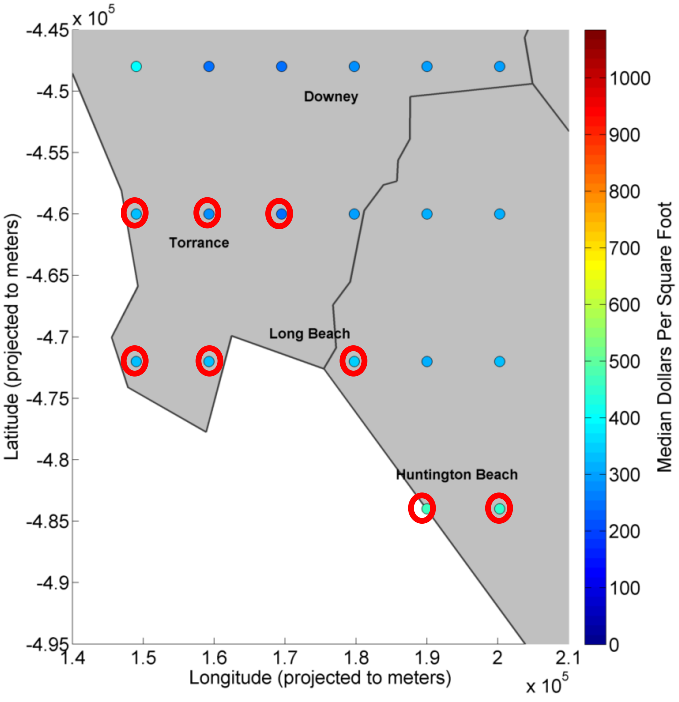


Figure 44 SoCAB Zillow™ Real-estate data correlated to candidate fueling locations

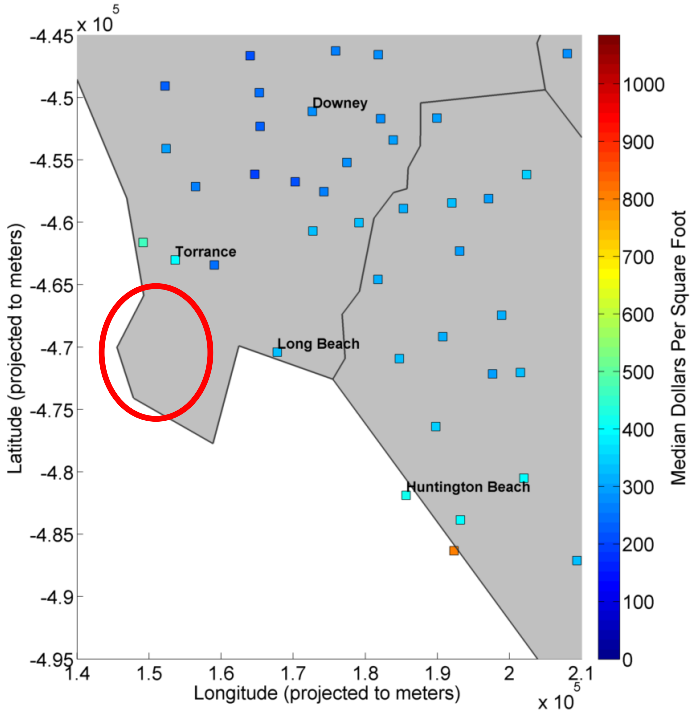


Figure 45 Zillow™ raw real-estate data for cities in the SoCAB

5.1.2.2 Northern California Focus

A similar investigation is carried out on the San Francisco Bay Area, with the Air Basin being the center of interest. Contrary to the ranking of the first set of points that was focused on, this set examines anomalies that consist of low overall rankings. It can be seen in Figure 46, that there have been an array of 12 locations of interest highlighted by red circles. Attention is drawn to these points due to the high rankings of nearby points. For clarity with regard to proximity to cities, Figure 47 is provided. Figure 47 is an equivalent spatial view as Figure 46.

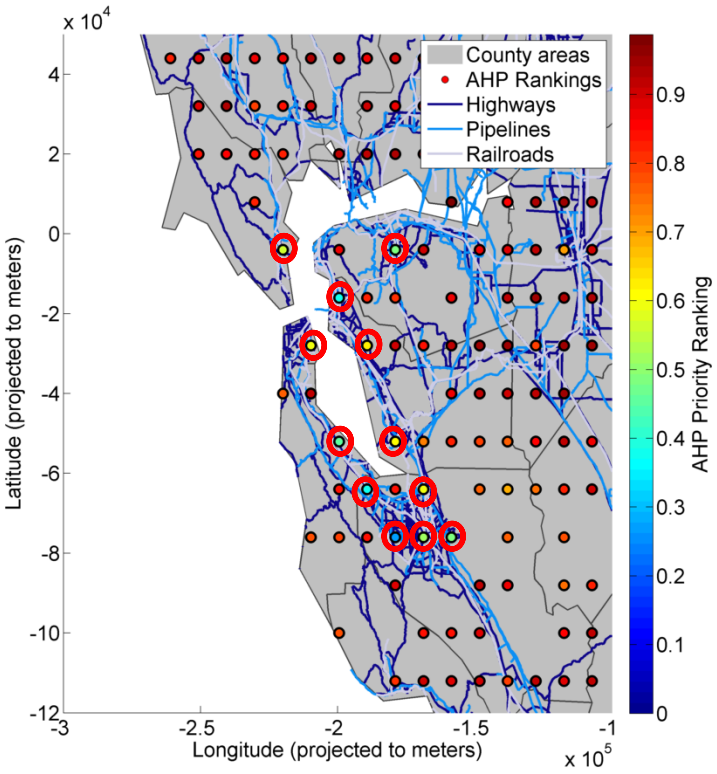


Figure 46 SFBAAB AHP priority rankings for fuel production locations and Infrastructure map

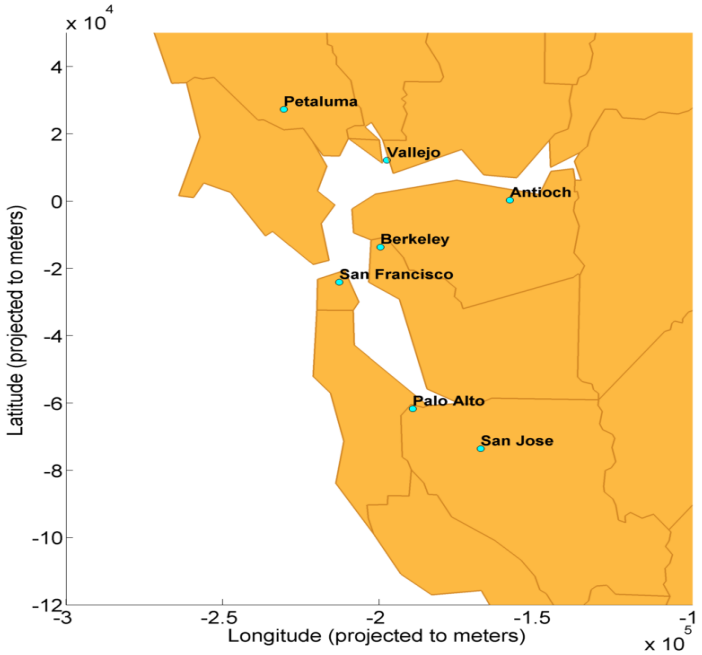


Figure 47 Detailed view of cities in the SFBAAB

It can be seen that all of the circled areas sit directly adjacent to existing infrastructure, which has the highest weighting. This indicates that all of the candidate points should have an equivalent and high ranking when it comes to this criterion, however, they do not.

The next most heavily weighted criterion is the proximity to power plants. In Figure 48, the ranked candidate locations and power plants within the state of California are displayed. A first observation of this figure is that the power plants appear to be in the water near the legend. This was addressed in previous sections and has been correlated to a lack of costal resolution utilized by the base map. With respect to ranking of the candidate locations, all of the points are close to or on top of existing power plant locations, except for the two locations circled in light blue. This is likely partially responsible for the sites' low rankings.

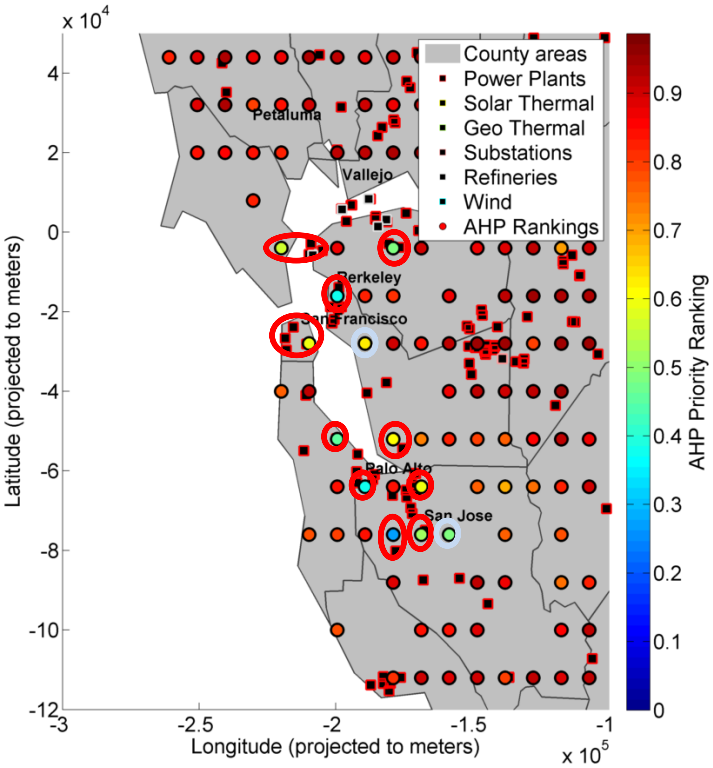


Figure 48 SFBAAB AHP priority rankings for fuel production locations and power plants map

The next criterion to investigate due to its weighting is the population. In Figure 49, it can clearly be seen that the points of interest fall into the category of moderate to high populations. An interesting facet is that the two locations circled in light blue only have moderate population values. This goes to show that the proximity to power plants, energy infrastructure and population criterion cannot be the cause of the rankings of these two outstanding points.

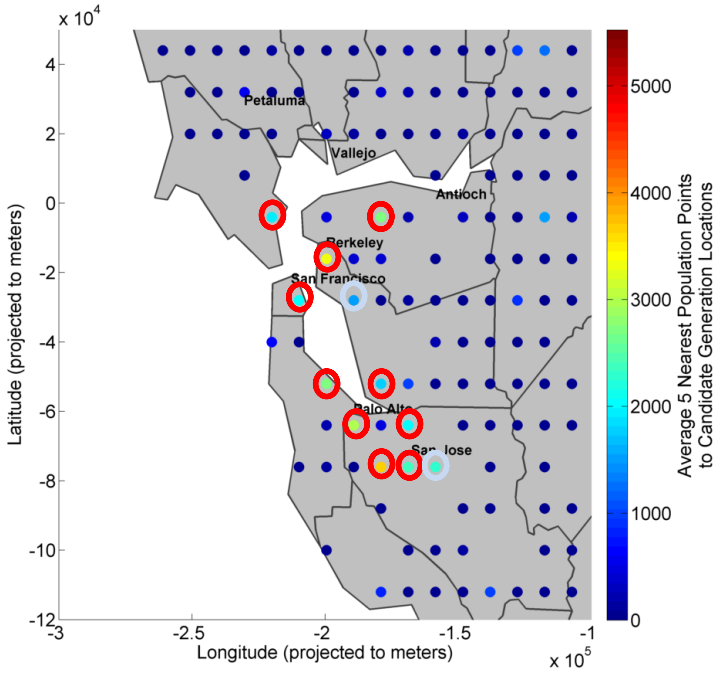


Figure 49 SFBAAB Average 5 nearest population points from LandScan™ data relative to candidate fuel production locations

Moving onto the next criterion brings the focus to water infrastructure proximity. Again, this dataset is neglected in this detailed view because there is not water infrastructure in the proximity of the 12 points of interest.

The final criterion to consider then becomes the surrogate land cost data. The raw data extracted from Zillow™ can be seen in Figure 50 and values assigned to the candidate locations based on the nearest Zillow™ data point can be observed in Figure 51. First, as a general observation all of the

housing data surrounding the San Francisco Bay are moderate to high values. This fact, in and of itself is most likely a contributing factor to the low ranking assigned to the nearby candidate generation locations. However, an extremely interesting artifact circled in red, can be observed in Figure 51. The three locations circled have some of the highest home values assigned to them, however, when observing Figure 46, it can be seen that these same locations receive a high overall AHP score. This solution can only be justified by observing Figure 49 and noticing that these three points have an extremely low population value. This makes sense due to the greater weighting assigned to low populations as compared to low land cost, in addition, if proximity to power plants and infrastructure are about the same, these three points would logically obtain a high ranking.

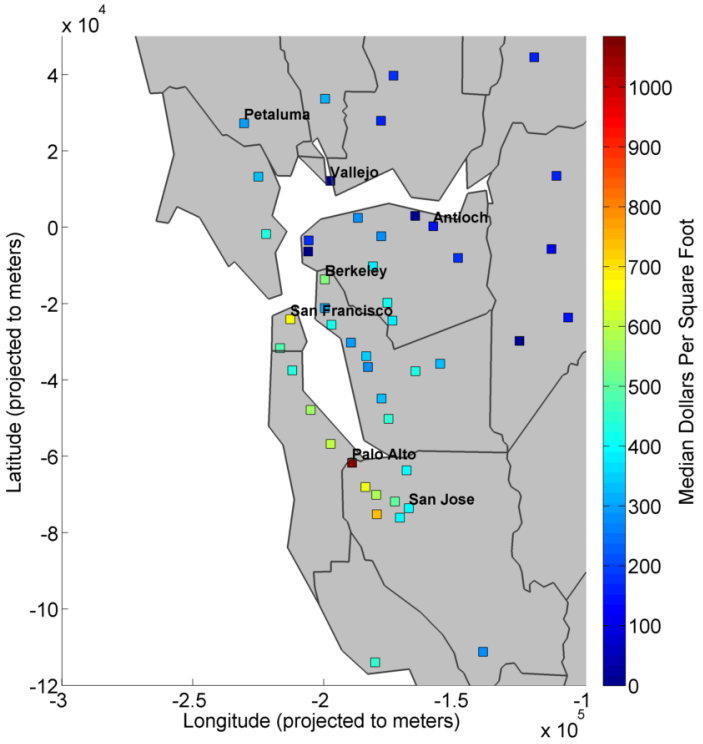


Figure 50 SFBAAB Zillow™ raw real-estate data

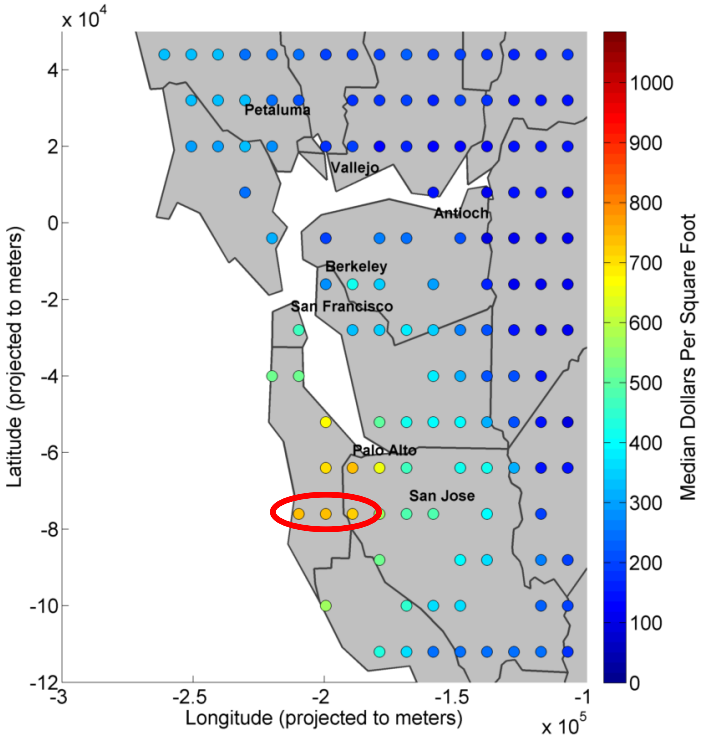


Figure 51 SFBAAB Zillow™ Real-estate data correlated to candidate fueling locations

From this section it can be seen that the cost of land and population data have the most influence out of the five criterion. This is mainly due to the uniformity of magnitudes in the first three datasets explored. Deciding which criterion influence certain rankings in a given area can also guide decision makers. The importance of certain criterion is not a sure thing as can be seen by the more highly resolved examinations of the two regions within this paper.

5.1.3 Summary: AHP Evaluation for Hydrogen Generation Siting

The AHP was utilized to rank candidate fueling locations for potential as hydrogen generation sites in order to: 1) examine the AHP as a fuel production facility siting tool, 2) Exercise the AHP tool in a case study for hydrogen fuel focusing on both Northern and Southern California, and 3) Examine the robustness and resolution of the analysis results through the exploration of anomalies in the results to verify its utility in complete modeling of hydrogen fuel cell vehicle roll out planning. In order to systematically rank these locations five criterion were chosen and are: 1) Proximity to Power Generation

Facilities, 2) Lowest Land Cost, 3) Least Populous, 4) Proximity to Existing Energy Infrastructure, and 5) Water Infrastructure Proximity. In order to generate the weighting metrics for each of these criteria and to carry out a case study on hydrogen production, five Hydrogen Fueling Supply Chain Experts were surveyed.

As was seen in this study, the AHP tool was demonstrated to rank various candidate generation sites in a reasonable fashion. There were some apparent abnormalities that upon further inspection revealed that the results indeed made sense given the rankings applied to the selected criteria. In addition, these apparent abnormalities really only exist for centralized generation schemes, whereas the results would make sense for distributed schemes. A lack of a single parameter delegating the overall decision exemplifies the power of the AHP. This process is capable of taking many metrics of varying units and combining them to come to an overall decision for complex, multilevel problems. It is clearly seen through the examination that was conducted, simply looking at the datasets and proposing candidate locations would be cumbersome and inaccurate. Trying to compare the distances from infrastructure and power plants, to the magnitude of a population and land cost, in order to come to an objective decision would be impossible without this de-coupling process. In all, the AHP will have utility in the complete modeling of hydrogen fuel cell vehicle roll out planning.

One shortcoming of this study is a carbon intensity and air quality signal. In order to prevent emissions intensive technologies from being installed in air quality management districts that are not in attainment, a parameter should be introduced that would account for emissions related to a certain technology. The AHP is versatile enough to accommodate such a signal through any sort of air quality and emissions data, along with another weighting parameter or two on the importance of air quality and or emissions.

The AHP was chosen due to its flexibility in the decomposition of complex problems. Therefore, in the future it is suggested that this methodology be expanded and utilized in order to decompose the decision in Figure 23 into several more sub-decisions. One suggested breakdown is of the EIP metric. This could be broken down into sub-criterion based on the type of infrastructure (Highways, Railroads, Natural Gas Pipelines and Electrical Transmission Lines). Each of these sub-criteria would receive a different weight when considering the generation of different fuel types. If a case study was conducted on natural gas as a transportation fuel, then the distance to natural gas infrastructure and highways would be more germane than the other two metrics. This could also be applied to Electricity as a transportation fuel, with a similar change in metric weights, favoring electrical infrastructure.

5.2 HFit Analysis: Full Hydrogen Supply Chain Build Outs

As an initial exercise and illustration of HFit's capabilities, a full supply chain case study was conducted. First, the hydrogen Demand and Dispensing module was exercised in order to illustrate its analytical power. Once the hydrogen Demand and Dispensing module analysis was carried out, the rest of the HFit was employed in order to conduct full supply chain analyses under varied conditions.

5.2.1 Hydrogen Demand and Dispensing Module Exercise

The first step in the examination of a future hydrogen economy was to model the projected future hydrogen demand for the desired year of 2050. For this particular case study the hydrogen demand due to a 75% FCV penetration was considered, because of the projections found in the "Advanced Clean Car Summary" produced by the ARB [103] . At the year 2050 the projected VMT is 1,244 million miles per day. When comparing this to other studies in the field, it is about 40% higher when normalized to the common study year of 2005 [104]. The VMT in this study is greater because it is an updated projection when compared to the study mentioned. Figure 52 outlines various proposed hydrogen station capacities compared to current gasoline station dispensing rates. The two hydrogen

station scenarios represent two future projections of FCV efficiencies with 68 MPKG being utilized from here on out.

There are three bars seen in Figure 52, each of which represents a different installed hydrogen station capacity and corresponds to a different penetration of current gasoline stations that would need to be converted to hydrogen dispensing locations. Table 13 displays the various hydrogen station capacities necessary in order to utilize certain percentages of current total gasoline stations within the state. Three penetrations were considered, 15, 26 and 100% of current gasoline stations. 15% was considered because previous analyses have shown that this is a sufficient number of converted gasoline stations in order to provide coverage to the California population based on a service time coverage algorithm [37]. By converting only 15% of current gasoline stations at the projected 2050 hydrogen demand, all stations would need to provide 9144 KGPD. This could become a throughput issue, therefore other greater penetrations that allow for smaller dispensing capacities are considered.

It can be seen from Figure 52 that by increasing the percentage of converted gasoline stations by a mere 10% a reduction of almost 4,000 KGPD required per station can be achieved. Therefore, it is assumed that some distribution between 26 and 100% of gasoline stations will be converted in the future due to market drivers for supply, demand and consumer convenience.

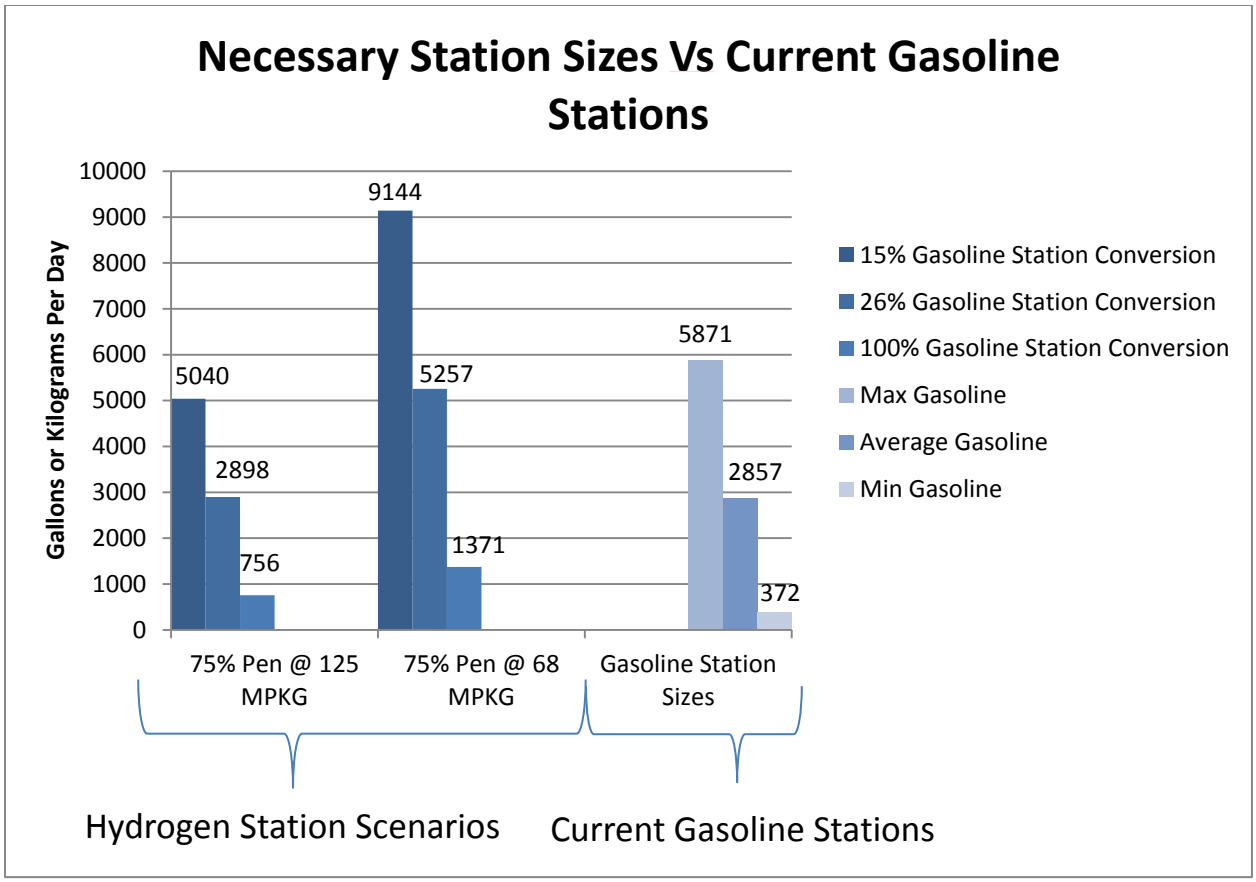


Figure 52 Proposed hydrogen station sizes compared to current gasoline station capacities

Table 13 Conversion percentage of current gasoline stations to meet future hydrogen demand.

	Gasoline Station Conversion Percentage		
75% Pen @ 68 MPKG	100%	26%	15%
KGPD Statewide	13,459,589	13,459,589	13,459,589
Number Gasoline Stations Considered	9,816	2,552	1,472
Number of H2 Stations Needed	1,371	5,300	9,141

5.2.1.1 Spatial Hydrogen Demand

After applying the methodology suggested in "Spatial Hydrogen Demand" section, the overall statewide hydrogen demand is disaggregated spatially and designated to current gasoline stations. The results from this spatial distribution of the projected demand can be seen in Figure 53 through Figure 58. By comparing Figure 55 with Figure 56 and Figure 57 with Figure 58 the improved resolution and spatial distribution of hydrogen demanded due to the integration of spatial gasoline demand and VMT can be seen. The main take away from this comparison is the fact that when only population is considered, the San Francisco Bay Area receives a much higher and the Los Angeles area a much lower hydrogen demand projection than when vehicle miles traveled and gasoline dispensed on a county basis is considered.

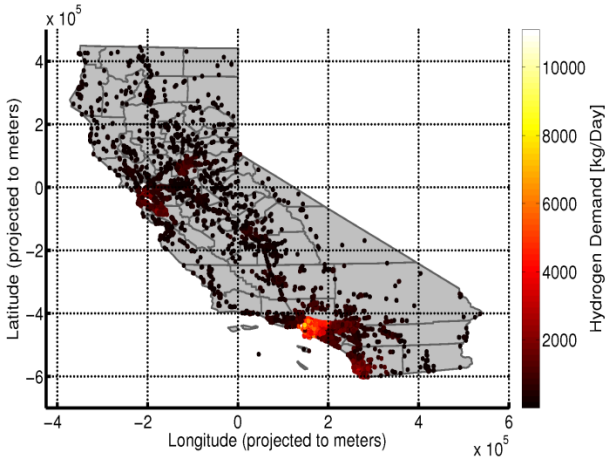


Figure 53 Statewide projected hydrogen demand based on increased VMT and spatial allocation to current gasoline stations based on spatial VMT, gasoline demand and population

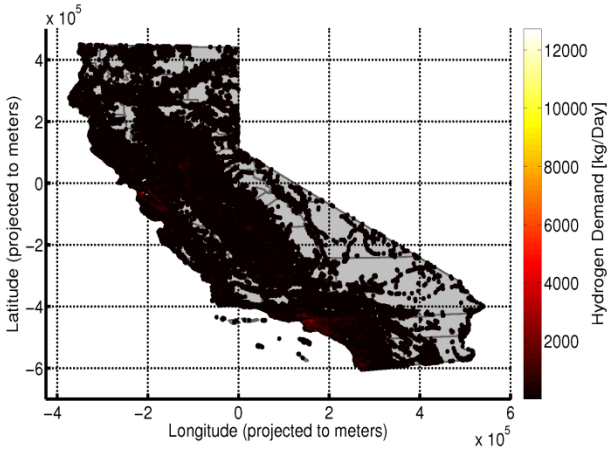


Figure 54 Statewide projected hydrogen demand based on increased VMT and spatial disaggregation due to normalized population distribution only

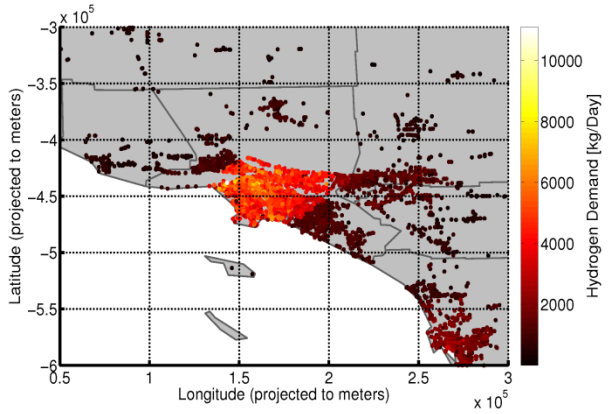


Figure 55 Port of Los Angeles focused, projected hydrogen demand based on increased VMT and spatial allocation to current gasoline stations based on spatial VMT, gasoline demand and population

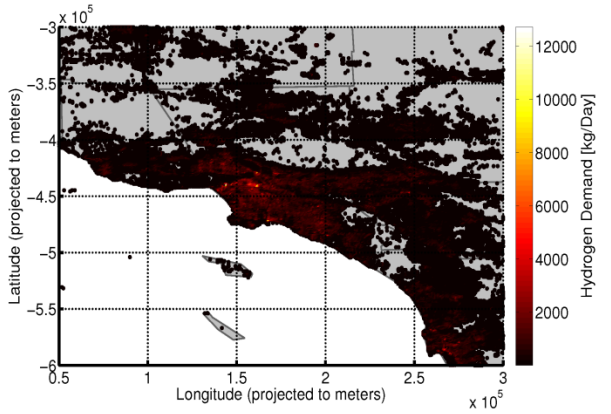


Figure 56 Port of Los Angeles focused, projected hydrogen demand based on increased VMT and spatial disaggregation due to normalized population distribution only

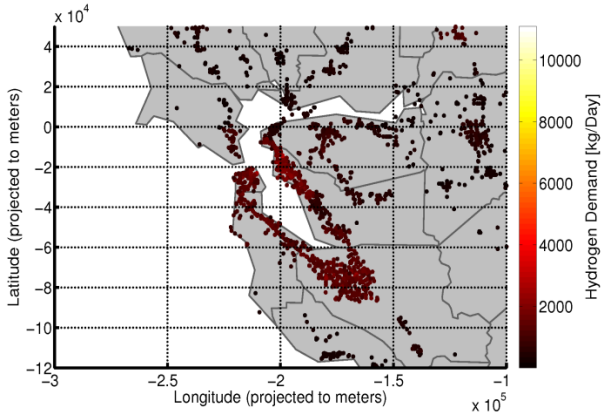


Figure 57 San Francisco Bay Area focused, projected hydrogen demand based on increased VMT and spatial allocation to current gasoline stations based on spatial VMT, gasoline demand and population

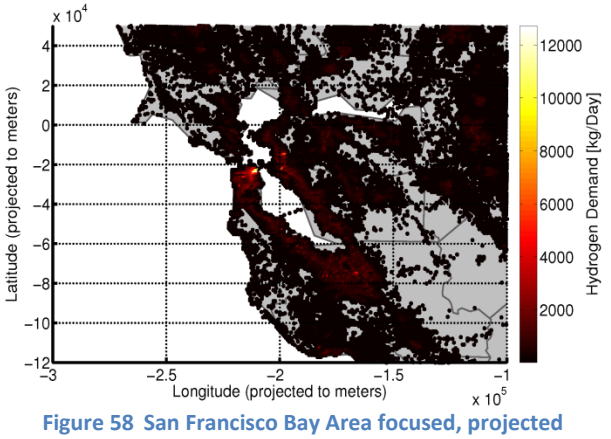


Figure 58 San Francisco Bay Area focused, projected hydrogen demand based on increased VMT and spatial disaggregation due to normalized population distribution only

5.2.1.2 *Hydrogen Dispensing Locations*

After the hydrogen demand is disaggregated spatially, it is allocated to the nearest candidate dispensing locations as explained in the "Hydrogen Station Siting" section. The results of the demand fulfillment section of this module under three different installed station sizes can be viewed in Figure 59 - Figure 61. The three scenarios suggest 100, 26 and 15 percent of current gasoline stations to be utilized. The spatial evolution between the three scenarios is apparent with the suggested dispensing locations occurring near the main population centers within the state.

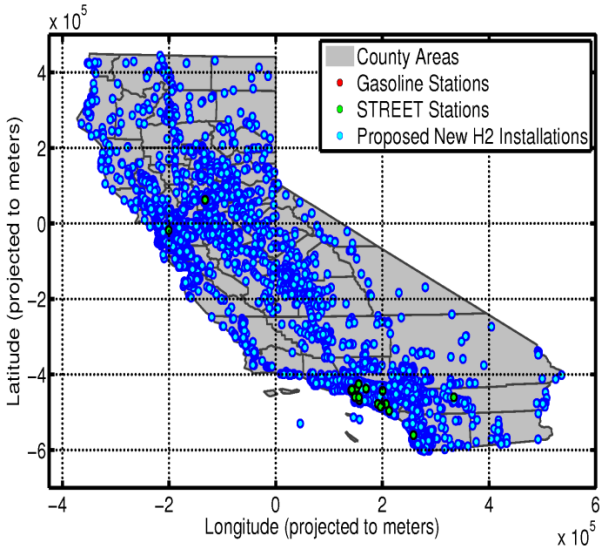


Figure 59 Proposed Hydrogen Fueling Locations in the Year 2050; 1371kg/day Stations equating to 100% gasoline station utilization

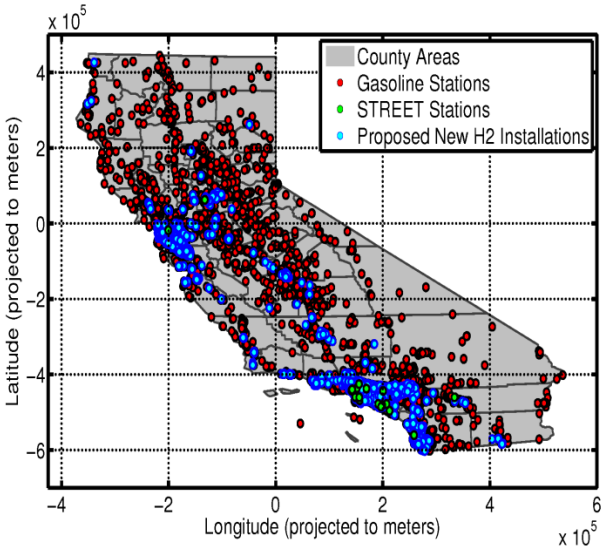


Figure 60 Proposed Hydrogen Fueling Locations in the Year 2050; 5300kg/day Stations equating to 26% gasoline station utilization

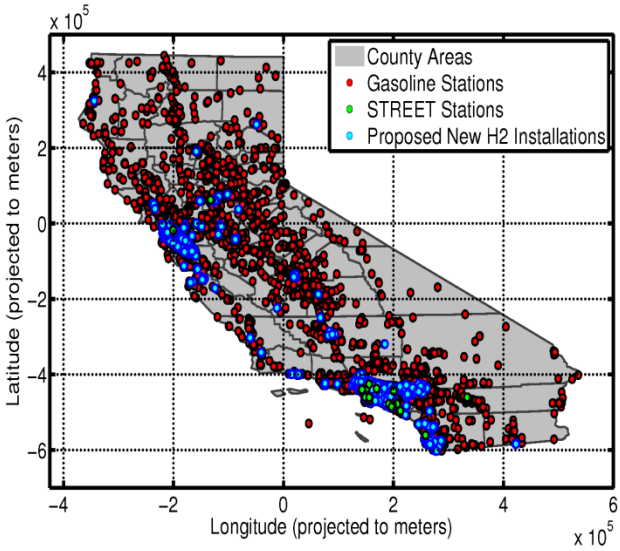


Figure 61 Proposed Hydrogen Fueling Locations in the Year 2050 9142kg/day Stations equating to 15% gasoline station utilization

5.2.1.3 Temporal Hydrogen Demand

The location of hydrogen dispensing locations is only part of the hydrogen demand story for this energy system. In order to obtain a complete illustration of hydrogen dispensing, hourly demand profiles must be generated. These hourly dispensing profiles are critical when examining the hydrogen energy systems interactions with other infrastructure such as the electrical grid. Hydrogen demand will vary diurnally along with the overall demand for electricity. As the demand for hydrogen increases the burden to the electrical grid will increase as well, due to the fact that hydrogen dispensing relies heavily on electricity. The quantification of these results is important for systems performance on a holistic level. The next section of the hydrogen demand module disaggregates the hydrogen demand into an hourly resolved dispensing profile that allows for detailed energy infrastructure interactions to be analyzed as outlined in the "Temporally Resolved Hydrogen Demand" section of this document.

The hourly dispensing profile displayed in Figure 62, exemplifies the strong dependence that hydrogen demand has on an hourly basis. This is an important factor when considering other energy infrastructures that have a similar resulting demand profile, for example, the electrical grid, which also has a similar hourly behavior. In addition to interaction with the electrical grid, this behavior is important when designing the overall hydrogen energy system. The quantification of this variation in demand is critical when considering such things as the storage system. Oftentimes large centralized hydrogen production plants are utilized in order to supply hydrogen. These plants run at a base-load capacity with fixed hydrogen delivery schedules to the dispensing locations. Therefore, it is critical that the storage system have enough capacity in order to handle these increases in demand. It is also important to not oversize such storage systems due to the incurred capital cost that will be garnered from such an excess in installed storage capacity.

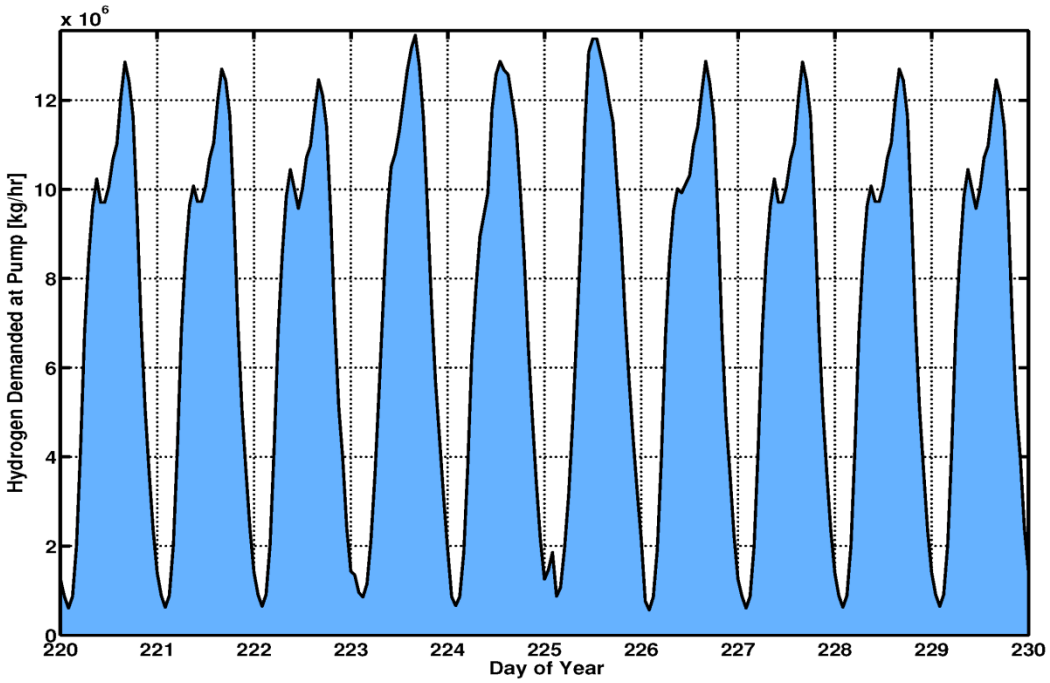


Figure 62 Hourly dynamic hydrogen demand profile for a ten day period based on gasoline station filling profile.

The hydrogen demand module illustrates the importance of choosing the properly sized hydrogen station in order to meet consumer need. It has been shown that a low percentage of current gasoline stations could be converted to hydrogen stations in order to meet a large future hydrogen demand. This low percentage becomes infeasible when looking at the capacity each station would have to be capable of dispensing from a customer convenience standpoint. Therefore, a range of lower capacity stations with a higher percentage of current gasoline stations being converted is suggested. The sensitivity of spatial hydrogen demand was also shown to rely heavily on the datasets deployed in order to rank the points considered. When combining spatially allocated VMT, population and gasoline demand, the most realistic overall results are obtained. When the hydrogen demand is allocated to current gasoline stations via an optimal allocation algorithm it can be seen that the stations are preferentially located in areas of high hydrogen demand. This is evident in Figure 61with the Los Angeles area having more hydrogen stations than the San Francisco Bay Area. Finally, the hydrogen demand has been shown to have a large diurnal fluctuation that is critical to consider when designing a hydrogen

supply chain. These diurnal fluctuations not only affect the designing of the overall system itself from a storage and energy balance perspective, but also from an energy demand perspective. These diurnal demand fluctuations will have an impact on other energy systems that are necessary in order to produce and supply hydrogen such as the natural gas and electrical energy systems.

5.2.2 AHP Survey Results

In order to apply the AHP, data are necessary for the weighting of the decision-making criteria. In order to generate data for this study, experts within the APEP were surveyed. The data collected from these surveys determined the corresponding weights for each of the three decisions that were explained in the "AHP Decision Making Methodology" section. These decisions led to the designation of a hydrogen generation and distribution mixture. The resulting supply chain was analyzed on the basis of energy consumption, emissions generated and interaction with other energy infrastructure such as the electrical grid.

Once the surveys were collected from the staff at the APEP, the results were aggregated in order to obtain overall weighting criterion for the corresponding decisions. The weighting criteria that ranked the first decision, or each of the candidate generation locations for their overall appeal to the citation of a generation facility, are shown in the final column of Table 14. The results in this table reveal that the survey participants designated Infrastructure Proximity to be by far the most important criterion. The heavy weighting suggests that the surveyed participants recognize the significance of delivery infrastructure on the movement of hydrogen fuel from its generation location to place of dispensing.

Table 14 Internal APEP survey results for technology independent spatially allocated generation facility siting decision.

Spatial Candidate Location Weighting Matrix						
	Power Plant Proximity	Least Land Cost	Least Populous	Infrastructure Proximity	Process Water Proximity	Normalized Principal Eigenvector (%)
Power Plant Proximity	1	0.74	1.15	0.21	0.75	10.78
Least Land Cost	1.35	1	1.45	0.24	0.51	12.23
Least Populous	0.87	0.69	1	0.22	0.54	09.49
Infrastructure Proximity	4.79	4.08	4.45	1	3.34	49.98
Process Water Proximity	1.33	1.95	1.87	0.3	1	17.53

Once the data were collected for the technology independent decision, the weighting matrix for the spatially allocated, technology dependent decision was synthesized. Once the surveys were collected and aggregated, Table 15 was generated. Similar to the previous weighting matrix, the relative importance of each criterion is displayed in the last column on the right. It is interesting to note that there is not a significant outlier in this relative importance calculation. It can be observed from these rankings that the energy conversion efficiency has been ranked as the most important parameter, yet closely followed by GHG emissions. It makes sense that these two criterion become the most important in this decision as they are both dependent on the system efficiency and most likely result from the knowledge the surveyed group has with regard to these measures.

Table 15 Internal APEP survey results for technology dependent spatially allocated generation facility siting decision.

Spatial Candidate Technology Dependent Weighting Matrix							
	GHG Emissions	Capital Cost	Operations & Maintenance Cost	Energy Conversion Efficiency	Feedstock Cost	Proximity to Feedstock Infrastructure	Normalized Principal Eigenvector (%)
GHG Emissions	1	1.48	1.59	0.95	1.39	1.94	20.98
Capital Cost	0.68	1	1.82	0.59	0.74	1.22	14.34
Operations & Maintenance Cost	0.63	0.55	1	0.4	0.4	0.67	9.08
Energy Conversion Efficiency	1.06	1.7	2.49	1	2.57	2.22	27.10
Feedstock Cost	0.72	1.35	2.51	0.39	1	1.73	17.13
Proximity to Feedstock Infrastructure	0.51	0.82	1.5	0.45	0.58	1	11.39

The last criteria matrix calculated in order to complete an overall supply chain analysis has to do with the selection of a preferential delivery methodology. Again, after the surveys were aggregated a culmitive matrix was generated and can be seen as Table 16. An interesting and important observation from this table is that the most heavily weighted criterion by far, is that of least energy consumption. The heavy weighting on this criterion continues the trend that the survey respondents have kept up across the past two decisions. It is clear that the surveyed group realizes and values the overall systems efficiency above many of the other parameters. This is curious and would certainly change if the group was shifted from that of an academic standpoint, to an industrial or possibly even a legislative perspective. This idea of changing audiences and recieveing differing results is one of the main reasons AHP was chosen for this type of analysis.

Table 16 Internal APEP survey results for delivery scenario decision.

Delivery Pathway Weighting Matrix					
	GHG Emissions	Least Energy Consumption	Capital Cost	Operations & Maintenance Cost	Normalized Principal Eigenvector (%)
GHG Emissions	1	0.71	1.39	1.6	25.73
Least Energy Consumption	1.41	1	2.67	2.98	42.04
Capital Cost	0.72	0.37	1	1.37	17.88
Operations & Maintenance Cost	0.63	0.34	0.73	1	14.35

After the synthesis of the surveys to come up with the overall weighting for each criterion, and examining their relative strengths, it is time to apply these weightings via the decision-making methodology and to quantify and analyze the results.

5.2.3 Hydrogen Generation Siting Decision Making Results

Each site is first ranked based on a spatial candidate location weighting matrix via the AHP, with the weightings that can be seen in Table 14, which score the overall appeal to the siting of a facility in general. Next, all of the same locations are re-ranked based on a new set of hydrogen conversion technology specific criteria, which are displayed in Table 15. Once these two decision-making processes have been carried out, the resulting datasets are combined in order to rank every candidate s within the state, for its appeal to the siting of a technologically specific hydrogen generation facility. For this case study, the assumption that 75% and 25% of hydrogen will be produced at a centralized and distributed location respectively has been adopted.

This dataset of proposed and now ranked candidate locations is sorted from the greatest overall ranking to the least. Due to the technology assigned to each point, a generation capacity has been determined. Therefore, the next step is to start at the top of the ranked generation locations and begin

to choose them in order to meet the state demand on an aggregate level. A list of the necessary generation facility sites and corresponding technologies is necessarily dictated after this step. The results displayed for this case study with the technology mixture are presented in Table 17 and the spatial allocation of these facilities is shown in Figure 63.

Table 17 Generation Technology Mixture for internal APEP AHP case study, percentage is calculated as number of facilities of a certain type divided by the total number of suggested facility installations.

Internal APEP AHP Case Study						
Technology	Centralized SMR	Solar Thermal Decomposition	Electrolysis	Coal Gasification	Distributed SMR	Distributed Electrolysis
Generation facility mixture percentage	0.00	0.00	7.89	0.00	92.11	0.00

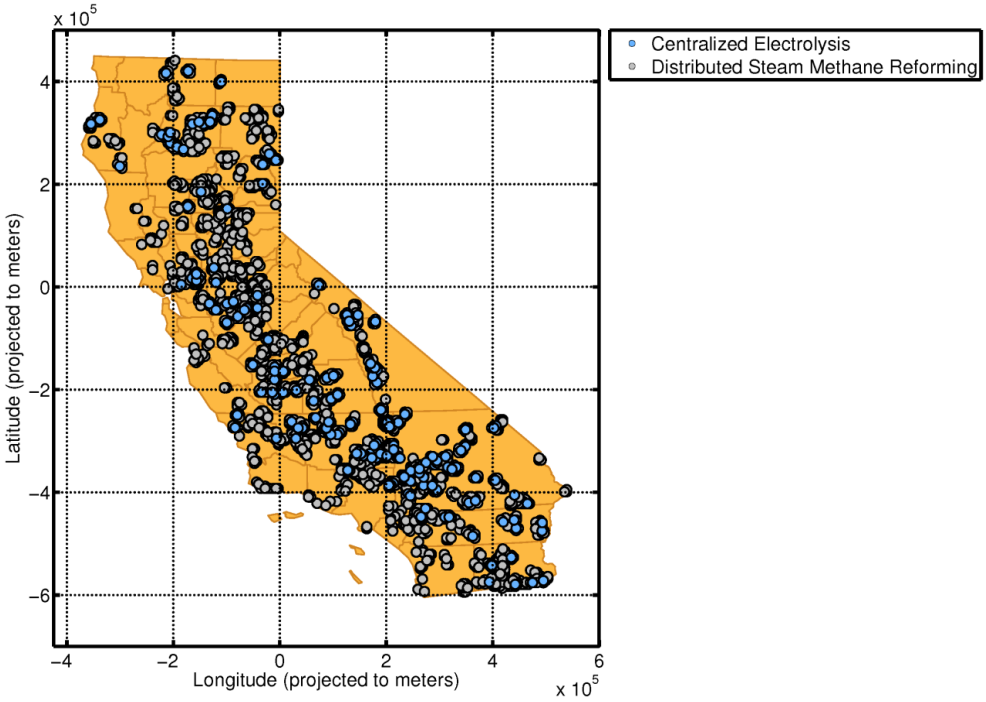


Figure 63 Hydrogen generation facility locations and technology mixture.

After the hydrogen demand is met, the supply to dispensing locations is disaggregated spatially. In order to carry this out, once the list of necessary generation locations has been formulated, it is revisited. Again, starting at the top of the ranked hydrogen generation facility list, the nearest proposed

hydrogen dispensing locations that were found from the hydrogen demand module, are searched for. Each generation facility fills one new dispensing location per loop iteration of the entire list of generation locations, to ensure that there is not spatial bias in the filling of the need of the dispensing facilities. This leads to a clustering of the stations in the closest proximity to the generation facilities.

5.2.4 Delivery Module Results

The overall procedure of the delivery module is to choose only one of the three possible delivery methods based on an AHP decision. The three methods again are gaseous hydrogen via a pipeline to a centralized terminal and then delivered via tube trailer to each station, gaseous hydrogen delivered from the central generation facility via a tube trailer and finally liquid hydrogen delivered from a central facility via a tanker truck. For the two methods that only employ trucks, the only difference is the number of trucks necessary in order to deliver the hydrogen, because the capacity of a liquid truck is about 6.5 times greater than that of a gaseous tube trailer in this modeling case.

In this analysis, the overall distribution methodology selected by the AHP was that of liquid hydrogen delivery via heavy duty truck. In order to show the difference between the three delivery scenarios and to justify this result, Table 18 was generated. It can be seen from Table 16, the survey respondents strongly chose the least energy methodology in order to transport the hydrogen. Therefore, it can be seen from Table 18 that the liquid hydrogen delivery methodology achieves the lowest energy by far out of any of the considered pathways. It is also interesting to note the large value of trucking miles even with hydrogen production being 92% from distributed SMR. This high value is due to the fact 92% of the production by number of plants is from distributed SMR, when in reality 75% of the hydrogen is produced at centralized electrolysis facilities. For the full build out analysis considered, this is where the analysis of the delivery methodology ends. However, some expository results with regard to the delivery mechanisms can be obtained when the size of the dispensing locations are changed as seen in the following section.

Table 18 Hydrogen delivery to 1371KGPD stations from a centralized generation facility to the supplied stations for the state.

Transportation Statistics: 1371 KGPD Stations				
	Pipeline	Trucking (from Terminal)	GH2 Trucking	LH2 Trucking
	Delivery Scenario #1		Delivery Scenario #2	Delivery Scenario #3
Number of Trucks Necessary	0	14,976	14,976	2,304
Total miles	23,459	1,596,612	3,727,983	165,733
Average Miles per Truck	0	52	121	228
Max Miles per Truck	0	129	260	509
Min Miles per Truck	0	6	7	11
Diesel Energy Consumed [MMBtu/day]		107,475	254,633	858

5.2.4.1 *Delivery Pathways Dependence on Installed Station Capacity*

As an illustrational result, outside of the focus of the APEP HFit case study, the simplification of the delivery routes obtained with a smaller fueling station capacity is demonstrated. For this example 1,371 KGPD station capacities are compared to 9,141 KGPD. These correspond to 100 and 15% of current gasoline stations being converted to hydrogen dispensing locations. This scenario was considered because the minimum possible considerable hydrogen dispensing location capacity with no Greenfield sites must be above 1,371 KGPD for the particular projected hydrogen demand. Table 19 was created in order to quantify the effect the station capacities will have on the overall characteristics of the hydrogen delivery mode. By observing Table 19 it is clear that for delivery scenario #1 (combination of truck and pipeline) that the overall trucking distance increases with smaller station sizes. This makes sense because the algorithm tries to pick the stations closest to the central plant first, then finds the centroid of the station cluster in order to apply the trucking delivery route. By taking these two steps, greater delivery distances will be incurred because the smaller stations will be clustered closer to the central facility and the center of the cluster may not be closer to all of the stations. Moving onto delivery scenario #2 and #3, it is clear to see that the overall delivery distance decreases with a decreasing station capacity. This is justified by realizing that the station selection module reduces the total number of considered gasoline stations to the exact number necessary to meet the statewide hydrogen demand and does this by selecting the highest ranking stations. Therefore, the possibility exists for a highly

ranked station to be further away from a centralized facility when there are larger station capacities being installed (i.e. larger station capacities return a smaller set of considered gasoline stations as dispending locations). These results are illustrated in Figure 64 through Figure 67. It can be seen, especially between Figure 64 and Figure 66 that when smaller dispensing capacities are utilized there are more stations and on average allow for the attainment of providing hydrogen to a station that is closer to the centralized generation facility.

Table 19 Quantification and comparison of delivery pathways when utilizing 1371 and 9141 KGPD station capacities

Transportation Statistics: 1371 KGPD Stations				
	Pipeline	Trucking (from Terminal)	GH2 Trucking	LH2 Trucking
Number of Trucks Necessary	0	14,976	14,976	2,304
Total miles	23,459	1,596,612	3,727,983	165,733
Average Miles per Truck	0	52	121	228
Max Miles per Truck	0	129	260	509
Min Miles per Truck	0	6	7	11

Transportation Statistics: 9141 KGPD Stations				
	Pipeline	Trucking (from Terminal)	GH2 Trucking	LH2 Trucking
Number of Trucks Necessary	0	15,054	15,054	2,316
Total miles	27,401	589,438	3,859,021	593,695
Average Miles per Truck	0	3	16	107
Max Miles per Truck	0	14	39	252
Min Miles per Truck	0	1	3	21

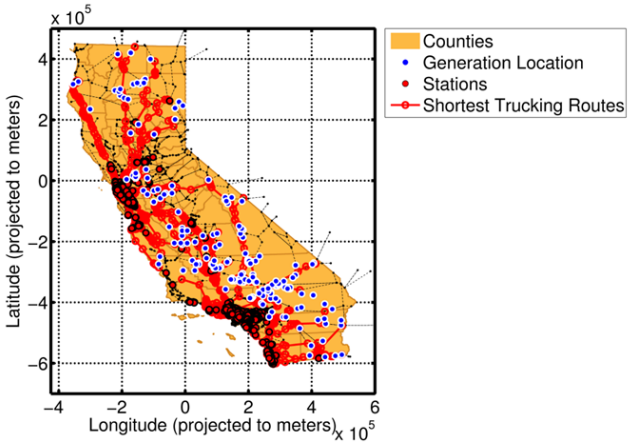


Figure 64 Trucking Routes Only From Centralized Facility to 9141 KGPD Stations

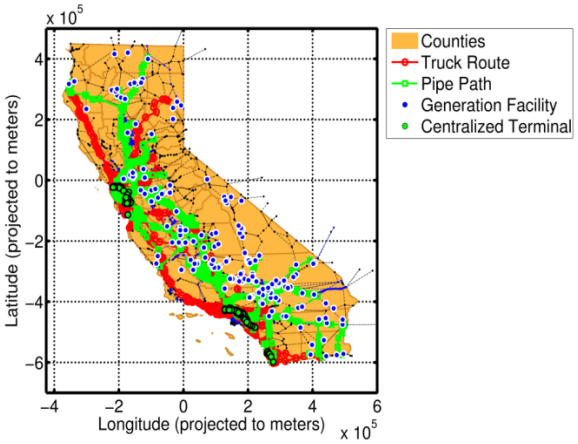


Figure 65 Pipeline to Central Terminal and Trucking From Central Terminal to 9141 KGPD Stations

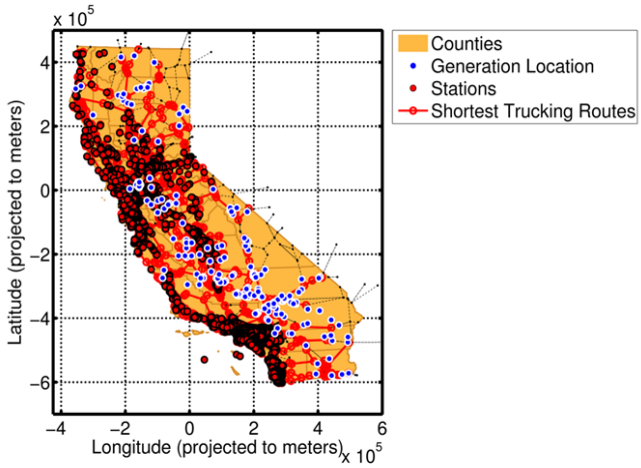


Figure 66 Trucking Routes Only From Centralized Facility to 1371 KGPD Stations

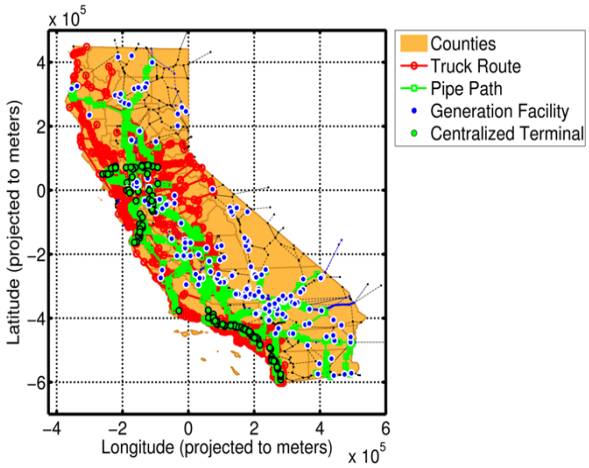


Figure 67 Pipeline to Central Terminal and Trucking From Central Terminal to 1371 KGPD Stations

5.2.5 Delivery Methodology Validation

Taking a step back and analyzing the numbers in Table 19, they may seem higher than one might expect. As a first step, a single centralized generation facility was isolated and its delivery routes displayed in Figure 68 through Figure 70. Two observations should be garnered from these maps: 1) the routes displayed appear to be the optimal routes (i.e., There exist no routes that circle back on themselves, etc.) and 2) Smaller station capacities prevent long distance travel to meet the demand of highly ranked dispensing locations (Figure 70 in particular displays this point). Next, examining the fundamentals of the delivery module, the high numbers seen in Table 19 are dissected. Several possible additional explanations are offered for these high numbers. A first proposition is that overbuilding of the hydrogen delivery pathways may exist. This overbuilding is an artifact of the way the hydrogen

delivery code works. The module isolates and connects only a single hydrogen generation facility with its correlated dispensing locations. Therefore, a small amount of extra capacity in a pipeline or fleet of trucks utilizing the same corridor cannot be co-utilized. Also, the Traveling Salesman Algorithm that has been implemented utilizes a near optimal genetic algorithmic approach that requires the initial population and iteration number to be determined [100]. This study utilizes a moderate starting population and iteration number in order to conserve computational horsepower and time. Therefore, if a greater initial population or iteration time were to be considered, the ending results would be closer to optimal.

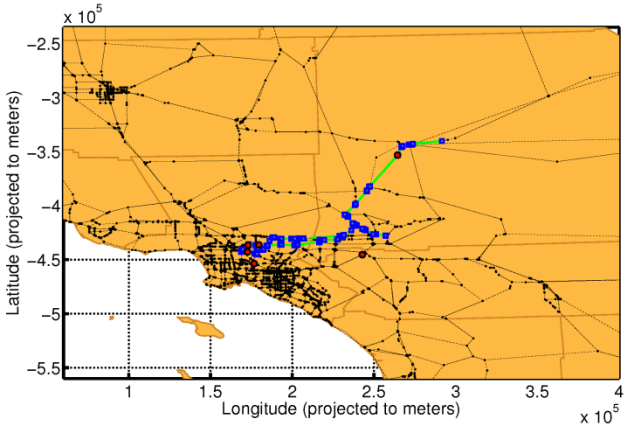


Figure 68 One generation facility and its served hydrogen dispensing locations of 9141 KGPD capacity with corresponding trucking delivery routes.

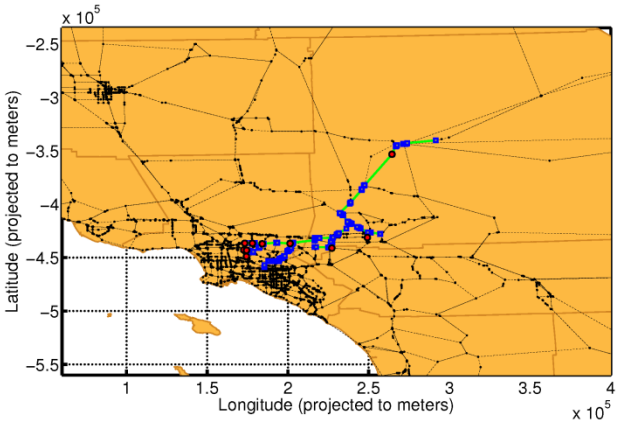


Figure 69 One generation facility and its served hydrogen dispensing locations of 5300 KGPD capacity with corresponding trucking delivery routes.

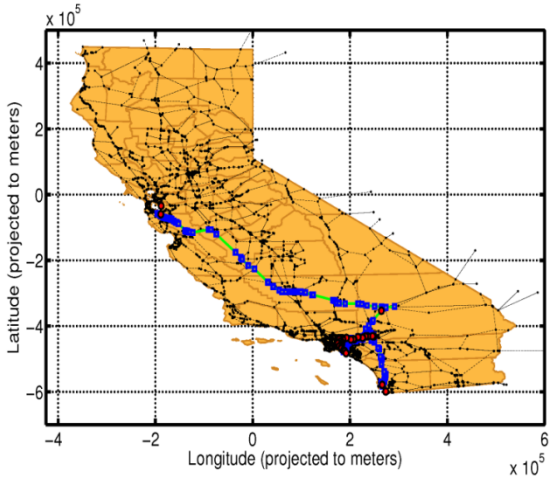


Figure 70 One generation facility and its served hydrogen dispensing locations of 1371 KGPD capacity with corresponding trucking delivery routes.

After noticing that the delivery routes seem to make visual sense, the results are compared to current Annual Average Daily Miles Traveled (AADT) for heavy duty trucks, current California statewide diesel consumption, registered diesel trucks and percentages of natural gas pipeline by the two dominant stakeholders in the state for the case of the combination pipe and trucking delivery. In order to make such comparisons data was gathered for these metrics. The AADT was taken from CalTrans and was shown to be 13,889,742 miles per day [105]. The number of registered diesel trucks was 515,558 and was found at the "Diesel Technology Forum" [106]. The overall statewide diesel demand was found on the CEC website under the energy almanac section and was determined to be 1,587 million gallons in 2012, which equates to 556,537 MMBTU/day [85]. Finally, the EIA mentions that in 2007-2008 California's natural gas pipeline network was dominated by California Gas Transmission Company and Southern California Gas which had 3,477 and 1,887 miles of pipeline, respectively [107]. These metrics are compared to the study results and displayed in Table 20.

It should be noted from Table 20 that from 1.2 - 27.8% of current AADT would need to go toward distributing hydrogen. This number seems to be reasonable given the fact the heavy duty fleet serves other sectors besides fuel energy transport. Next, the percentage of the current heavy duty fleet that would need to be devoted to hydrogen delivery would range from 0.4 – 2.9%. This number seems low, but when the overall heavy duty fleet is considered to have about 516 thousand vehicles, and therefore, makes sense that only a small fraction would be devoted to the delivery of hydrogen. Moving onto the overall statewide diesel demand comparison it can be taken from Table 20 is that 0.2 – 47.4% of the current diesel demand would be devoted to the delivery of hydrogen. The maximum value of 47% seems high, but can be correlated back to the large projected miles needed to deliver gaseous hydrogen due to its lower energy content. It has been noted in the literature that the number of trucking trips for the delivery of gaseous hydrogen would increase ten-fold as compared to liquid hydrogen delivery [52]. The diesel demand, while high, shows that the results provided by the distribution module are still

within a reasonable range. Finally, in contrast, the pipelines required in order to supply hydrogen are shown to be 437-511% longer than that of California's current natural gas pipeline network (i.e., 4-5 times the amount currently installed for natural gas delivery). This magnitude of pipeline required may seem large, but considering that Texas has 45,000 miles of intrastate natural gas pipeline, this corresponds to about 52-61% of that pipeline length being devoted to hydrogen delivery. This overall comparison makes the prescribed results from HFit for a full hydrogen economy appear to be reasonable.

Table 20 Comparison of current California transportation metrics to proposed delivery of hydrogen by HFit.

	1371 KGPD			
	Pipeline	**Trucking (from Terminal)**	**GH2 Trucking**	**LH2 Trucking**
Percentage of overall AADT [%]		11.5	26.8	1.2
Percentage of overall Diesel Fleet [%]		2.9	2.9	0.4
Diesel Consumed by H2 Transport (PCA Calc) [MMBtu/day]		107,474.8	254,633.4	858.1
Percentage of current diesel use per day [%]		19.3	45.8	0.2
Hydrogen pipeline percentage of SoCalGas Network [%]	437.3			
	5300 KGPD			
	Pipeline	**Trucking (from Terminal)**	**GH2 Trucking**	**LH2 Trucking**
Percentage of overall AADT [%]		4.9	27.2	4.2
Percentage of overall Diesel Fleet [%]		2.9	2.9	0.4
Diesel Consumed by H2 Transport (PCA Calc) [MMBtu/day]		44,511.4	258,266.7	3,012.0
Percentage of current diesel use per day [%]		8.0	46.4	0.5
Hydrogen pipeline percentage of SoCalGas Network [%]	507.3			
	9141 KGPD			
	Pipeline	**Trucking (from Terminal)**	**GH2 Trucking**	**LH2 Trucking**
Percentage of overall AADT [%]		4.2	27.8	4.3
Percentage of overall Diesel Fleet [%]		2.9	2.9	0.4
Diesel Consumed by H2 Transport (PCA Calc) [MMBtu/day]		38,513.6	263,868.0	3,077.4
Percentage of current diesel use per day [%]		6.9	47.4	0.6
Hydrogen pipeline percentage of SoCalGas Network [%]	510.8			

The final level of evaluation comes by comparing the GHG emission results of HFit to those in the literature. In Table 21 and

Table 22 the gaseous and liquid hydrogen delivery methodologies, respectively, are explored. The last row in the tables shows the results produced by HFit. Looking at the last column of each of the tables where a kg/mile comparison is made, it can be seen that in both the gaseous and liquid hydrogen delivery cases, HFit actually slightly under predicts the amount of GHG Equivalent emissions that are

generated by the delivery methodology. This means that the emissions intensities of other studies applied to the same delivery distances as calculated by HFit, would provide a greater overall emissions intensity. This comparison confirms that the HFit predictions of heavy duty truck emissions associated with hydrogen delivery are reasonable.

Because of these high levels of both GHG and criteria pollutant emissions experienced by the delivery of hydrogen via heavy duty truck, a novel case study is considered in which hydrogen powered delivery trucks are deployed, which is explained in the following section.

Table 21 Gaseous hydrogen delivery methodology emissions under a delivery scenario that requires 3,727,983 miles per day of trucking delivery. (Note: units are in g/mile of FCEV travel)

WTW Truck Delivery Emissions						
Delivery Distance (miles/day)	GH2	LH2				
3,727,983	670	4372	kg per truck			
GH2	CO2	GHG Eq				
PCA 2010 & 2015	15,548,175,731	15,557,332,709	g/day	341.268124	341	kg/mile
PCA 2030	15,580,577,885	15,583,830,615	g/day	341.979321	342	kg/mile
PCA 2060	15,584,923,547	15,587,938,872	g/day	342.074705	342	kg/mile
UCDavis	55,636,830,771	--	g/day	1221.17715	--	kg/mile
GREET	35,395,006,914	36,671,059,746	g/day	776.887772	805	kg/mile
H2A	66,881,916,103	61,720,245,248	g/day	1467.9964	1,355	kg/mile
HFit	--	--	--	--	321	kg/mile

Table 22 Liquid hydrogen delivery methodology emissions under a delivery scenario that requires 165,733 miles per day of trucking delivery. (Note: units are in g/mile of FCEV travel)

WTW Truck Delivery Emissions						
Delivery Distance (miles/day)	GH2	LH2				
165,733	670	4372	kg per truck			
LH2	CO2	GHG Eq				
PCA 2010 & 2015	342,125,453	342,326,945	g/day	1.15079064	1.15	kg/mile
PCA 2030	342,838,437	342,910,011	g/day	1.15318887	1.15	kg/mile
PCA 2060	342,934,060	343,000,410	g/day	1.15351051	1.15	kg/mile
UCDavis	17,263,381,062	--	g/day	58.0679897	--	kg/mile
GREET	36,276,243,396	38,685,250,591	g/day	122.020624	130.12	kg/mile
H2A	2,143,674,579	1,884,166,839	g/day	7.21057323	6.34	kg/mile
HFit	--	--	--	--	1.08	kg/mile

5.2.6 Application of Hydrogen Fuel Cell Heavy Duty Trucks for H2 Delivery

A novel approach was suggested for the delivery of hydrogen in order to realize the full potential environmental benefit of moving toward a full-fledged hydrogen economy. In this section 0 and 100% penetration of hydrogen fuel cell powered delivery trucks for the transport of liquid hydrogen

are examined as extreme cases. Zero percent hydrogen fuel cell powered delivery trucks represents a scenario where 100% of the hydrogen is delivered via standard heavy duty diesel trucks. As an illustration the 5300 KGPD station scenario is considered because it harbors a great deal of potential to reduce delivery emissions, while retaining a moderate throughput for each station allowing for acceptable access by customers. In Figure 71.a.1-b.2 the emission reduction benefit from the deployment of Heavy Duty Fuel Cell Electric Vehicles (HDFCEVs) for the transport of liquid hydrogen can be realized. A reduction of about 2.8 kg/mile of CO_2 can be achieved as an example with large reductions in criteria pollutants as well, evident from the comparison of Figure 71.a.2 and Figure 71.b.2.

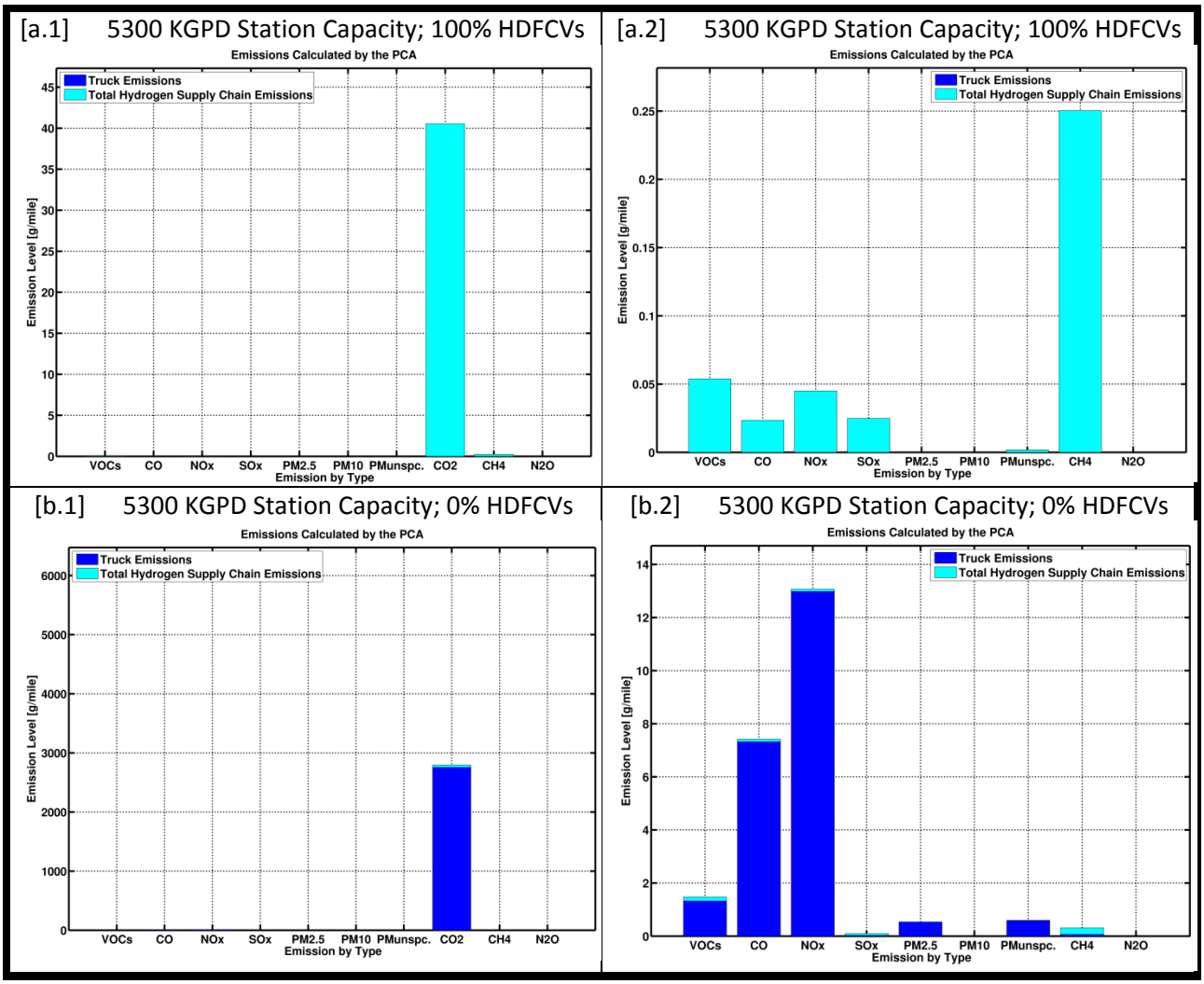


Figure 71 Comparison of 0 and 100% penetration of Heavy Duty Fuel Cell Vehicles (HDFCVs) for the delivery of liquid hydrogen to the dispensing locations (note large difference in scale).

5.2.7 Delivery Module Conclusions

In conclusion of the hydrogen delivery module section, several dominant points should be noted. The first is that the delivery method selected by the AHP for this internal APEP case study was that of liquid hydrogen delivery via heavy duty truck. The next is that the delivery pathway may be shortened and simplified by increasing the initial population size and number of iterations in the traveling salesman algorithm. Also, large potential GHG and criteria pollutant reductions can be achieved with the deployment of HDFCVs for the delivery of liquefied hydrogen to the final dispensing locations while only reducing the overall passenger vehicle fleet penetration by about 1%. Finally, this analysis concludes what is formally known as the HFit process. From here on, the data that HFit generated will be post processed by other models encompassed by STREET.

5.3 Post Processing Analyses and Results

This section will dissect the scenario that was simulated via the STREET methodology, which includes the HFit, HiGRID and PCA models. The scenario parameters that are varied are outlined in Table 23. For this case the same AHP weighting criteria are utilized from the APEP, as previously mentioned, giving rise to the name "APEP Specific Analysis" below. When all hydrogen generation technologies are considered, the AHP suggests that centralized electrolysis and distributed steam methane reformation be deployed as depicted in Table 17. For all of these results, hydrogen delivery via liquid truck is prescribed and varying amounts of trucking are carried out via heavy duty hydrogen fuel cell trucks. This delivery methodology choice is justified in the "Delivery Methodology Results" section of this document.

Table 23 HFit case studies conducted with APEP survey and weighting criteria

HFit Test Matrix	HiGRID
• **Simulated Year: 2050** • **75% Centralized Generation** • **25% Distributed Generation** • **All Generation Technologies Considered** • **75% FCV Penetration** • **3 Different HDFCV penetrations** • **3 Different Dispensing Station Sizes** • **Liquid Hydrogen Delivery Via Truck**	243 GW Installed Renewables

5.3.1 APEP Specific Analysis

For the first supply chain scenario considered, the parameters and summary of results can be viewed in Table 24. The key takeaways from Table 24 are as follows:

- Hydrogen demand of 13.5 million KGPD
- Renewable penetration of 80-81% corresponding to 243 GW installed renewable capacity
- The renewable hydrogen generation percentage varies between 60 and 61, which equated to 8-8.2 million KGPD
- Natural gas demand varies between 0.0125 and 0.013 kg/mile
- Diesel demand varies from 0.00 – 0.28 gallons/mile
- Water consumption ranges from 0.073 – 0.324 gallons/mile which corresponds to 0.095 – 0.419% of California's current water demand
- The overall WTW GHGEq emissions vary between 0.06 and 2.88 kg/mile
- The WTW GHGEq emissions are greater for the delivery of hydrogen because it only accounts for 75% of the overall hydrogen supplied and therefore in the g/mile calculation fewer miles are able to be supplied giving rise to greater emissions intensities.

The overall supply chain will be broken down in order to more closely examine the energy and emission characteristics.

Table 24 APEP Case Study Results Summary, Full Technology Suit Considered

0% HDFCV			100% HDFCV		
13,459,588	13,459,588	13,459,588	13,459,588	13,459,588	13,459,588
1371	5300	9141	1371	5300	9141
243	243	243	243	243	243
81	81	80	81	81	80
61	61	60	61	61	60
156	146	146	156	146	146
22	23	23	22	23	23
0.01	0.01	0.01	0.01	0.01	0.01
0.08	0.27	0.28	0.00	0.00	0.00
858	3,012	3,077	0	0	0
127.02	111.74	105.69	127.02	111.74	105.69
3.87	3.88	3.88	3.87	3.88	3.88
0.11	0.20	0.20	0.08	0.07	0.07
0.23	0.32	0.32	0.20	0.19	0.19
0.01	0.01	0.01	0.00	0.00	0.00
0.01	0.02	0.02	0.01	0.01	0.01
1,672,168	1,708,664	1,708,699	1,672,168	1,708,664	1,708,699
105,210	104,836	104,871	105,210	104,836	104,871
0.88	2.82	2.88	0.07	0.06	0.06
1.08	3.68	3.75	0.00	0.00	0.00

5.3.1.1 PCA Emissions and Energy

By observing Figure 36, it is apparent that the initial post processing step is to exercise the PCA model. This calculation produces resources consumed and emissions produced due to the generation, distribution and dispensing of the modeled hydrogen demand. By utilizing the proposed hydrogen production mixture and hydrogen delivery method chosen by the AHP, in conjunction with the PCA, per mile emission profiles were generated. These per mile emission profiles are displayed in Figure 72.a.1-c.1, with focused plots in in Figure 72.a.2-c.2, that have the carbon dioxide emissions removed for better scaling and visualization of the data. The results displayed are for the scenario where heavy duty hydrogen powered delivery trucks are not considered. If HDFCVs are considered, the emission levels from the truck delivery can be reduced by the penetration percentage of those vehicles. It is apparent from this analysis, that delivery via conventional diesel-fueled heavy duty truck has a dominant contribution to the overall emission signature of the hydrogen supply chain, both in terms of GHGs and criteria pollutants. This is a significant finding in that part of the potential for FCVs is that local air quality could improve due to a lack of tailpipe emissions. However, these improvements have the potential to be overwhelmed by the emissions of the delivery method that one considers within this case study. The

results herein identify the importance of deploying low emissions technology for hydrogen delivery (e.g., pipelines or hydrogen powered heavy duty trucks). The emission profiles in Figure 72.a.1-c.2 become a starting point for the construction of an overall picture of the associated hydrogen supply chain emissions.

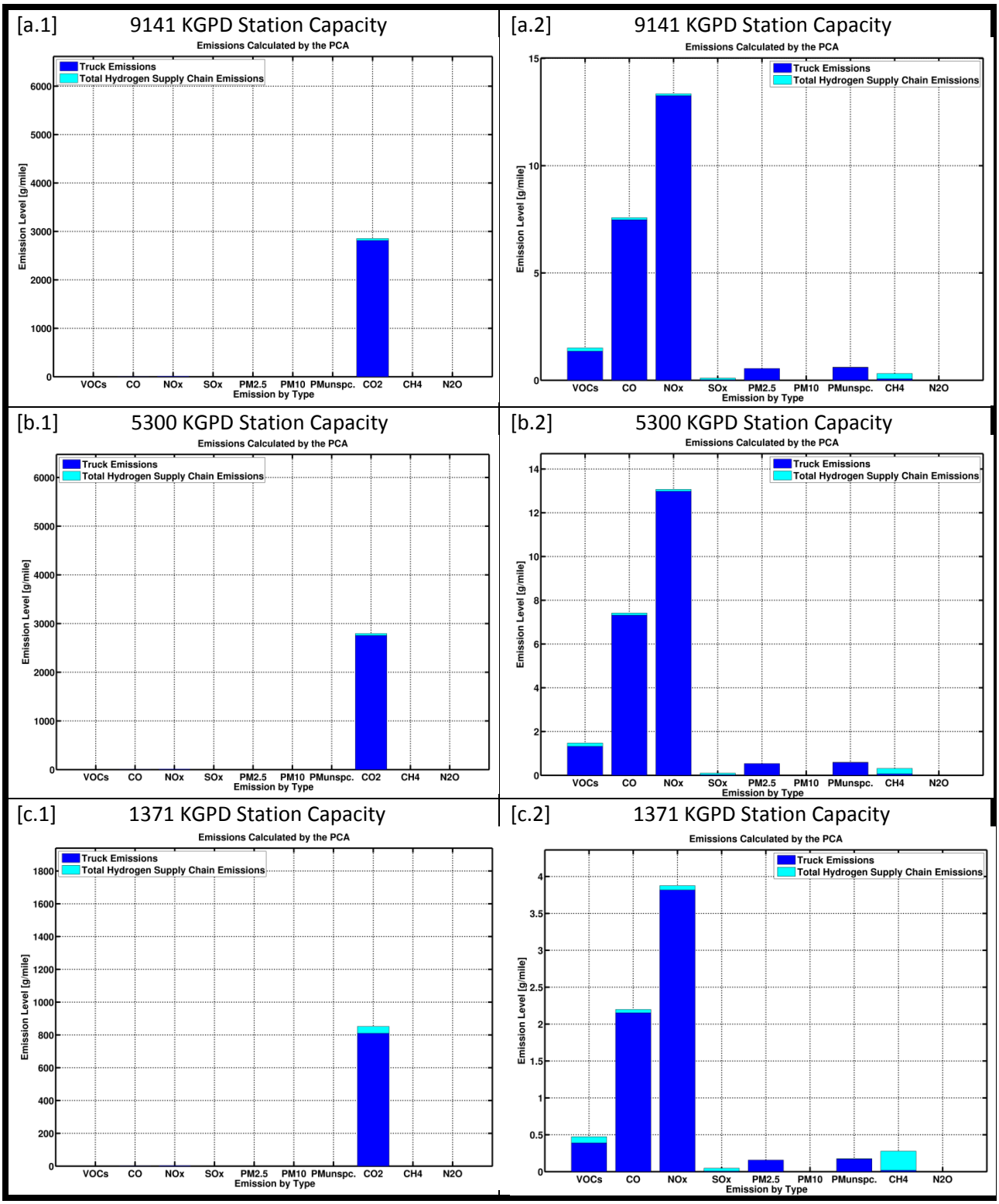


Figure 72 Emissions results from the PCA based on varied dispensing location capacities, each row represents one scenario, figures in the left column are all emissions generated and the right column excludes CO_2 for greater clarity.

The PCA also has the capacity to calculate the resources consumed by the hydrogen supply chain. In this case study, there are four primary resources of interest. These are water, diesel fuel, natural gas and electricity.

The consumption of diesel fuel for the delivery of hydrogen in its liquefied form via truck ranges from 0.00 – 0.28 gallons/mile or 0.00 to 256.388 million gallons per day, depending upon the dispensing station sizes and the penetration percentage of hydrogen fuel cell powered delivery trucks, as seen in Table 24. This is an interesting and noteworthy result, because according to the California State Board of Equalization, in the fourth quarter of 2012, California consumed about 653 million gallons of diesel fuel [108]. This number equates to about 10.883 million gallons per day. This analysis suggests an extreme increase in the amount of diesel fuel consumed currently. Therefore, in the construction of a future hydrogen infrastructure, a focus on delivery trucks that utilize hydrogen fuel cell technology should be considered and is incorporated into this analysis. There are two possible reasons for this dramatic rise in diesel fuel consumption. The first is this scenario assumes that the diesel trucks will be added to the current trucking fleet, without the removal of any of the trucks supplying gasoline, which will be displaced in a future hydrogen economy. The second reason was explained in the “Delivery Mode Module” section of this document and has to do with the utilization of a near optimal genetic algorithm for the solution of the Travelling Salesman Problem. This algorithm has a tradeoff between approaching an optimal solution and computational time, which could lead to a greater calculated trucking distance than what will be actually implemented.

Meeting the non-electrolysis hydrogen demand via distributed steam methane reformation as suggested in Table 17, shows a resulting demand of 0.0125 to 0.013 kg/mile, or 11.469 – 11.861 million kilograms of natural gas per day. According to the CEC in 2012 the state consumed 12,844 million therms of natural gas [109]. This breaks down to about 72 million kilograms per day. When comparing this number from the CEC to those obtained by the HFit-PCA simulation, the results seem to fall within a

reasonable range, as results suggest 15.9 – 16.5% of the current natural gas demand will be needed for hydrogen production. In this case study, the consumption of water and electricity are not finalized until after the electrolysis dispatch module has been employed in conjunction with the HiGRID model.

5.3.1.2 HiGRID Analysis

As an introduction to the HiGRID model, Figure 73 is presented. Figure 73 illustrates the strength of this tool by showing its ability to calculate the energy demand, supplied and curtailed. The case shown in Figure 73 is a base case with extremely high installed renewable capacity that does not consider the generation of hydrogen in any form. The base case is setup to have 243.08 GW of installed renewable capacity that leads to a 71.7% renewable energy penetration level and is defined in Table 25. This scenario was chosen based on analyses done by Tarroja, B. J. (2014) on future renewable penetrations and the coupling of the hydrogen economy [104]. The areas of red in this figure should be noted. These areas are regions of excess energy that cannot be utilized with current utility grid network installed technology; this phenomenon is known as curtailment. Additional attention should be given to the operational characteristics of the peaking and load following power plants displayed in this profile. Curtailment and operation of these non-renewable power plants will be focused on as a visual comparison metric between different scenarios.

Table 25 Renewable capacity installed by technology type

Binary Geothermal	Flash Geothermal	Fixed Solar	1-axis Solar PV	2-axis Solar PV	Solar Thermal Trough	Local Wind	Regional Wind	Units
4.00	0.0	50.21	0.0	0.0	158.48	0.0	30.39	GW

Figure 74.a.1-c.1 illustrate what occurs when electrolyzer dispatch is incorporated into the balancing of the electrical load. It should be noted that in Figure 74.a.1-c.1 the amount of curtailed energy is drastically reduced, meaning the energy was either utilized by the grid or stored as hydrogen. Hydrogen that is produced from the grid can be quantified as renewable by observing the renewable penetration percentage, along with the percentage of overall hydrogen generation via electrolysis and is

displayed in Table 24. This renewable hydrogen has the ability to assist California in not only meeting its renewable penetration standards, but also its renewable hydrogen mandates.

Figure 74.a.1-c.1 display some undesirable results that should be noted. Overall, in these figures, the orange area increased when compared to the base case of Figure 73. This region is concerning because it represents fossil based load following power plants. Due to the nature of these load-following power plants, when they increase their operation, a corresponding increase in emissions will occur. Therefore, it is the desire of this work to have fossil based generation facilities in operation for a minimal time and load. These results will be quantified later in the “Average Grid Emissions” section.

It should be heeded that the caption of Figure 73 shows a renewable penetration of 71.7%, this is in fact the same as the numbers shown in the titles of Figure 74.a.1-c.1 and displayed in Table 24. This percentage is the overall annual renewable energy delivered to load divided by the total electrical energy load. In the scenarios, even keeping the installed renewable capacity constant, will see an increase in the penetration percentage as the amount of hydrogen generation is increased to a certain point. This displayed increase is due to a greater amount of renewable energy delivered to the load due to the dispatch of electrolyzers. In order to further illustrate the large load required from the proposed electrolyzers, Figure 74.a.2-c.2 show the percentage of the total electricity demand due to generation of hydrogen. Because hydrogen generation and delivery methodologies do not vary in Figure 74.a.1-c.2, there is no variance in the load applied to the grid. In future studies, the projected hydrogen demand, generation and delivery scenarios should be varied in order to illustrate the change in dynamic interaction of the hydrogen and electrical energy systems.

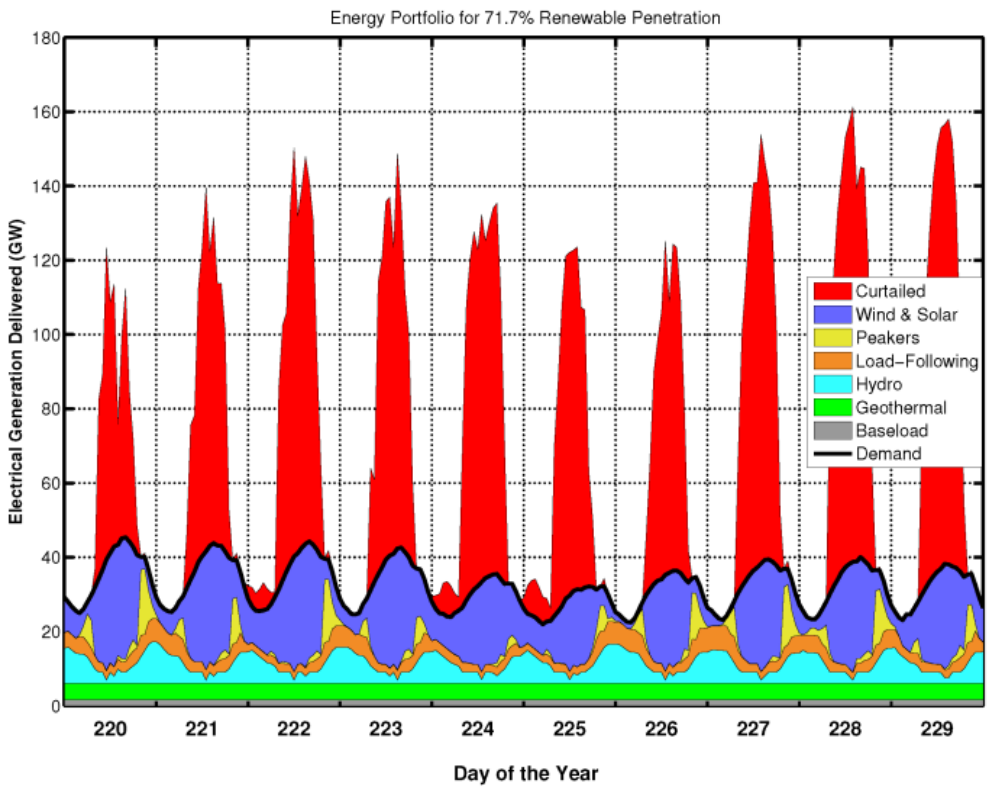


Figure 73 HiGRID Base Case Hourly Energy Portfolio:
71.7% Renewable Penetration, Renewable Generation set at: 243 GW

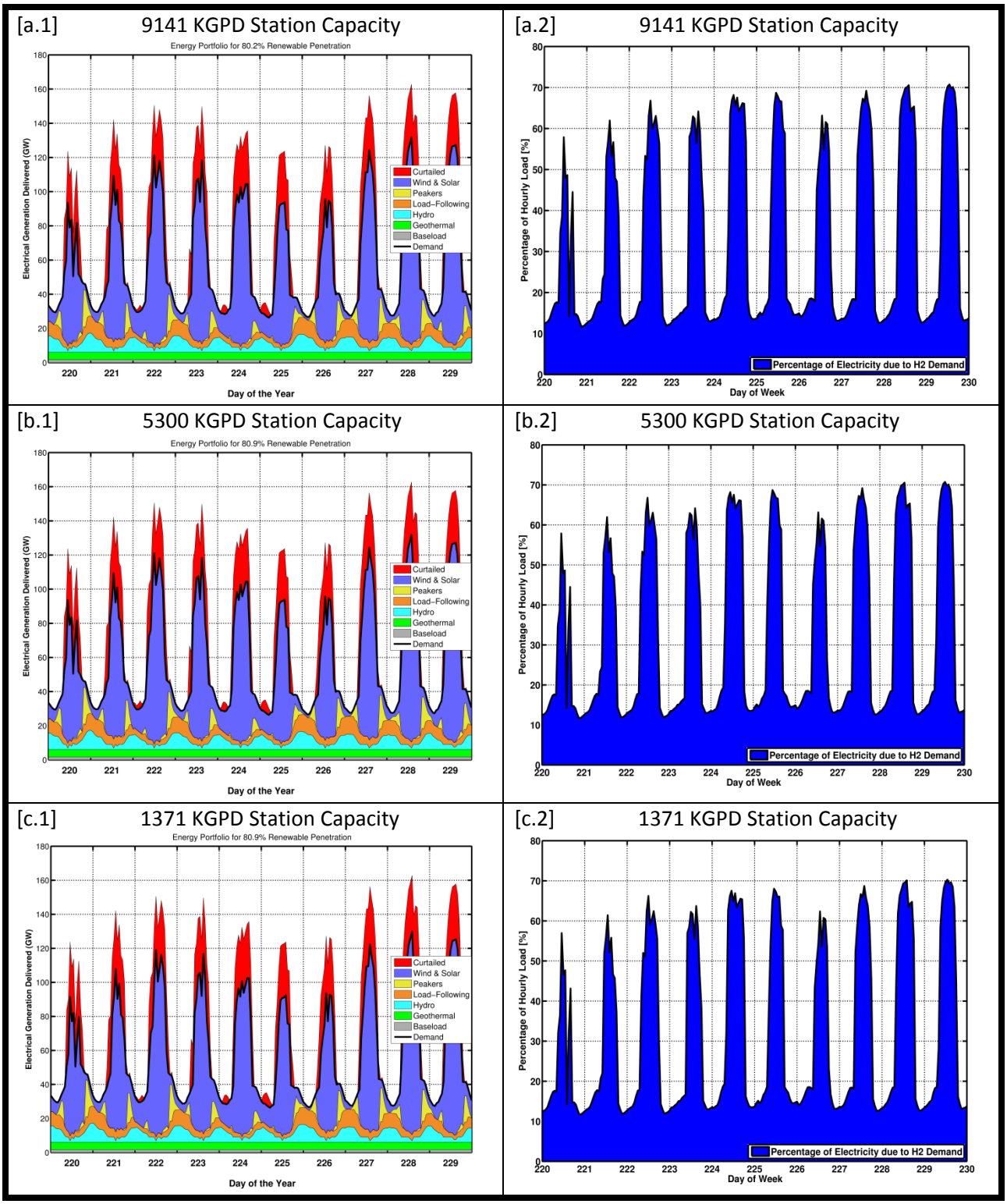


Figure 74 HiGRID generation portfolio (column1) and hydrogen generation load as percentage of total grid load (column2), where each row represents a different hydrogen dispensing location size.

5.3.1.2.1 Hydrogen Production and Storage

In order to explore further the behavior of the hydrogen energy system being modeled, the hydrogen generation and storage curves will be examined. The overall state hydrogen production can be viewed in Figure 75.a.1-c.1, for a ten day period. The diurnal variation in this figure is due to the dispatch of the electrolyzers, as the steam methane reformation in this case has been set to base load. In Figure 75.a.1-c.1 it should be noted that the three different profiles are the same due to the same hydrogen demand being utilized.

The annual state of the hydrogen storage system due to the production profiles found in Figure 75.a.1-c.1 can be viewed in Figure 75.a.2-c.2. It can be seen from Figure 75.a.2-c.2 that the hydrogen storage system has been properly sized, in order to ensure that the supply meets the demand, while preventing curtailment. It is known that the system has been properly sized, because as seen in Figure 75.a.2-c.2, the level never goes below a value of zero. Therefore, the amount stored is always greater than or equal to the amount supplied. A key observation that should be garnered from Figure 75.a.2-c.2 is that the profiles are not exactly the same even under the same hydrogen demand. This result comes from the fact that at each installed station, there is a fixed installed storage capacity. Therefore, in the case of smaller dispensing capacities, there will exist more storage due to a greater number of installed stations.

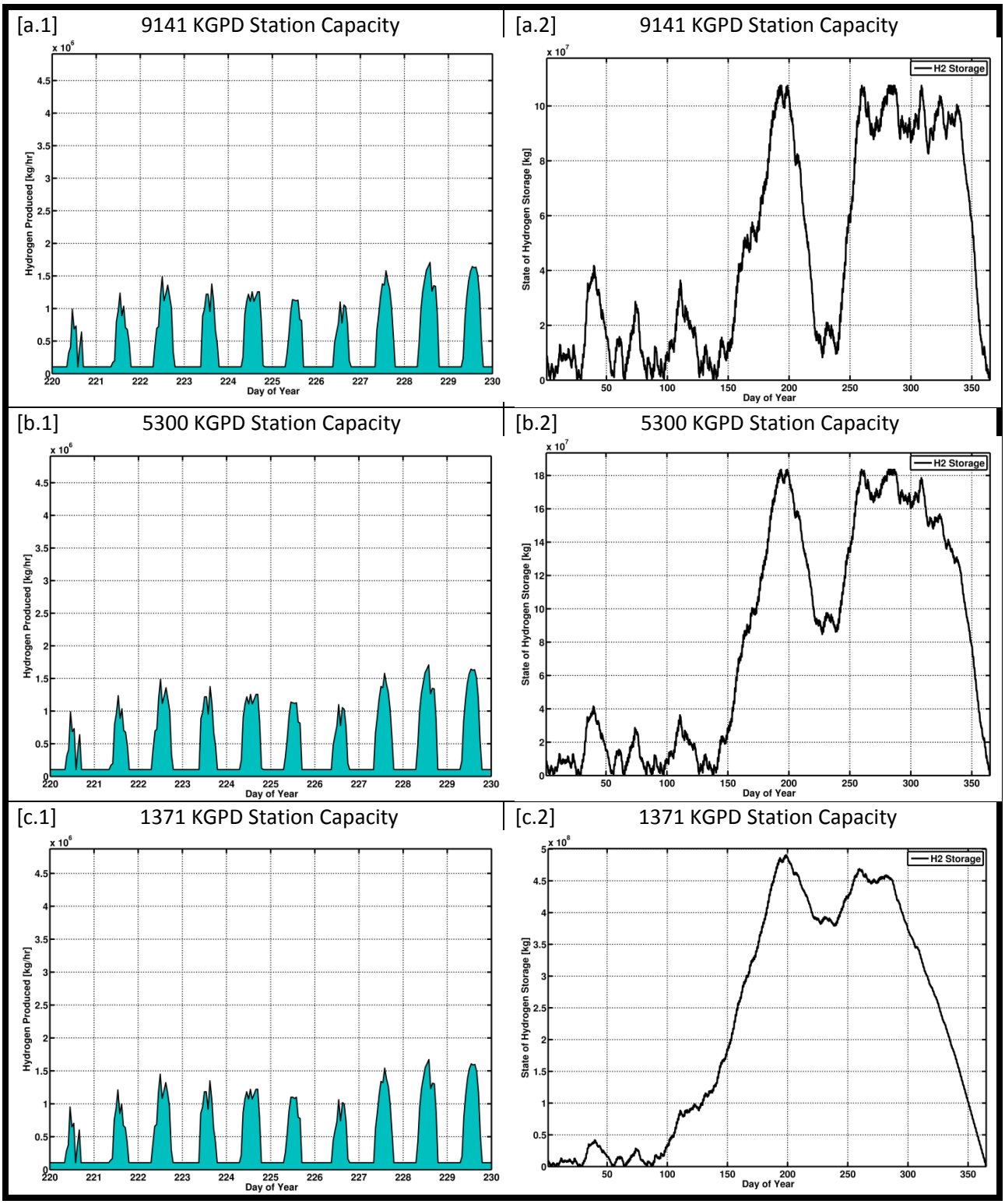


Figure 75 Overall hydrogen generation profile (column1) and hydrogen energy storage system (column2), where each row is a different hydrogen dispensing station size.

5.3.1.2.2 Water Consumption

Now that the hydrogen production and storage has been quantified, the energy utilized in the supply chain will be further examined. Initiating this exploration, a parameter that is often overlooked, but could be recognized as the most important measure of an energy system overall, is that of water consumption. The overall water consumption for a ten day period in order to generate the demanded hydrogen can be observed in Figure 76.a.1-c.1. The total consumption varies between 0.073 – 0.324 gallons/mile. According to a study done by the Pacific Institute, California consumes about 65 million acre feet of water annually [110]. This equates to about 58,028 million gallons per day. Therefore, at peak water consumption in this case study, the production of hydrogen would require about 0.116 – 0.510% of California's current consumption. At this point in time it is unclear as to the long term impacts this may have on the water system due to the large amount of uncertainty in the future supply of fresh water due to such things as climate change.

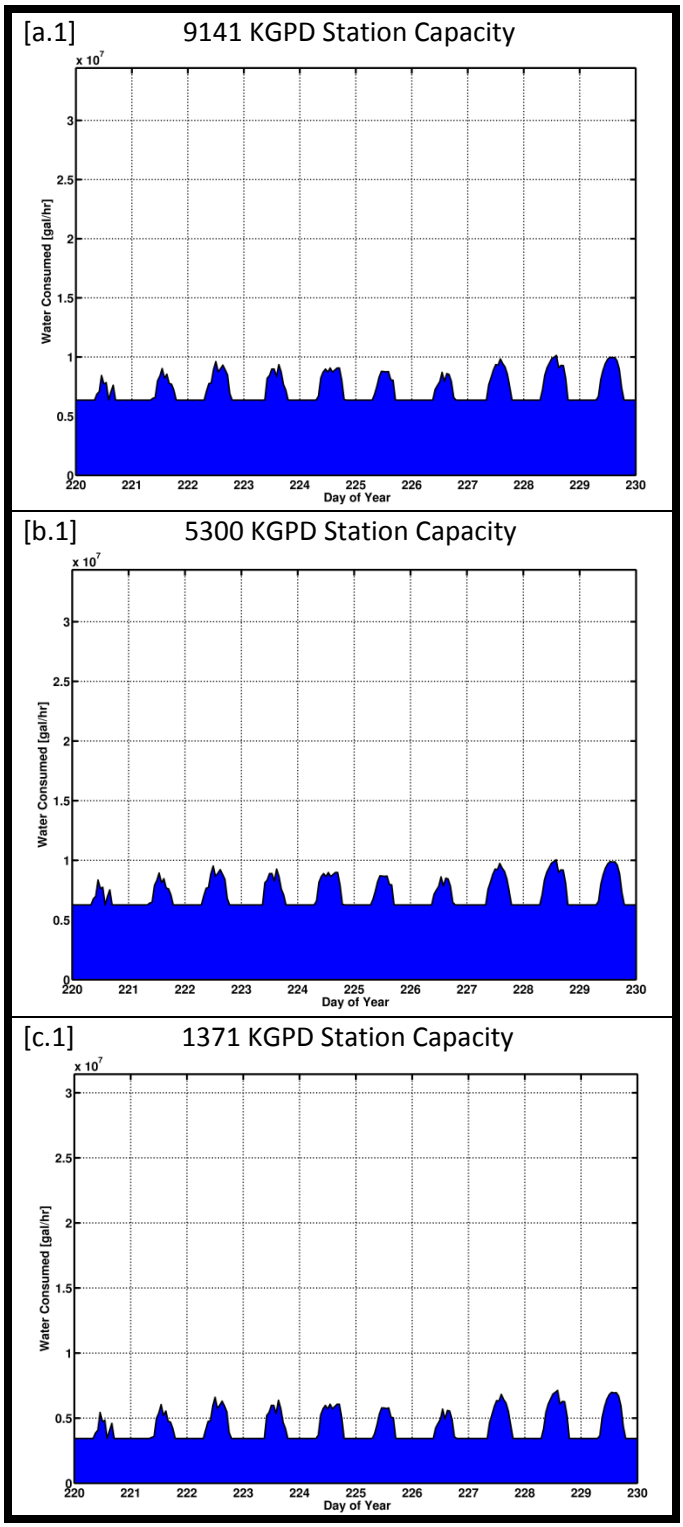


Figure 76 Water consumption due to overall hydrogen production for the state, VMT scenario 1-3 correspond to a.1-c.1.

5.3.1.2.3 Average Grid Emissions

In order to better understand the complex interaction between the electrical generation system and that of hydrogen, the continued buildup of an overall supply chain analysis is furthered. By applying an averaged emission factor for the generation of electricity in California from the California specific GREET model, a break down for the level of emissions due to grid utilization for the production of hydrogen can be calculated for certain renewable penetration levels. This factor will only be a rough estimate due to the complex operational characteristics of an electrical grid which will affect the emission mixture at any given hour.

This case study, with its high projected hydrogen demand highlights another extremely noteworthy point. As mentioned in the beginning of the "HiGRID Analysis" section, the operational profiles of load following power plants increases with a high hydrogen demand. This increase in operation is critical in that these load following plants generate both GHG and criteria pollutant emissions. Demanding this large amount of hydrogen via electrolysis will actually tend toward producing more emissions when compared to the base case. This large increase in emissions is apparent when comparing Figure 77, the HiGRID base case with no hydrogen generation, with Figure 78.a.1-c.1. The comparison of these figures shows that the additional burden on the electrical grid induced by the generation of hydrogen at this renewable penetration level will actually increase the amount of carbon dioxide released by almost 6,000 – 6,500 Metric Tons of CO2 per day. Therefore, in order to meet a large future hydrogen demand via the dispatch of electrolyzers, it would be wise to focus heavily on optimal grid operation in order to capture the most renewable resources and minimize the need for fossil based generation and or other deploy other generation technologies that do not directly emit carbon dioxide emissions such as nuclear energy.

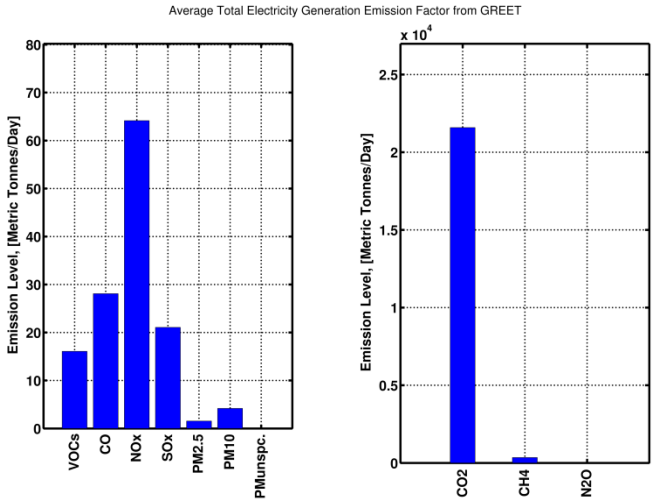


Figure 77 Calculated average grid emission factor utilizing the California specific GREET emission factors and HiGRID base case with default renewable generation capacity of 243 MW

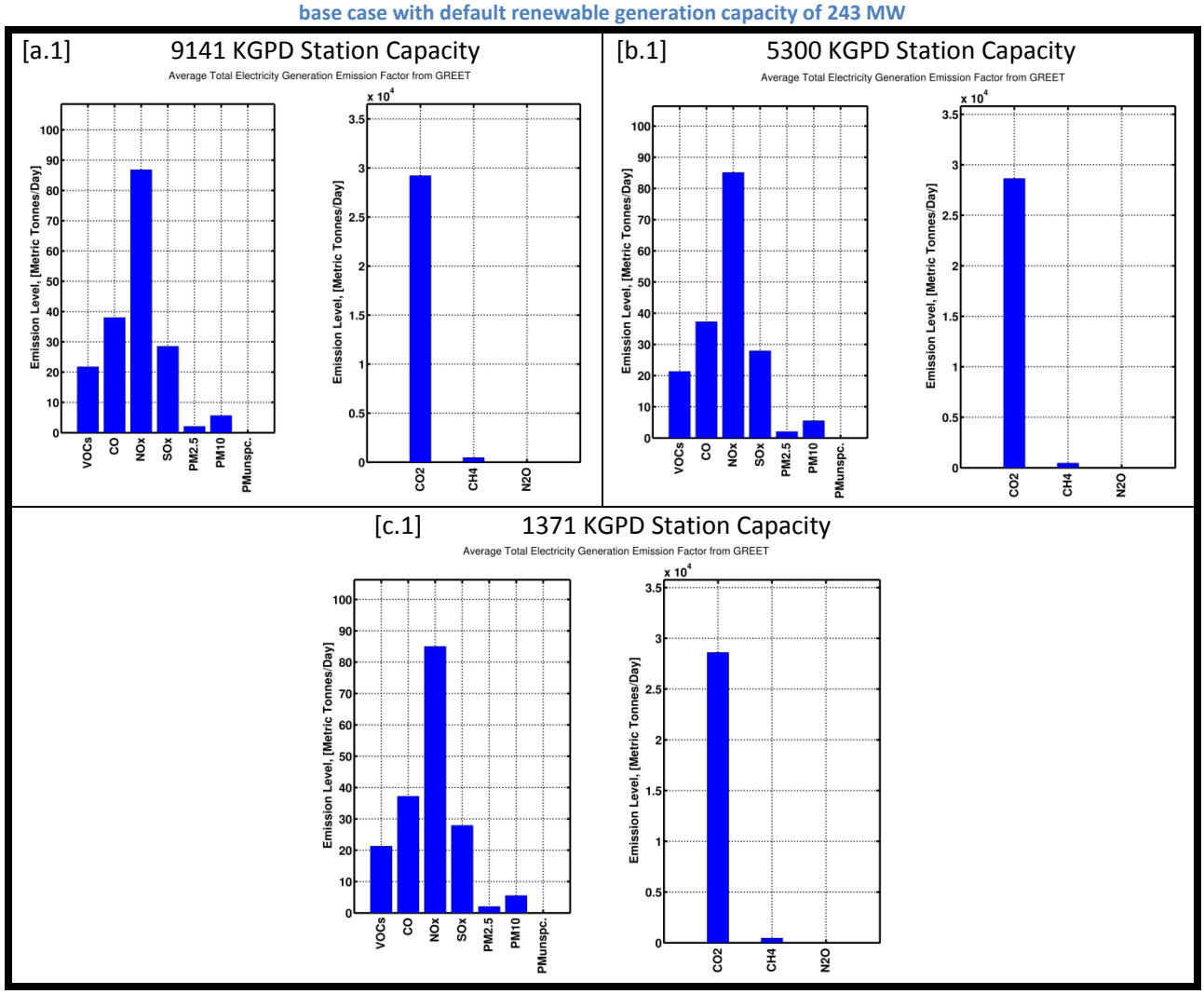


Figure 78 Average electrical grid emission factor based on HiGRID fuel use and emission factor from GREET.

The next step in the construction of an overall picture of the hydrogen supply chain is to combine the generation and delivery emissions and to analyze the results.

5.3.1.3 Overall Hydrogen Supply Chain Emissions

The breakdown of the hydrogen supply chain built up this far can be viewed in Figure 79.a.1-c.1 and for better clarity; the emissions due to truck delivery are left out in Figure 79.a.2-c.2. It is apparent from Figure 79.a.1-c.1 and Figure 79.a.2-c.2, that emissions from electricity generation play a significant role in the overall profile of the hydrogen supply chain. Additionally, it should be noted from these figures that the delivery of hydrogen via heavy duty trucks, again is by far the largest emitter of criteria pollutants and carbon dioxide. Figure 79.a.2-c.2 is essentially the hydrogen supply chain with 100% penetration of HDFCEVs for liquid hydrogen delivery. These observations lead to the conclusions that in order to supply hydrogen with the lowest emissions impact, carbon free sources of electricity and alternative modes of hydrogen delivery must be deployed.

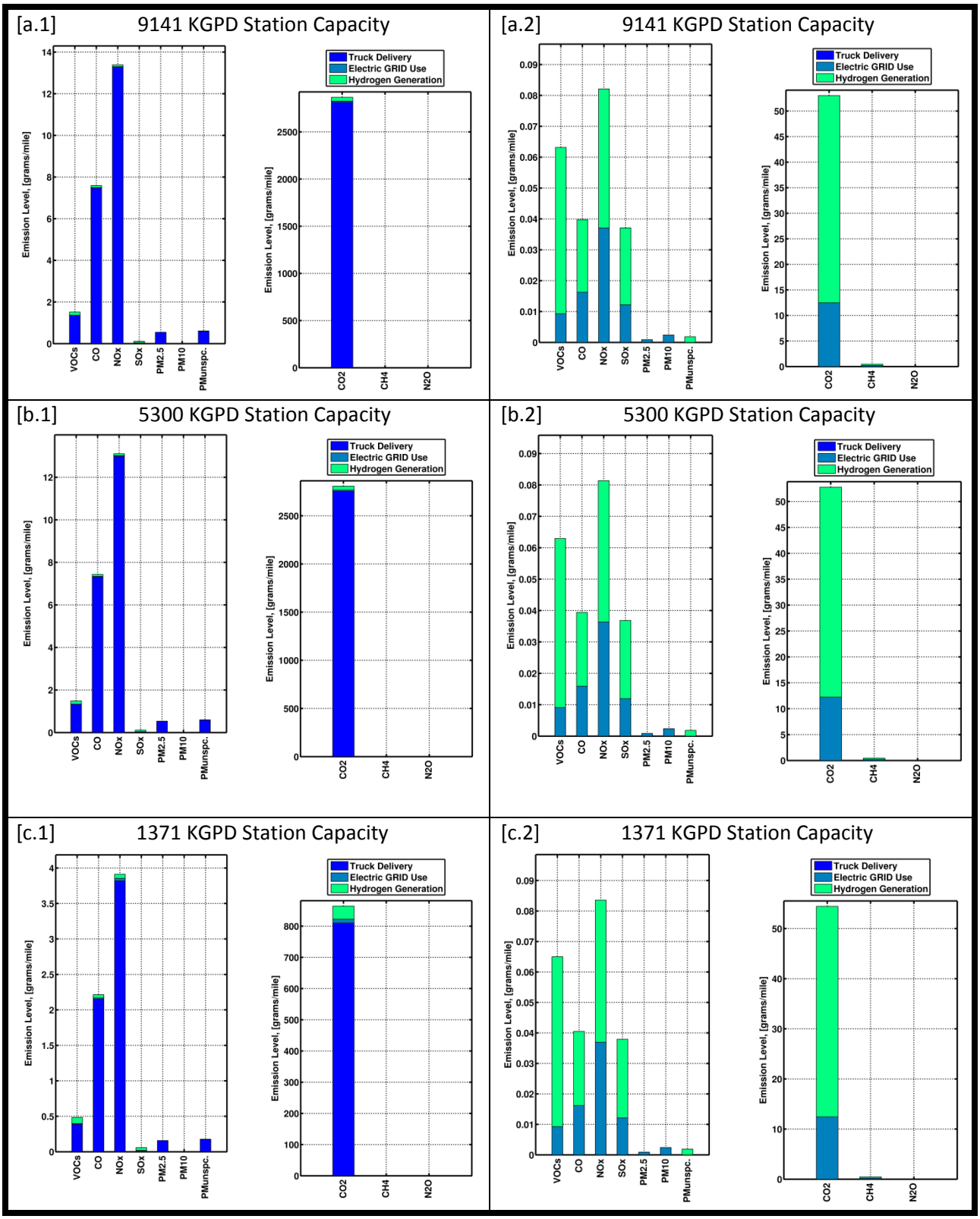


Figure 79 Hydrogen supply chain emissions including upstream energy, hydrogen generation and hydrogen delivery emissions, full supply chain emissions presented (column 1), hydrogen conversion and upstream emissions re-plotted for clarity (column 2). (note significant difference in scale)

5.4 Gasoline Supply Chain Emissions Results and Comparisons

In order to obtain a comparative supply chain analysis, California refineries were examined for their current emissions and possible future emission reductions due to an increased hydrogen vehicle penetration. To initiate such an analysis that is spatially and temporally resolved, the methodology described in the "Petroleum Pathway Module" section was applied. As an illustration, emission intensity for refineries within California, carbon dioxide emissions are displayed in Figure 80. From this figure it can be seen that the refineries in California are clustered in four main regions. Three out of four of these regions are air management districts that have issues with air quality.

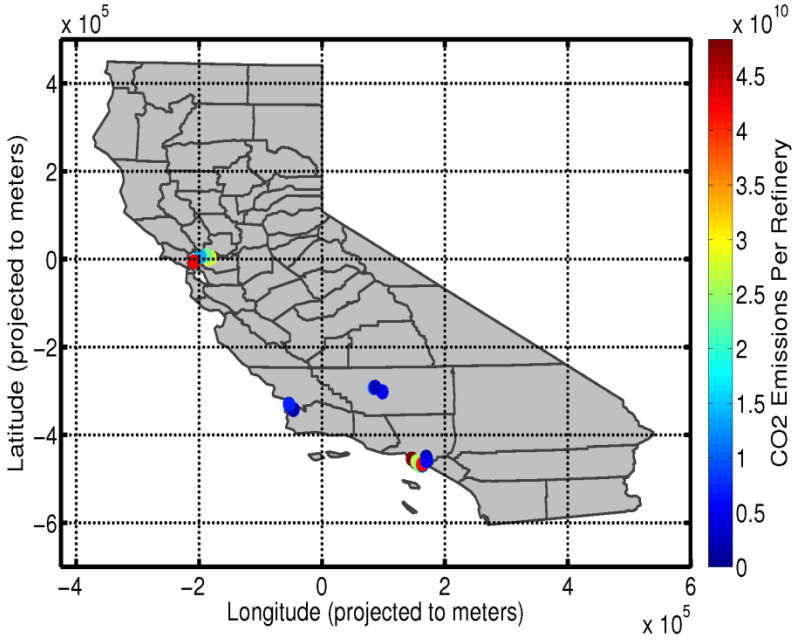


Figure 80 Location and carbon dioxide emissions of current refineries in California based on GREET emission factors for California reformulated gasoline, along with upstream natural gas and electrical emissions.

Next, the petroleum supply chain module was exercised in order to compare the relative emissions from refining to meet future projected gasoline demands in combination with a FCV penetration rate of 75% in the year 2050.

It should be noted that the emission factors for electricity and natural gas are able to be easily removed from the analysis. This capability was developed because in the near term, the integration of

models internal to APEP will allow for a more detailed analysis of energy consumption and emissions from these two energy infrastructures. It has already been demonstrated that the HiGRID allows for a more dynamic representation of the electrical infrastructure when examining such energy systems. There has also been a model developed that takes into account energy and emissions due to the natural gas infrastructure within California by members within the APEP. These two models will take the place of the static emission factors that are currently being utilized as surrogates from the GREET model.

The pinnacle of this entire modeling endeavor is the comparison of the overall supply chain emissions from the proposed hydrogen economy, with that of the current California Reformulated Gasoline projections for 2050. Because the comparison of the current petroleum based supply chain to a future hydrogen infrastructure is not equivalent, a projected petroleum supply scenario is compared to a future hydrogen infrastructure build out. The projected scenario utilizes equivalent efficiency projections (34 MPG and 68 MPKG) and the same VMT for both ICVs and HFCEVs. It should be noted that for this comparison, the delivery of the fuel was neglected. This is primarily due to the fact that the model considered herein is on a kilogram of hydrogen basis, and on this energy basis, a kilogram of hydrogen is comparable to that of a gallon of gasoline. Therefore, it is assumed that any reduction in gasoline delivery would be replaced by an equivalent amount of hydrogen delivery. The supply chain and fuel utilization comparisons can be seen in Figure 81, with each sub figure a-c corresponding to the three different dispensing location capacities and column1 and column2 corresponding to standard heavy duty diesel liquid hydrogen delivery and 100% hydrogen fuel cell electric vehicle liquid hydrogen delivery. Comparing these scenarios with one another, it is clear to see that the case with the smallest dispensing locations obtains the overall lowest carbon footprint due to a lower emission profile from the hydrogen delivery methodology when standard trucks are considered. When hydrogen powered heavy duty trucks are considered for delivery, the overall supply chain emissions become equivalent for the three different dispensing station sizes because the only emissions that are generated are due to the

production of hydrogen. The high overall emission profile of the standard delivery methodology again appears here. It is clear to see that potential benefits of hydrogen utilization could be severely discounted by the impacts of the selected delivery methodology. Therefore, these results strongly suggest the utilization of alternative efficient and low emitting hydrogen delivery methodologies.

The analysis of the emissions generated from these two supply chains not only facilitates the determination and comparison of GHG intensities, but also facilitates air quality modeling, which will be conducted after spatially and temporally resolving these emissions results. This air quality modeling will be able to illustrate the positive attributes that hydrogen has as a future energy carrier on reducing local air pollutant concentrations. This postulate is upheld by the preliminary results presented in Figure 81, with hydrogen clearly having a much lower criteria pollutant emission profile, as compared to the current petroleum supply chain. These lower emissions may lead to lower ambient concentrations of major pollutants, which can only be assessed after consideration of atmospheric chemistry and transport within specific regions. This is an important observation, because as mentioned earlier these refineries are located largely in areas of poor air quality. Thus, by deploying FCVs and reducing the demand for gasoline, there is a great potential to improve local air quality in the problem areas. However, it has been postulated that these refineries may not reduce their throughput and may, in turn, begin to export their gasoline supply, or shift to producing other products such as diesel fuel. This is a key point that legislators may wish to focus upon in the future as hydrogen becomes a greater source of transportation fuel.

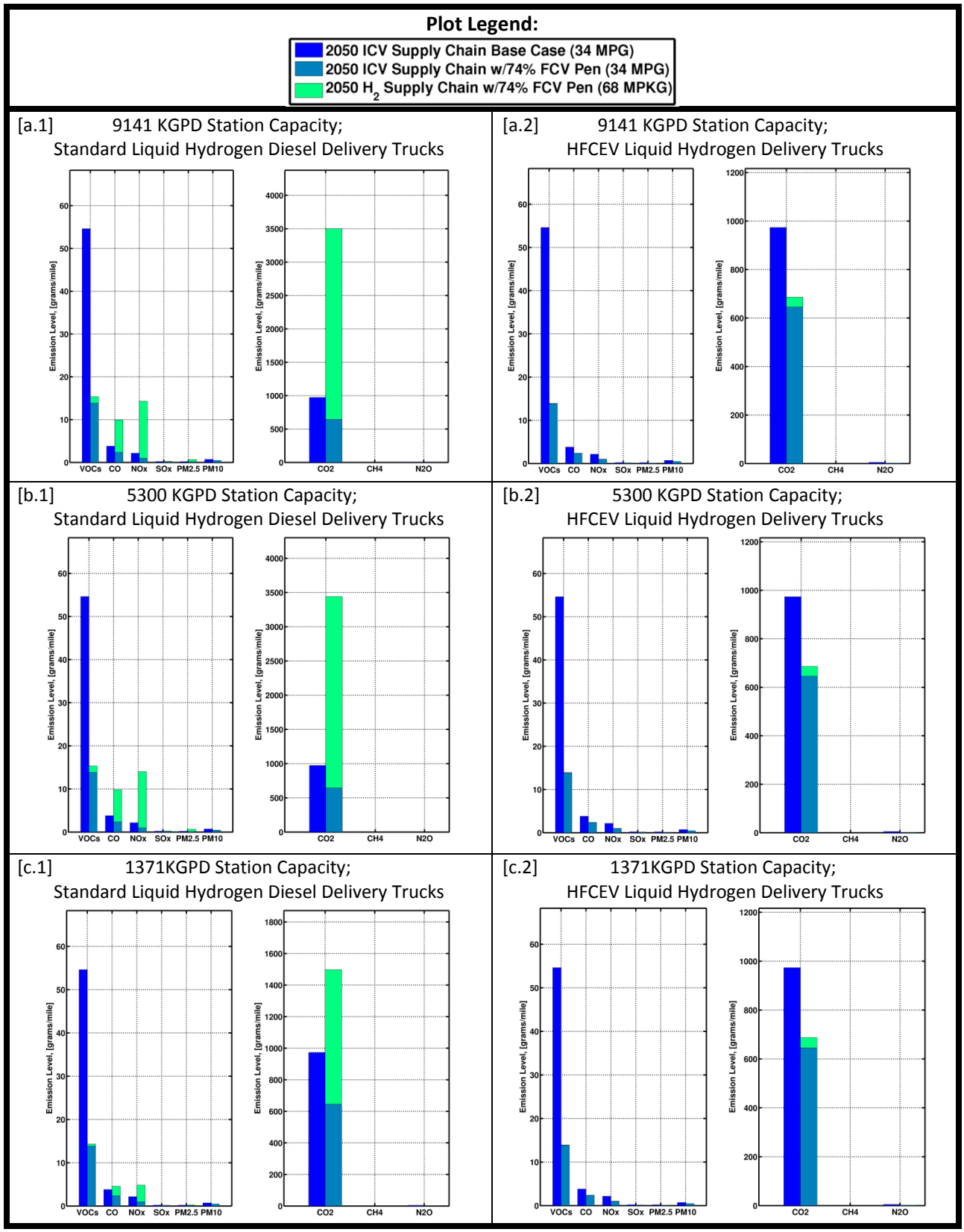
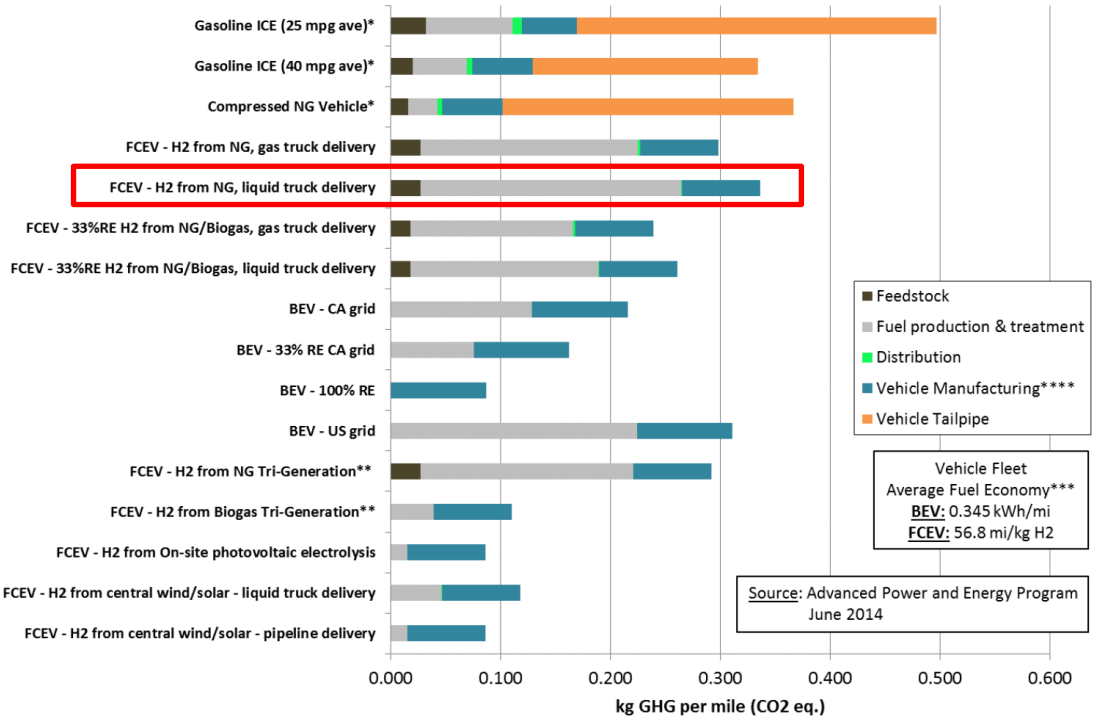


Figure 81 Comparison to Gasoline APEP Case Study #1: Overall hydrogen supply chain emissions compared to the estimated future gasoline supply chain.

The results in Figure 81 allow for comparison to previous work conducted at the APEP with regard to hydrogen supply chain emission intensities. Figure 81 clearly illustrates the need to consider alternative methods for the delivery of hydrogen in the near term. This figure also shows the importance of considering moderate dispensing capacities in order to save energy during the delivery of hydrogen. Figure 82 displays prior work and illustrates the differences between many different vehicle fuel supply chain and fuel utilization emissions. When observing the pathway nearest to the one suggested within this case study, a GHG equivalent value of 0.32 kg/mile is seen highlighted in red. After calculating the resulting GHG equivalent for the methodology prescribed by the HFit with 8% centralized electrolysis, 92% distributed SMR and liquid hydrogen delivery via truck the overall WTW GHGEq emissions vary between 0.06 and 2.88 kg/mile. On average this factor is much greater than the value obtained in Figure 81 mainly due to the much greater emission impact calculated for the delivery methodology. In order to obtain a fair comparison to other literature results the HFit methodology was applied while constraining the hydrogen generation methodology to that of SMR. Under this purely SMR scenario, a value of 1.12 - 3.67 kg/mile GHGeq was obtained. This is a remarkably high number when compared to the other studies delineated in Table 26. The results are however justified when considering the high value obtained from the emission calculation due to the delivery of hydrogen.



* Gasoline ICE and Compressed NG vehicle WTW information obtained from the Low Carbon Fuel Standard, except vehicle manufacturing.
**Tri-Generation is a novel technology that was conceived by the National Fuel Cell Research Center in 2001 to simultaneously generate electricity, hydrogen, and heat. It was developed into the first prototype in collaboration with FuelCell Energy, Inc., and Air Products and Chemicals, Inc. The first demonstration of this technology in the world is currently being demonstrated at the Orange County Sanitation District while operated on renewable biogas derived from the wastewater treatment process. For more information on Tri-Generation please visit: http://www.apep.uci.edu/3/research/partnership_TRI-GEN.aspx
***Fleet-wide average fuel economy is the representative fuel economy of the average vehicle in the light-duty vehicle fleet. This is a weighted average of the fuel economy of different size vehicles. Each vehicle class is weighted by their contribution to the total light-duty vehicle fleet according to the CARB EMFAC model.
****Vehicle manufacturing emissions obtained from automaker data input.

Figure 82 GHG Equivalent Emissions Analysis conducted by the APEP for various transportation technologies.

Table 26 WTW GHG Comparison of three different studies

Source	Scenario	Value [kg/mile]	Vehicle Efficiency [MPKG]
APEP	SMR, LH2 Truck	0.33	57
APEP	SMR, GH2 Truck	0.29	57
NREL	SMR, Pipeline	0.35	48
NREL	SMR, LH2 Truck	6.41	48
HFit	SMR, LH2 Truck (1371 KGPD)	1.12	68
HFit	SMR, LH2 Truck (5300 KGPD)	3.56	68
HFit	SMR, LH2 Truck (9141 KGPD)	3.67	68

Sources:
NREL: Ramsden, T., Ruth, M., Diakov, V., Laffen, M., & Timbario, T. A. (2013). *Hydrogen Pathways Updated Cost , Well-to-Wheels Energy Use , and Emissions for the Current Technology Status of Ten Hydrogen Production , Delivery , and Distribution Scenarios*.
APEP: Advanced Power and Energy Program. (2014). *Well-to-Wheels Greenhouse Gas Emissions of Advanced and Conventional Vehicle Drive Trains and Fuel Production Strategies*. Retrieved from www.apep.uci.edu/3/Research/pdf/SustainableTransportation/WTW_vehicle_greenhouse_gases_Public.pdf

5.5 Summaries and Conclusions from Full Build out Analysis

This case study exercises and represents in a limited way some of the more powerful abilities of the HFit modeling methodology. In order to utilize expert input data for the AHP, hydrogen infrastructure experts within the APEP were surveyed. The results of these surveys showed a strong weighting on the proximity to infrastructure, low GHG emissions and high energy conversion efficiency when considering the location and technology mixture of hydrogen generation facilities. For the delivery mode, it was shown that the least energy consumption of a delivery method was deemed most important. These survey results dictated a hydrogen generation mixture that consisted of 92% distributed steam methane reformation and almost 8% centralized electrolysis on an overall number of facility basis (i.e., The number of SMR facilities divided by the total number of hydrogen generation facilities in the state). The number of required dispensing locations was shown to depend directly on the

daily capacity of the installed stations. It was also revealed that the overall delivery routes and configuration are dependent on the size of the dispensing sites.

The overall emissions of the considered supply chains were examined by the PCA. This model illustrated that the trucks needed in order to deliver the liquefied hydrogen to the dispensing locations emit a large amount of carbon dioxide and oxides of nitrogen. These delivery trucks are also projected to increase California's diesel demand by a significant amount in all cases. This shows that the consideration of alternative fuels for the delivery of said hydrogen should be seriously considered and was therefore considered in the form of heavy duty hydrogen delivery trucks. By deploying these trucks for the delivery of hydrogen, large environmental benefits in the form of GHG and criteria pollutant emission reductions can be realized while only reducing the penetration of passenger vehicles by about 1%.

The resulting impact of dispatching hydrogen electrolyzers on the electrical grid at high renewable penetrations was also explored. It was shown that, the balancing of the electrical grid via the dispatch of hydrogen electrolyzers allows for the utilization of what would otherwise be curtailed and mostly renewable energy. The capture of this energy does show some downside, with an increase in emissions due to load following and peaking power plants. These fossil based power plants are deployed in order to assist in grid balancing under the high fluctuation of power generation and demand.

The resulting balance of the hydrogen energy system was examined by ensuring the overall storage system always remained in a positive state.

Finally, the consumption of the valuable energy resource, water, was explored. It was shown that the overall generation mixture suggested by this case study would require anywhere from 0.116 – 0.510% of California's current water consumption.

An important parameter that was not mentioned in the prior discussion is that of renewable hydrogen. This is a critical parameter when considering the build out of hydrogen infrastructure

especially within the state of California, due to legislation such as SB 1505 which sets a goal of having 33% of hydrogen being generated from renewable sources [22]. It is difficult to quantify the amount of renewable hydrogen produced per day; therefore, an annual average value must be taken. The annual average renewable hydrogen produced by each case study is presented in Table 24. The renewable hydrogen generation percentage varies between 60 and 61%. This holds hope for hydrogen as a future energy storage device and carrier in the effort to help California meet its renewable penetration goals along with its renewable hydrogen generation targets.

Some of the more powerful results from HFit have been extracted and outlined; however, there are many more hydrogen production and demand cases that this methodology has the ability to analyze.

6. Overall Summary

The AHP has been implemented as a strategic decision-making tool, which allows for the critical analysis of proposed hydrogen infrastructure build out scenarios generated by policy makers and industry experts. This novel application and methodology created for the exploration of a hydrogen infrastructure deployment was applied to several case studies in order to fully demonstrate its capacity.

In the first case study, the analysis was set up to focus on the siting of hydrogen generation facilities in general, along with the exploration of anomalies that arise from such a study. Two key points garnered from this initial case study were the following. 1) Some results that appeared to be at least initially anomalous, turned out to be, upon further inspection, justified given the rankings applied to the selected criteria. In addition, these false abnormalities only exist for centralized generation schemes, whereas the results would not be anomalies for distributed schemes. 2) The AHP is capable of taking many metrics of varying units and combining them to come to an overall decision for complex, multi-level problems.

The second case study utilized a separate set of expert inputs in order to fully illustrate the build out of a hydrogen supply chain and its ramifications with regard to energy use, the environment and other energy infrastructure. In order to understand the analysis conducted in the case study, the reader is referred to Table 23 for the inputs to the model, and Table 24 for a tabular overview of the most important results obtained.

Hydrogen as a transportation fuel has been demonstrated to be a viable alternative to the current petroleum supply chain. However, the typical isolated energy systems approach to analysis cannot be utilized. The current work has demonstrated that the interaction between related energy systems is complex and must be considered in detail. On another level, the proposed approach allows for the disbanding of the dissociated paradigm of research focused engineering and those affecting the implementation side, such as policy makers and industry stakeholders. Therefore, this approach allows for the evolution of a new cross-cutting, multidimensional paradigm in the resolution of energy issues and development of new energy infrastructure.

7. Conclusions

- The AHP is capable of taking many metrics of varying units, integrate and apply them to analyze and come to an overall decision for complex, multilevel problems.

It is clearly seen through the multi-criteria examination that was conducted herein, that simply looking at the datasets and proposing candidate locations for future hydrogen stations would be cumbersome and inaccurate. Trying to compare the distances from infrastructure and power plants, to the magnitude of a population and land cost, in order to come to an objective decision would be impossible without the de-coupling process of AHP. In all, the AHP is useful in the complete modeling of

hydrogen fuel cell vehicle roll out planning due to its ability to accommodate real world expert input into the its design process.

- Hydrogen demand is strongly tied to VMT and population projections.

Due to the manner in which future hydrogen demand was modeled in this study, it is closely coupled to the VMT. This is important due to the uncertainty of future VMT in the state of California. There are many things that could happen that would either increase or decrease the VMT. The most obvious driver in VMT change would be a strong increase in gasoline prices that would most likely drive the demand for hydrogen up in the near term.

Additionally, the spatial allocation of this hydrogen demand is strongly coupled to population data as it was the primary dataset utilized in this analysis. This serves as a first approximation in the disaggregation of a state-wide hydrogen demand. In the future, other datasets, such as vehicle sales data, commuter travel patterns and population migration statistics, can be deployed for more realistic results.

- Shortest transportation routes and alternatively fueled vehicles for hydrogen distribution should be considered in the near term.

As was seen in the “PCA Emissions and Energy” sections of each case study, the emission levels due to hydrogen delivery trucks were always dominant. Figure 71 and Figure 72 illustrate the importance of considering alternative fuels for the delivery of hydrogen. The large emissions magnitude from this hydrogen delivery is most likely due to the algorithm employed to solve the Traveling Salesman Problem in this modeling approach and the inherently low volumetric energy density of hydrogen compared to gasoline. It was also shown that the complexity of the delivery infrastructure was dependent upon the dispensing location capacity. The obtained results were shown to be on the right

order of magnitude by comparing them to the current heavy duty trucking sector in Table 20. This clearly delineates the importance of alternative fueled heavy duty trucks for the delivery of hydrogen in the near term.

- Energy and emissions necessary for the delivery of hydrogen as a future transportation fuel have been greatly underestimated and under examined in the literature.

A novel approach was applied to the calculation and determination of the best overall delivery methodology for hydrogen. This methodology was evaluated by comparing it to several benchmarking parameters and literature studies. Data from the current California heavy duty sector and natural gas industry were utilized as points of reference for comparison. It was shown that the results suggested by HFit only require a small amount of current heavy duty vehicles and miles traveled. The increase in diesel consumption varied greatly and in its most extreme case showed a large increase in diesel demand due to the truck delivery of hydrogen. The length of hydrogen pipelines suggested is high compared to California's current interstate natural gas pipeline system, but is only about half as large as the natural gas system in Texas. When comparing emission results from the literature for the truck delivery of hydrogen to those obtained with HFit, the literature is very close but appears to have a slightly larger estimate. This confirms the large energy and emissions requirement suggested by the hydrogen delivery module of HFit.

- It has been shown that if refineries reduce operations to only meet projected gasoline demands that both GHG emissions and criteria pollutant emissions can be reduced.

This postulate is upheld by the results presented in Figure 81. From this figure it is apparent that the hydrogen supply chain retains a similar carbon dioxide emission profile, but drastically reduces emissions in all other categories when compared to gasoline supply and utilization. The addition of

HDFCVs for the delivery of hydrogen solidifies the appeal of hydrogen as a future transportation sector energy vector.

- It has been shown that by dispatching hydrogen electrolyzers to meet a high hydrogen demand under large renewable penetration levels allows for a sizeable portion of hydrogen to be generated from these intermittent renewable resources.

SB 1505 which sets a goal of having 33% of hydrogen being generated from renewable sources was shown to have the potential to be met through this analysis under a high renewable penetration using what would have otherwise been curtailed renewable resources [22]. The annual average renewable hydrogen produced by each case study is presented in Table 24. The renewable hydrogen generation percentage in these cases is around 60%. This holds great hope for hydrogen as a future energy storage device and carrier in the effort to help California meet its renewable penetration goals along with its renewable hydrogen generation targets.

8. Recommendations

As with any work in the research and development field, there is always room for expansion and improvement. Therefore, in this section, recommendations for the future evolution of this project are detailed. The proposed future trajectory of the mission to model and deploy hydrogen as a transportation sector energy vector is listed as follows:

1) Deploy the HFit with a variety of policy maker and industry expert inputs.
2) Conduct spanning VMT scenarios, and simulation years that correspond to a broad range of FCV penetrations.
3) Projected hydrogen demand, generation and delivery scenarios should be varied in order to illustrate the change in dynamic interaction of the hydrogen and electrical energy systems.

4) Modify and expand the Hydrogen Demand Module to:
    a. Incorporate the consideration of Greenfield sites. This would allow the citing of hydrogen stations at locations other than current gasoline stations.
    b. Improve spatial allocation of hydrogen demand beyond the utilization of population data to include as vehicle sales data, commuter travel patterns, and population migration statistics. This would allow for capturing more behavioral trends such as the amount that is driven in a certain area with refined detail (e.g., San Francisco has a large population, but might not drive as much on average as residents in the Los Angeles area).
    c. Be capable of varied station sizes as the infrastructure is built out. This could assist in obtaining a more optimal solution for having the lowest capital cost (e.g., Installing small, low capacity stations at first) and then transition to economies of scale as the hydrogen demand increases. This would also change the number of hydrogen dispensing locations.
5) Expand the hydrogen generation technologies to include Post-consumer Refuse gasification, Biomass Gasification, Biogas Utilization, Tri-Generation Technologies, and Thermochemical nuclear water splitting.
6) Modify the delivery module to :
    a. Eliminate very short pipeline lengths.
    b. Eliminate back tracking from a centralized terminal to a dispensing location near the generation facility, in the case of pipeline to truck delivery.
    c. Take into account new pipeline corridors that are not included in the current natural gas infrastructure, but are necessary in order to install a hydrogen pipeline from the generation facilities to centralized terminals.

d. Deploy a pipeline only delivery scenario.

7) Integrate the CANGAM model once it has become better spatially and temporally resolved.
8) Expand the spatial decision-making methodology in order to decompose the decision in Figure **23** into several more sub-decisions.
9) Conduct spanning air quality modeling scenarios that result from the modeled future hydrogen infrastructure build out.

9. Appendices

Appendix A

Definitions:
Decision#1: **Power Plant Proximity (PPP)** – Distance to closest electricity generation location (e.g., Solar Farms, Wind Farms, Natural Gas Power Plants). **Least Land Cost (LLC)** – Average Housing Values from the US Census Fact Finder. **Least Populous (LP)** – Lowest population based on Land Scan data that is resolved to 1kmsq. **Infrastructure Proximity (IP)** – Nearest distance to current transportation infrastructure (Highways, Railroads, Natural Gas Pipelines) **Water Infrastructure Proximity (WIP)** – Nearest source of water available for utilization during the hydrogen generation process.
Decision#2: **Greenhouse Gas Emissions (GHG)** – GHG emissions generated by the conversion of the primary energy source to hydrogen. **Capital Cost (CC)** – Capital Cost of a given conversion technology. **Fixed Operations and Maintenance Costs (FOM)** – The Fixed O&M for a given technology. **Energy Conversion Efficiency (ECE)** – The Energy Conversion Efficiency for a given technology. **Feedstock Cost (FC)** – The primary energy source Feedstock Cost that corresponds to a given technology. **Proximity to Feedstock Infrastructure (PFI)** – The nearest distance to a primary energy source infrastructure location.
Decision#3: **Greenhouse Gas Emissions (GHG)** – GHG emissions generated by the delivery of hydrogen from the conversion facility to dispensing location. **Least Energy Consumption (LEC)** – The energy required to deliver hydrogen from the conversion facility to dispensing location. **Capital Cost (CC)** – The total capital cost involved in the installation of the delivery pathway. **Operations and Maintenance Cost (OM)** – The total cost of maintaining and operating the delivery pathway.

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