Siting Hydrogen Refueling Stations for Heavy Duty Vehicles within California

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Siting Hydrogen Refueling Stations for Heavy Duty Vehicles within California

THESIS

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by

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ABSTRACT OF THE THESIS

Siting Hydrogen Refueling Stations for Heavy Duty Vehicles within California
by
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Professor G. Scott Samuelsen, Chair

Heavy-duty vehicles (HDVs) are one of the largest contributors of both greenhouse gas (GHG) and criteria pollutant emissions in California. The burning of heavy diesel fuels and even the cleaner burning of natural gas within internal combustion engine (ICE) trucks are unsustainable. As such, as part of California's goals to reach net zero GHG emissions by 2045, California has mandated that all drayage trucks must be zero-emission by 2035 and all other HDVs be zero-emission by 2045. This mandate will force the adoption of zero-emission technologies such as battery electric trucks (BETs) and fuel cell electric trucks (FCETs).

While battery electric technology has begun to succeed in the light-duty vehicle (LDV) market, the challenges associated with battery power are exacerbated in HDV applications including long charge times, immense power demands on grid infrastructure, heavier vehicle weight, and limited vehicle range. Hydrogen fueled FCETs have the advantages of faster refuel times, lighter vehicles, and larger vehicles ranges, all of which are more comparable to the performance of modern diesel trucks. As such, hydrogen fueled

FCETs will play a major role in all HDV vocations, likely dominating in long-haul applications.

The major inhibition to the adoption of FCETs is the lack of refueling infrastructure, the subject of this thesis. To study and aid the initial deployment and rollout of Hydrogen Refueling Stations (HRSs), a model was developed in ArcGIS to spatially optimize HRS deployment within California and optimally support the predicted adoption of FCETs in the coming years. The model aims at optimizing refueling coverage to provide the most support possible and the least compromises of desired truck routing. The model also accurately informs the number of HRSs needed within the state to cover the anticipated fueling demands and how different station parameters might affect the performance of the network. While stations will be required to meet the total demand of the state, an initial subset of well optimized stations can effectively meet a majority of the trucking demand in California.

INTRODUCTION

With the increasing importance of reducing the impact of climate change and air pollution, California has begun to prioritize and incentivize the growth of new renewable and clean technologies. As of 2018, 28.2 percent of Greenhouse Gas (GHG) emissions in the U.S. came from the transportation sector [1]. Passenger cars, which make up 41.2 percent of these emissions, have been the largest target for emissions reductions through the growth of battery electric vehicles (BEVs) and fuel-cell electric vehicles (FCEVs) [1]. However, to reach carbon neutrality in California by 2045, heavy-duty vehicle (HDV) powertrains will need to be electrified as well. HDVs hauling freight currently contribute approximately 23.2% of all transportation GHG [1]. Additionally, HDV VMT has experienced a 113% increase between 1990 and 2018 which has resulted in an increase of CO_2 emissions by 87 percent [1]. To reduce the emissions of vehicles, Governor Gavin Newsom established Executive Order (EO) N-79-20 that will make all drayage truck operations zero-emissions by 2035 and all other MDV and HDV operations zero-emissions by 2045 [2]. To reach these extreme emissions reductions, the next few decades will require immense growth in the electrification of heavy-duty trucks utilizing both battery and fuel cell electric technologies.

The electrification of HDVs will also substantially reduce criteria pollutant emissions. Medium and heavy-duty trucks currently contribute 33% of NOx emissions, a major precursor of ozone [3], [4]. Electrifying HDVs negates these emissions at the source. Additionally, electrification through hydrogen fuel-cells could reduce the PM2.5 emissions of trucks by 73%, a major contributor to poor health conditions [5]. In addition to reduced emissions from electrifying the vehicle, brake and tire wear emissions in electric trucks also decrease upwards of 50% from diesel trucks due to the use of regenerative braking [5], [6]. Other emissions such as nitrous-oxides and sulfur-oxides also show a decrease in MHDV life-cycle emissions when electrified [5]. When it comes to hydrogen as a fuel as compared to other liquid or gaseous fuels, an ecological study by Valente et al. found that hydrogen produced from electrolysis has the lowest ecological burden compared to any other heavy duty vehicle liquid or gaseous fuel [7].

When electrifying a fleet of both short-haul and long-haul trucks, both battery electric trucks (BETs) and fuel cell electric trucks (FCETs) are being considered, just as is seen in the light-duty sector [8]. BEVs face several additional challenges as opposed to FCEVs when attempting to roll out a zero-emissions HDV fleet. For one, the limited range and the potentially long charge times greatly limit the use case of HDVs [9]. Additionally, BETs are weighed down by heavy batteries which decreases hauling capacity [10], [11]. Therefore, because of the use-case of most HDVs, which necessitates longer ranges and shorter refuel times, FCETs will likely dominate the HDV sector as opposed to battery electric technologies which have been thriving in the LDV market [12]. It should be noted though that BETs will likely have many use-cases related to short-haul trucking as BETs benefit from high energy efficiency if charge times and distance are not a major concern [8], [11].

Regardless of use-case, fueling and charging infrastructure is today the greatest resistance facing the implementation of ETs. BET charging infrastructure suffers many restrictions due to extreme power demands of fast-charging BETs. For instance, one truck charging with a 1 MW connection draws as much power as 2500-4000 homes [10], [13].

Electric grid infrastructure is currently not built out to support the adoption of large BET fleets: the stacking power demands of fast charging BETs has the potential to reach the equivalent power draw of tens of thousands of homes. This power draw could require upgrades throughout the system, anywhere from transformers up to local power generation. Likewise, these high charging demands of BETs pose resiliency challenges on the grid, such as rolling blackouts, especially compounded with the recent high volumes of BEV adoptions within the light-duty vehicle sector [14].

Similar to BETs, the greatest resistance that currently stands in the way of further development of FCETs is the lack of fueling infrastructure [15]. Currently only 55 hydrogen refueling stations (HRS) are available in California to serve light-duty FCEVs (California Fuel Cell Partnership, 2022) and only one trial station in California at the Port of Long Beach is available to service FCETs [17]. While refueling infrastructure is difficult and expensive to establish [18], [19], the growth of a hydrogen market is required to manage the diurnal variation and intermittencies associated with solar and wind. Hydrogen can be produced from curtailed renewable electricity and later used as a transportation fuel or as an additional power source for the electric grid when renewable generation is low. Therefore, hydrogen production, storage, and applications serve as a pathway to integrate more renewable energy within California's total energy economy [20], [21].

Unfortunately, due to the infancy of the current hydrogen refueling network for HDVs, it is nearly impossible for fleet owners to adopt the usage of FCETs without building their own HRS. Therefore, it will likely take a combined effort of several parties, including the state of California, to begin planning future HRS deployment to enable FCET adoption

[20]. To this end, a methodology must be created to determine current diesel and natural gas heavy-duty vehicles refueling and driving patterns and apply this understanding in such a way that deployed HRSs are most effective and efficiently service the greatest number of service routes.

Therefore, the goal of this research is to create and demonstrate a methodology for spatially and temporally determining the number and location of FCET HRSs within California to support the anticipated growth of FCETs over the next 3 decades.

To achieve this goal, the following objectives must be met:

1. Characterize and locate the current fleet of HDVs in California.
2. Characterize and locate candidate HRSs for HDV in California.
3. Determine and validate an adequate driving network suited for HDVs
4. Create a series of hydrogen demand points within ArcGIS to represent the refueling needs of future FCETs within California
5. Create a siting model that can allocate the projected hydrogen demand points to the candidate HRSs along the driving network to locate and evaluate the optimal locations of HRSs in California given a series of parameters
6. Evaluate the input parameters and their impacts on the results of the siting model
7. Showcase the capabilities of the model by siting the best HDV HRSs in California for 2025.

CHAPTER 1: BACKGROUND

1.1 Hydrogen Future

With sustainability becoming a major concern and focus of the world, transitioning away from fossil fuels has become ever more important. Thus other, more sustainable fuels and forms of stored energy are rising in popularity. While biofuels and battery stored electricity are showing signs of promise as alternatives to fossil fuels, it is abundantly clear due that hydrogen is essential for sustainability [21]. Its ability to alleviate solar and wind intermittency through its storage capacity, its function as a zero-emission fuel, and its ability to be distributed at a low cost have made it clear that for zero-emissions futures, hydrogen must play some role.

Over the past few decades, several sources including the state of California have attempted to identify what the hydrogen economy will look like and to what scale it will exist [22]. The future of hydrogen seems to hang in a cloud of uncertainty, however over the past decade since McDowall and Eames wrote their literature review, hydrogen technology has rapidly begun to take shape. As of June 2022, there are 14,106 fuel cell cars sold and leased within the US, 66 fuel cell buses in operation, and 56 hydrogen stations available [16]. With Governor Gavin Newsom's executive order for zero-emissions vehicles in place, the number of vehicles is only going to increase within the next three decades [2]. California Fuel Cell Partnership has suggested that 1,000 HRSs within California by 2035 will be needed to support up to one million light-duty FCEVs [20].

The growing success of FCEVs is not only limited to LDVs and buses. Demonstration projects showcasing FCETs are beginning to take place such as a 10 FCET demonstration at the ports of Los Angeles in a Toyota, Kenworth, and Shell collaboration [17]. While still in their infancy, heavy-duty FCEVs are likely to grow beyond the current market for light-duty FCEVs due to the niche needs of trucks. While currently, due to the youth and higher present costs of hydrogen systems, BETs currently have a lower Total Cost of Ownership (TCO) than FCETs, FCETs are estimated to have a lower TCO in both the 10-year and 30-year time spans [19]. With BETs and FCETs being the best way of having a vehicle with zero tailpipe emissions and ZEVs being mandated by the state of California, it is likely that FCETs will dominate the truck market in the next 10 to 30 years.

In California, the California Energy Commission approved a $1.4 billion plan for ZEVs with $77 million of which is for hydrogen refueling infrastructure by the year 2025. Furthermore, to increase the supply and accessibility of hydrogen in the U.S., the DOE recently launched an $8 billion program for building clean hydrogen hubs across the U.S. [23]. Hydrogen is here to stay and is going to play an integral part in the future of the energy economy as well as in transportation.

1.1.1 Hydrogen Demands from Fuel Cell Electric Trucks

With hydrogen being an integral part of the future of trucking, it is important to understand the projections of hydrogen demand to site HRSs. Blake Lane developed the Transportation Rollout Affecting Cost and Emissions (TRACE) methodology to create realistic growth scenarios for different alternative fuel vehicles [18]. TRACE considers factors such as TCO, fuel feedstocks, governmental laws, and other factors that could affect the adoption of the variety of alternative fuels. TRACE therefore outputs different scenarios up through 2050 which depict the percentage of vehicles utilizing each type of fuel. Depending on the scenario, sometimes battery electric will be favored more heavily for trucks, but for most scenarios hydrogen as a fuel for FCETs has the highest adoption rate.

1.2 Hydrogen Refueling Station Siting

Meeting the anticipated demand of hydrogen fueled HDVs requires the rapid deployment of a reliable statewide hydrogen refueling network. Planning out the expansion of the current hydrogen network requires understanding of the economics, traffic flow, technologies involved, and anticipated growth of demand. Presently there is no predominant or accepted methodology for siting hydrogen refueling stations for HDVs. Furthermore, there are no studies or data on any current hydrogen refueling stations due to their lack of presence.

There are three main refueling station types that need to be addressed, either directly or indirectly, by a siting model. Satellite refueling, fleet refueling, and destination refueling. Fleet refueling occurs at the home or resting location of the HDV. Destination refueling is refueling that occurs at one or more destinations of the HDV. Satellite refueling is any refueling that occurs between the fleet or origin of the HDV and the destination. Common fleet refueling applications are local service route vehicles such as buses or MDV delivery vehicles which return to a depot each day and are often privately owned and operated. Most HDVs require a mix of the three refueling station categories with satellite refueling especially pertinent in enabling long routes between origin and destination.

1.2.1 Heavy-duty Hydrogen Refueling Station Siting

University of California, Davis has produced a spatial modeling methodology for HDV travel and refueling patterns in California, which uses transportation analysis zones (TAZs) as the primary indicator of travel [24]. However, this methodology, since origin/destination in nature, does not accurately represent the demands of satellite, or on the road, refueling. Satellite refueling is especially important for FCETs due to a decreased range in comparison to their Diesel counterparts. The UC Davis methodology may, however, show merit in denoting the locations of fleet refueling. Satellite refueling is seen though as the more important issue when it comes to station siting because fleet owners may install their own private refueling stations for their fleets but need satellite stations to enable FCETs to cover their entire trucking routes. Another limitation of the UC Davis model is the ability to expand analysis beyond California's borders due to the nature of the TAZ data set which does not exist for the whole of the continental US. Finally, their methodology is incapable of locating where within TAZs a station should be placed, it simply counts the number of stations that should be within a TAZ. My thesis seeks to develop a methodology which addresses these three issues of satellite station siting, the ability to give exact locations for optimal stations, and an ability to be extended beyond the borders of California.

An alternative fuel refueling station location model for Germany was developed by Rose et al [25]. However, this model suffers from many of the same assumptions as the Davis model. It uses origins and destinations between different nodes, like the TAZs described in the Davis model. However, it should be noted that these nodes all are aligned upon the German highway network which does provide better siting locations than the TAZ nodes which are simply the centroids of a TAZ. The main limitation of this model is that siting the early years of the transition FCET will be impractical due to the model forcing 100% refueling of FCETs. The model developed in this thesis seeks to provide coverage to the anticipated adoption of FCETs without necessarily attempting to service every current diesel truck route within California during the early years of FCET adoption.

1.2.2 Light-duty Hydrogen Refueling Station Siting

While no other work has been conducted on HDV hydrogen station siting, similar station siting work has been performed on Tri-Generation Fuel Cell systems and LDV hydrogen refueling stations using a method known as the Spatially and Temporally Resolved Energy and Environmental Tool (STREET) [26]. The station siting method in this research will be based upon the methodology of STREET to resolve the spatial and temporal locations of HDV stations as opposed to LDV stations.

Another siting methodology as described in Sun et al was modified to include the costs of stations within the siting optimization [27]. This model is also able to link hydrogen sources to the HRSs. Limitations of this model include needing source locations, hydrogen station cost predictions, and the optimization is limited to one expressway be analyzed at a time, thus not being able to provide full spatial coverage. This model was then expanded to also optimize siting and station sizing within a metropolitan area based upon such factors as hydrogen sources, transportation methods, and storage methods, thus optimizing the hydrogen supply chain [28]. Like the methodology of STREET, the model developed by Sun et al. represents VMT in grid-like demand points that can then be serviced by candidate stations.

Unfortunately, with the lack of data behind HDV HRS performance and cost as well as the current infancy of hydrogen production within California it is impractical to consider the factors of the hydrogen supply chain in current station siting analysis. Additionally the many considerations to utilize on-site hydrogen production at HRSs could make hydrogen production considerations more obsolete as well as offer means of better utilizing renewable energy sources [26], [29]–[32]. It should be noted that these studies do not consider production large enough to support a HDV HRS and thus it cannot be stated for certain whether on-site hydrogen production will be present at HDV HRSs or if dedicated hydrogen production facilities or tri-gen facilities will be necessary for the growth a HDV HRS network.

1.3 Background Summary

Current literature has shown that FCETs are a successful alternative to diesel trucks and may outperform other forms of zero-emission trucks, with the anticipated number of FCETs being heavily studied. FCETs can reduce statewide GHG and criteria pollutant emissions from current levels all while maintaining a performance comparable to modern diesel trucks. While the technology of the trucks is rapidly improving, supporting hydrogen refueling infrastructure remains the largest barrier standing in the way of fleets adopting and utilizing FCETs. Several siting methodologies and many studies on the performance of light-duty HRSs have been conducted as light-duty HRSs begin to be deployed throughout

California and the world. Conversely, HDV HRSs have been largely understudied. The methodology developed in this thesis aims at helping fill this gap by applying and adapting some of the successful LDV HRS siting methodologies to HDV HRSs with the intent of providing government agencies, station developers, and truck manufactures with a methodology for the optimal deployment of HDV HRSs that best support the necessary adoption of FCETs.

The station siting method used in this research is (1) based upon the methodology of STREET to resolve the spatial and temporal locations of HDV stations as opposed to LDV stations, and (2) builds upon previous research conducted on the feasibility of a variety of FCETs to determine the on-board storage and range of many of these new hydrogen fuel cell vehicles [12]. The pressures, ranges, and efficiency of these vehicle systems will be important in determining the frequency, volume, and technology of the stations. For station data, due to the lack of literature and data on HDV HRSs, many assumptions from current LDV and bus HRSs are considered. The station siting method also builds upon projections for FCET adoption from the TRACE model and applies a spatial spread to the data to derive hydrogen demand forecasts in combination with the FCET research data.

Therefore, the methodology seeks to create a station siting method for HDV HRSs that uses a new methodology for creating forecasted spatial hydrogen demand. It is then showcased for California in the year 2025 as a means of displaying the capabilities of this new methodology as well as its potential future applications for the future growth of hydrogen infrastructure.

CHAPTER 2: APPROACH

Task 1

Characterize and locate the current fleet of HDVs in California

Due to a lack of FCET data from any trucking operations, FCET refueling patterns are modeled off the current behavior of trucks within California. Registration data is gathered to represent relative fleet location and density, and VMT data is collected to represent where fuel is consumed and the areas experiencing the greatest flow of traffic.

These data are used for projections into future years since the stations are siting for future years. An understanding of the current and future trends of these data are key to supporting the purpose of this task.

Task 2

Characterize and locate candidate HRSs for HDVs in California

Since truck stops and refueling sites have restrictions and accessibility needs, a set of viable locations for truck stops are collected. The methodology developed takes current diesel truck stops and maps them into ArcGIS. These stations are either expected to be replaced, become shared use stations between diesel and hydrogen, or act as locational proxies for a new station within proximity. Because of the lack of data on HDV HRSs, station operation and capacity are based upon both current diesel refueling stations, current light-duty HRSs and expert opinion.

Task 3

Determine and validate an adequate driving network suited for HDVs

Since trucks cannot drive on all public roads within California and have different driving speeds than normal light-duty traffic, it is important to utilize a fully developed driving network specifically designed to simulate truck traffic. This means routes generated on the driving network can be taken by any FCET. Siting a station for demand that takes truck inaccessible routes is unproductive. This network must be validated such that all routes are real and valid, and that all turns and directions are generated correctly within ArcGIS.

Task 4

Create a series of hydrogen demand points within ArcGIS to represent the refueling needs of future FCETs within California.

The methodology developed can take current and projected truck VMT and registration data from Task 1 and apply anticipated FCET performance and adoption rates to create a set of realistic hydrogen demand points for drayage and line-haul trucks. These demand points are analyzed to assure the results accurately represent areas that will experience a high and a low demand of hydrogen in order to site refueling stations to meet the demand.

Task 5

Create a siting model that can allocate the projected hydrogen demand points to the candidate HRSs along the driving network to locate and evaluate the optimal locations of HRSs in California given a series of parameters.

This task combines the data from Task 2, Task 3, and Task 4 within an optimization algorithm in order to locate the optimal stations within the candidate station data set and allocate the modeled hydrogen demand to evaluate the stations' ability to service hydrogen demand. Changing input parameters such as station capacity, hydrogen demand projections, station service range, and number of stations are analyzed to establish the extent to which the locations and performances of chosen stations are affected.

Task 6

Evaluate the input parameters and their impacts on the results of the siting model.

Since the model developed in Task 5 will be untested, the input parameters are evaluated such that their effects on the results of the methodology are understood with the goal to inform future usage and potential limitations of the model.

Task 7

Showcase the capabilities of the model by siting the HDV HRSs with high demand coverage and station performance in California for 2025.

To finally validate and demonstrate the usage of the HDV siting methodology developed in this paper, results for 2025 are presented showcasing the optimal HDV HRS locations and their respective performances. This goal is to demonstrate how best to use the methodology as well as what factors and assumptions must be considered when evaluated results.

CHAPTER 3: METHODS

3.1 HDV Hydrogen Demand

In this section, California HDV fleet VMT and refueling demand is spatially located and combined with projections for FCET adoption to create a spatial demand load for the siting model. This process is done for the projected year of 2025 in order to characterize the first transition towards FCETs. This process is intended to work for other years as well with the years of 2035 and 2045 in mind when formulating the process.

Projected VMT data for HDVs from the California Air Resources Board's Emission FACtor (EMFAC) model as seen in Figure 3.1**Error! Reference source not found.** are the base data for representing FCET hydrogen demand [33]. These data are separated by county and provide a breakdown of VMT, as well as other useful information such as emissions, for individual vehicle vocations. To match the categories used in FCET adoption projections, the vehicle vocations from EMFAC were grouped into four categories: drayage, in-state line haul, out-of-state line haul, and other. The correlations between these four categories and EMFAC's classification is detailed in Table 3.1. Two categories are ignored in the scope of this methodology: "other" as it is largely constituted by construction equipment and other non-trailer vehicles which follow different refueling patterns than those studied here, and "out-of-state linehaul" as the scope of this methodology is limited to vehicles that primarily operate within California. Out-of-state linehaul vehicles are to be considered in future studies, particularly those focusing on 2035 and the years beyond.

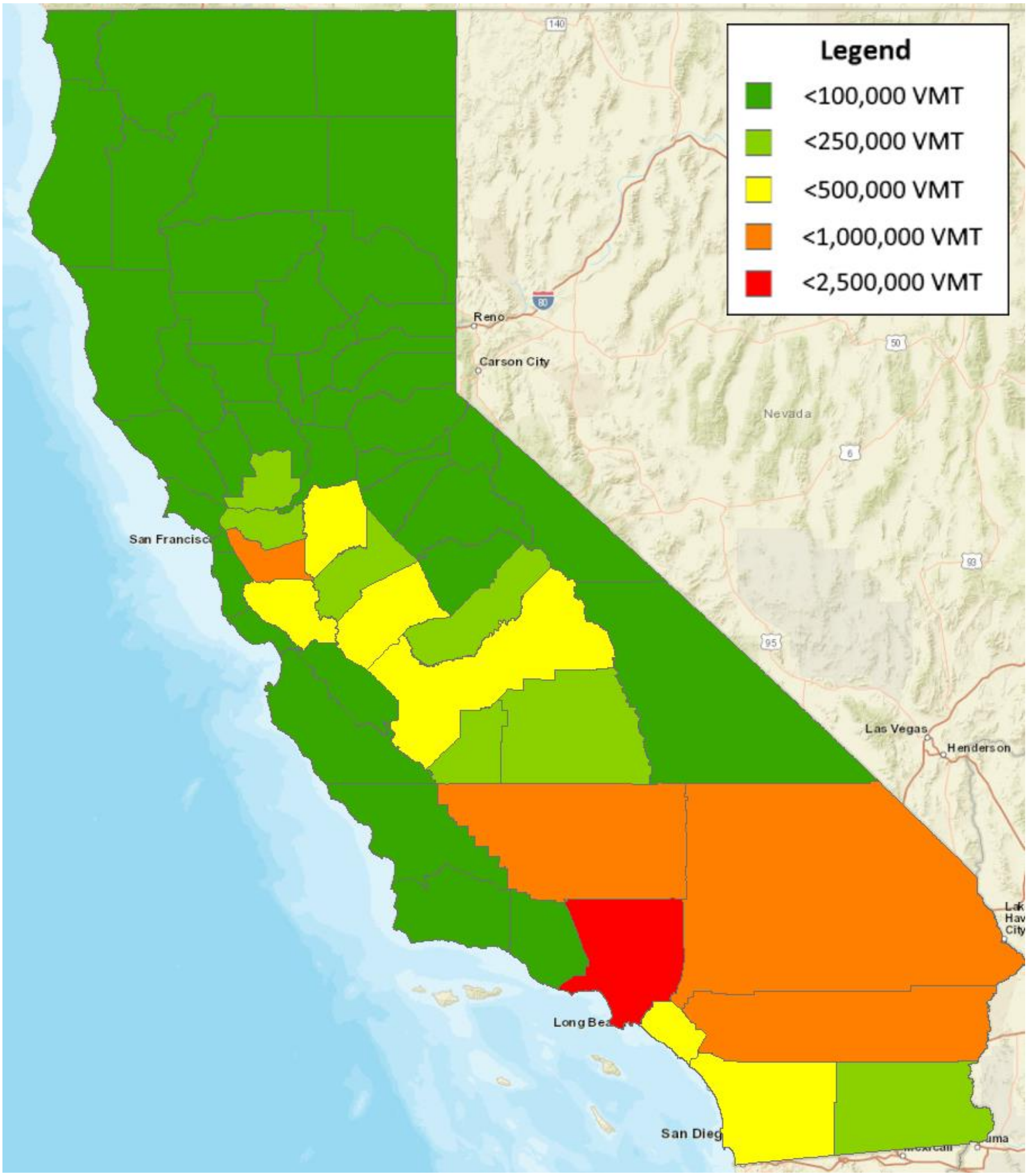

Figure 3.1: EMFAC county drayage and in-state linehaul VMT data for 2025

Table 3.1: Simplified categories for EMFAC VMT classification

Simplified HDV categories	EMFAC T7/class 8 vehicle categories
Drayage	Other Port
	POAK
	POLA
In-state linehaul	Tractor
Out-of-state linehaul	NNOOS
	NOOS
Other	Public
	CAIRP
	Utility
	Single Concrete/Transit Mix
	Single Dump
	Single Other
	SWCV
	T7IS

While the EMFAC's VMT data are a valued baseline for representing truck demand, the county-wide resolution is insufficient. To overcome this, the EMFAC truck registration data, which are provided with zip code resolution, were combined with the VMT data to distribute the VMT down to zip code level based on the weightings of the registration data. The registration data, while not vocation separated, shows the number of trucks registered in each ZIP code within California as shown in Figure 3.2 Assuming that FCETs seeking to refuel at a HRS are more likely to refuel close to their "home base", rather than during transit when possible, VMT data within the county can be weighted proportional to the number of trucks registered within the ZIP codes in the county.

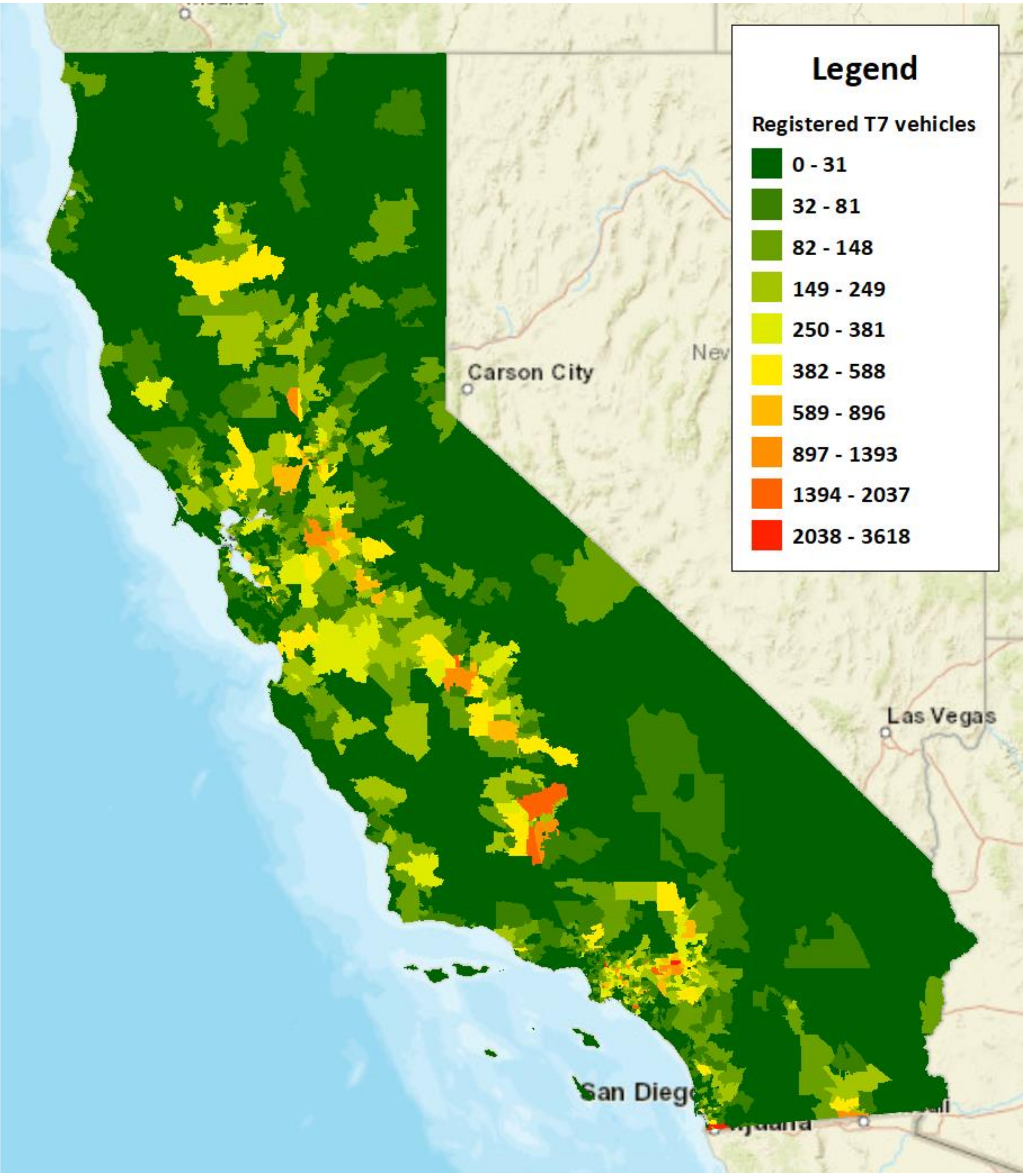

Figure 3.1: Number of trucks registered per zip code (EMFAC)

The next step is to transform the VMT data into a series of points rather than large polygons. Representing the space within the polygon with a grid of demand points allows the full space and demand of the polygon to be represented and corrects for the mismatched overlay of zip codes and counties. To accomplish this, a grid of square kilometer (sqkm) points is used and VMT is overlayed onto these points after receiving the zip code registration data weighting creating sqkm points with VMT per sqkm data. Figure 3.2 provides a graphical representation this data manipulation. Other methodologies such as those that use TAZ zones for station siting tend to only use the centroid of the polygon. By using a grid of points instead of a centroid, demand can more accurately be divided between stations. For example, vehicles at the northern edge of a zone may prefer refueling at a station to the North whilst the rest of the vehicles in zone prefer refueling at a station in the South. Having only the centroid represented would cite all the demand towards the Southern station as it cannot split up demand allocation from a given zone.

Once these processes are complete, what is left are a series of sqkm points with VMT per sqkm with zip code level granularity and VMT separated by category. Once these points are created, they can be assigned a hydrogen demand by taking the VMT and applying a conversion from VMT to hydrogen demand. This conversion uses data from the TRACE model [18] for 2025 to obtain a percentage of drayage and line haul that is expected to have switched to hydrogen (9.16% of drayage and 2.91% of in-state linehaul in 2025) and then applying the efficiency of a FCET. See Equation 3.1 for the conversion from VMT per year to kg of hydrogen demand per day. The process is depicted in Figure 3.3 which shows how VMT is weighted to zip code level, distributed onto square kilometer points and converted from VMT to a hydrogen demand.

Equation 3.1

$$\left(\frac{kgH2}{day}\right) = \left(\frac{VMT}{year}\right) * \frac{1}{365}\left(\frac{day}{year}\right) * \left(\frac{H2VMT}{totalVMT}\right) * \left(\frac{kgH2}{VMT}\right)$$

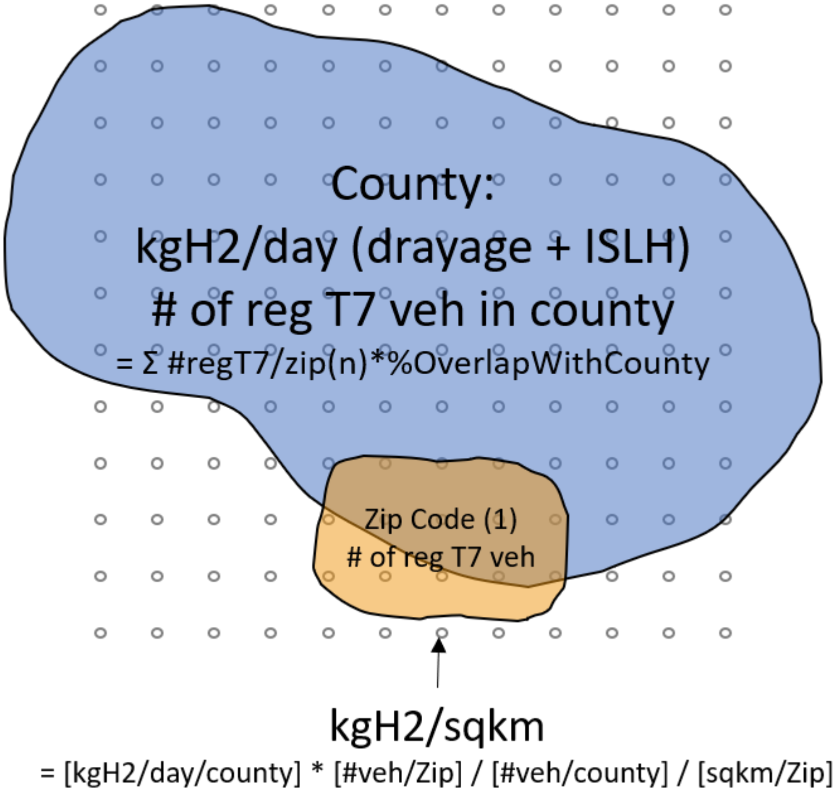

Figure 3.2: Diagram of demand point generation

To create a low and high demand case, a high efficiency of 9.4 mi/kg is used for the low demand and a low efficiency of 5.5 mi/kg is used for the high demand. This efficiency is represented by the kgH2/VMT value in Equation 3.1. It should be noted that current FCETs have a typical efficiency of 7.5 mi/kg [9], [34]. Using these two efficiencies creates two bounding cases from which the real hydrogen demand is likely to fall within. In total the high-demand case has a hydrogen demand of 83,073 kgH2/day and the low-demand case has a hydrogen demand of 48,607 kgH2/day which is shown in Figure 3.4. Due to the cases only differing based on an efficiency multiplier, the low and high demand cases have the same spatial distribution.

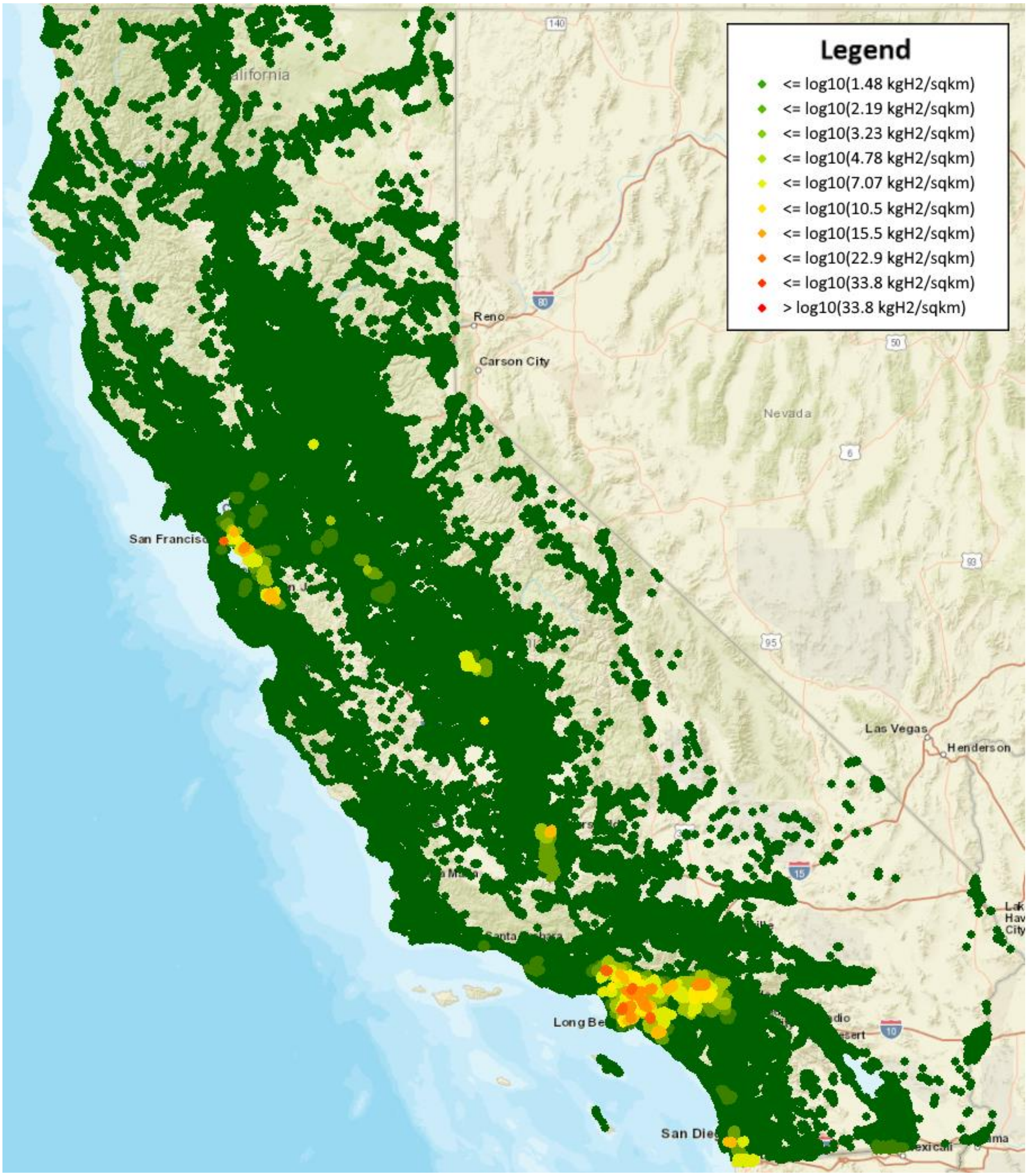

Figure 3.3: Hydrogen demand points, low demand case

This method of creating low and high demand cases is not a perfect method but helps represent the uncertainty of HDV hydrogen demand. For instance, it is uncertain which percentage of HDVs will convert to FCETs and which percentage of HDVs will convert to BETs. A series of factors including charge/refuel times, fuel/charge costs, vehicle costs and availability, infrastructure costs and availability, and vehicle use case will all affect the decisions of fleet owners seeking to adopt zero emissions vehicles. Changing factors such as these can create wildly varying hydrogen demand cases with varying degrees of FCETs being adopted in either the drayage or line haul sectors.

Instead of attempting to simulate many of these outlier cases as individual extreme cases, the TRACE model was used to simulate the most probable adoption rate based on current indicators. As mentioned before, efficiencies of the FCETs were largely varied to create two encompassing cases, showcasing the wide range in possible hydrogen demand. While this will not shift the locations and relative weight of the demand, unlike adjusting FCET adoption rates, it will give an understanding of how the utilization and performance of a simulated HDV hydrogen station network under varying degrees of stress.

It should be noted that the demand data set created does not consider origins and destinations nor is it able to fully realize fleet refueling needs as vehicles registration does not always align with fleet location. As such the results of the model will be only used to site public refueling stations based mostly upon the presence of truck VMT. An alternative is to use TAZ zone data to consider the origins and destinations of truck VMT [24]. These data, however, are region limited and do not specify vocation which is important when considering the adoption of FCETs.

3.2 Candidate Hydrogen Refueling Stations

In this section, a set of candidate hydrogen refueling stations are located to provide viable locations where, if cited, a hydrogen refueling station could viably be constructed and serviced. Due to the current lack of HRSs for HDVs and no current examples to base them upon, the locations and performance of candidate stations may have to be altered in the future.

3.2.1 Locating Candidate Hydrogen Refueling Stations

The set of locations for candidate HRSs needs to meet two key requirements. Firstly, the station must be accessible by HDVs. In California, not every road is truck accessible or truck legal. If the sited station has no truck accessible routes to it or any viable connections to a highway, then it will not function as an HDV HRS. Secondly, the station must be in a location that could receive the proper permits for construction. For example, a station sited in the middle of a residential zone would be impossible to build due to zoning laws within California, aside from the dangers and disruption a heavy-duty refueling station would cause the residential community.

To simultaneously meet both requirements, the current set of public diesel truck stops in California was used to designate the set of candidate hydrogen refueling stations. While more viable locations may exist for hydrogen refueling stations, this set of 675 stations not only meets the two requirements of being road accessible by trucks and legally zoned locations, but it also ensures that these locations are already being utilized by current trucking routes. This set of candidate stations can be seen in Figure 3.5.

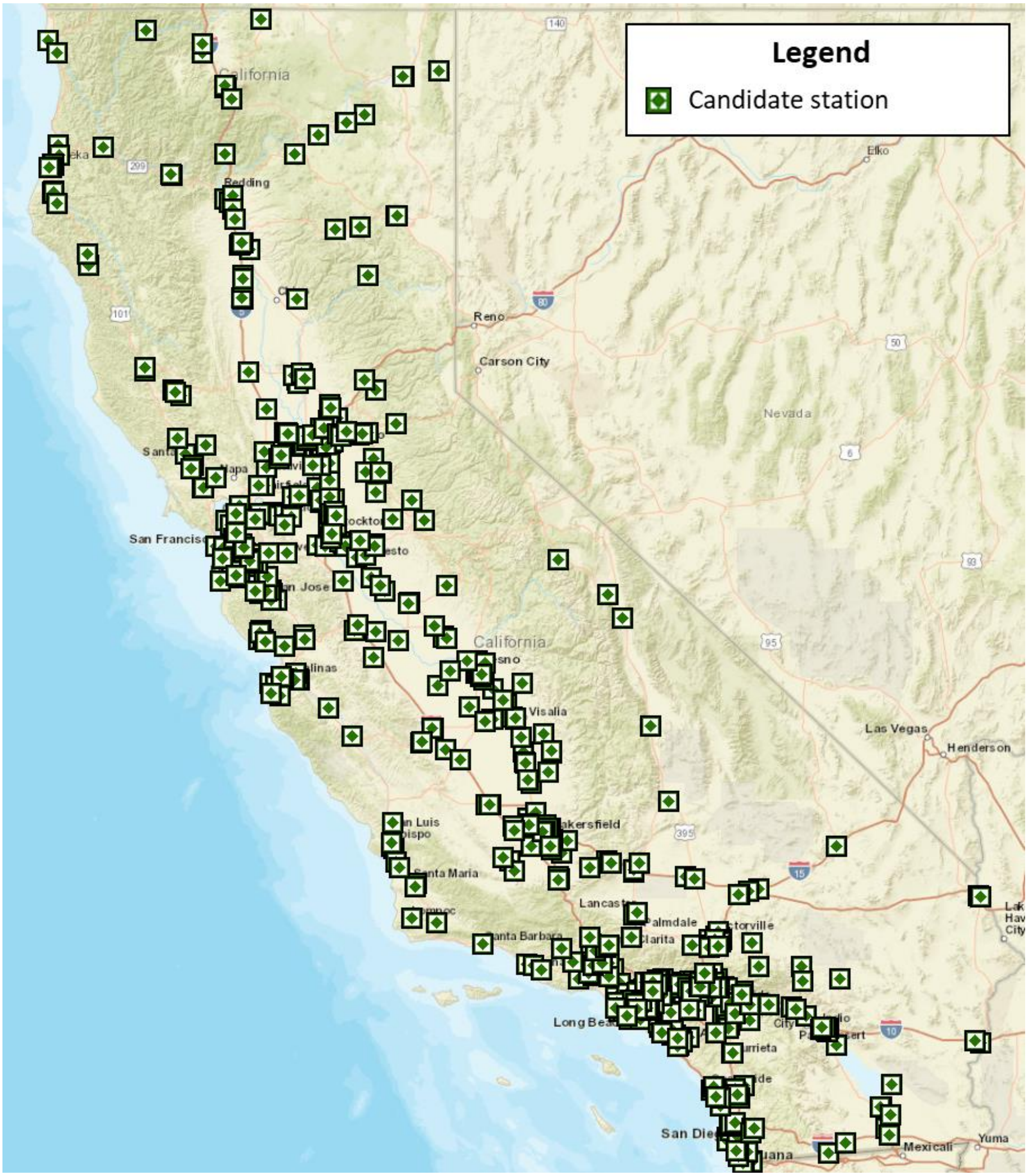

Figure 3.4: Candidate HDV HRS locations based on current diesel truck stops

No private truck stops are used as candidate stations for several reasons. For one, this methodology does not address the siting of private HRSs, it is not the problem being addressed. Second, the vast majority of truck refueling within California occurs at public truck stops and not at private locations and it is believed that public refueling has the best potential for FCETs [35].

Some concerns with using current diesel truck stops is the impact on disadvantaged communities, both the station itself and the local traffic associated with the station. It would be a disservice to disadvantaged communities to increase density of truck stops and therefore truck traffic within disadvantaged communities. Not only the emissions of trucks, of which FCETs still have some mostly from brake and tire wear, but the traffic itself of large trailer trucks can further disadvantage a community. Truck traffic not only can slow down transit in an area, but it can also pose a danger to the community population. Therefore, when siting HRSs, it will be important to prioritize replacing current diesel truck stops within disadvantaged communities with HRSs to reduce diesel truck flow through the communities, as well as to site new HRSs entirely outside of disadvantaged communities. See Figure 3.6 to see the current set of truck stops within disadvantaged communities. Currently, 236 out of 675 stations are within disadvantaged communities. This means while 25% of communities are disadvantaged communities, 35% of public HDV fueling stations are within disadvantaged communities. Current HDV fueling disproportionally affects disadvantaged communities.

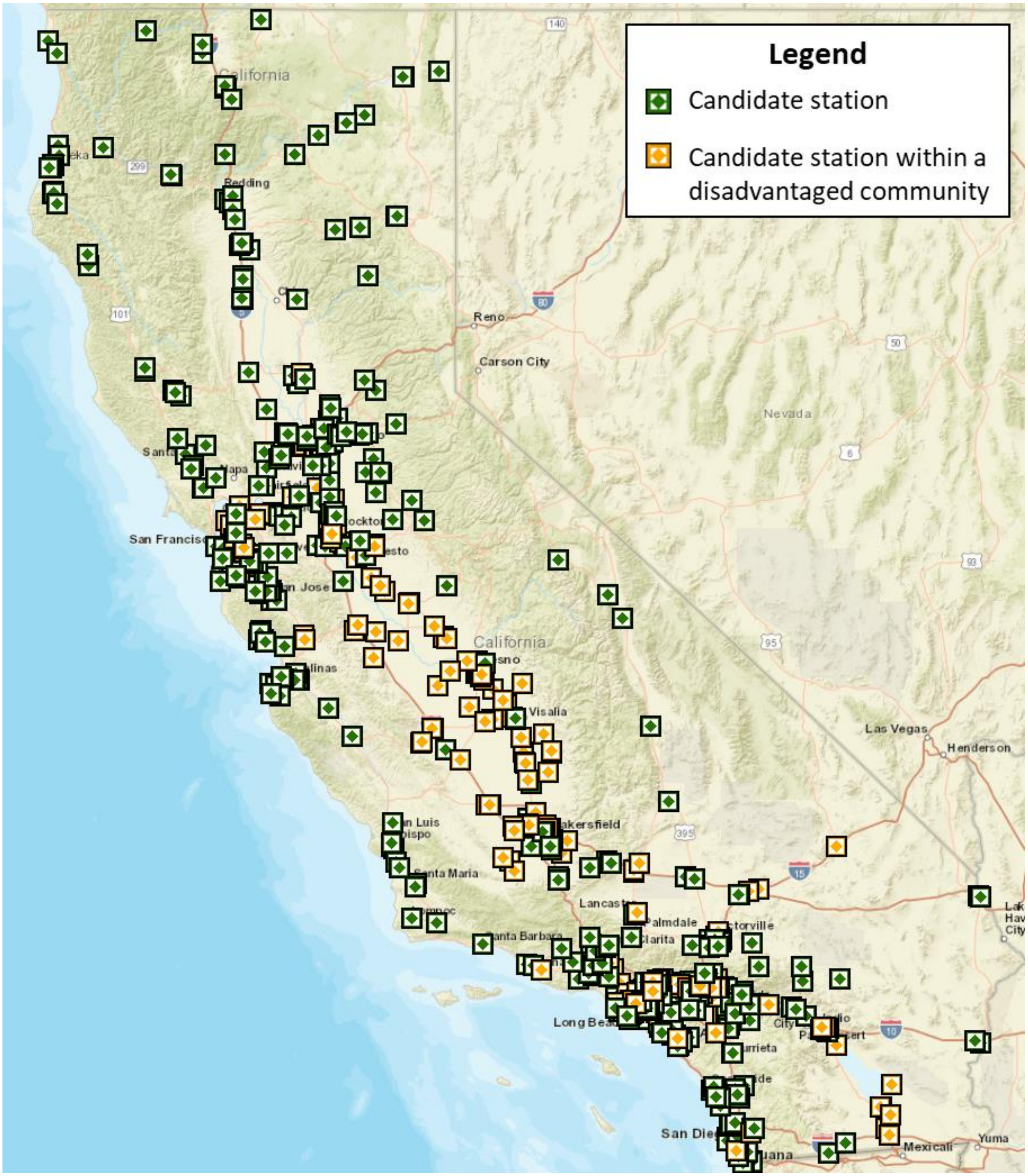

Figure 3.5: Candidate HDV HRSs in relation to disadvantaged communities

An additional concern of current diesel truck stops is the proximity of some to buildings such as hospitals and schools. The goal of newly sited stations should be to locate the stations away from those who are sick and young to reduce the impact of truck and station emissions as well as reduce traffic accidents and incidents near to these facilities.

3.2.2 Attributes of Candidate Hydrogen Refueling Stations

The refueling capabilities of the candidate stations are important in siting HDV HRSs. If stations have a high performance, then fewer stations will be required to meet total demand. Unfortunately, with no publicly operated HDV HRSs currently deployed, there is a lack of data on the performance of HDV HRSs. Most of the performance metrics of HDV HRSs must be estimated based upon expert feedback, current LDV HRSs and current diesel truck refueling infrastructure.

The most important metric for this model is the station's service capacity, or how many kilograms of hydrogen the station can dispense within a day (kgH2/day). While it is known that many light-duty vehicle HRSs can serve 300+ kgH2/day, it is assumed that HDV HRSs will be built with greater service capacity and greater resiliency granting higher service capacities than LDV HRSs. Based on expert feedback from a hydrogen refueling company, three station sizes are selected to represent realistic HDV HRS configurations:

Small station – 5,000 kgH2/day

Medium station – 12,500 kgH2/day

Large station – 18,750 kgH2/day

However, due to the novelty of HRSs, HDV HRS will likely experience similar reliability issues as current LDV HRSs face. LDV HRSs are experiencing many instances of station downtime and often underperforming their nameplate capacity due to many factors such as hydrogen supply issues and equipment failures. With expert feedback, stations are assumed to have an actual capacity that is 80% of the nameplate capacity of the station. This also helps to ensure that sited stations are not overburdened. An overburdened HDV HRS could have decreased reliability, and reliability of HDV HRSs is one of the most important factors in enabling the deployment of FCET fleets. Therefore, the adjusted station capacities are as follows:

Small station – 4,000 kgH2/day

Medium station – 10,000 kgH2/day

Large station – 15,000 kgH2/day

For the sake of this model, it is assumed that these stations operate reliably at their adjusted station capacities. As future work is conducted and real HDV HRS data starts to be released, these numbers, both the nameplate and the capacity adjustment, may need to be adjusted.

The next most important attribute of HDV HRSs is the service range. Service range is the furthest distance a vehicle would be willing to drive to refuel at the HDV HRS. This factor is mostly impacted by FCET driving range, refueling needs of FCETs, and where the station is location along truck routes. Unfortunately, no studies have been done to quantify the effective service range of an HDV HRS. Estimates can be made based on the performance of HDVs and the desired performance of a complete HDV HRS network.

HDVs operate over a large area, especially when considering long haul trailers which can drive hundreds of miles a day. FCET range has been shown to be greater than 200 miles per full tank with a full load, and likely reach ranges greater than 400 miles per refuel [12], [34], [36]. Being conservative, these numbers would imply a service radius of 100 miles for HDV HRSs, allowing a truck to depart and return to the station in one trip, and be able to leave one station and make it to the next sequential station. However, station reliability being a potential issue as well as the limitations that a larger distance between stations makes 100 miles too high a number. Truck drivers cannot afford to drive too far off route and if one station is down it may be impossible to reach the next station for a refuel.

The FHA has released guidelines that request electric charging infrastructure every 50 miles along all major highways [37]. This is effectively a 25-mile service radius for electric charging infrastructure. Since HDVs need less refueling infrastructure than light-duty and FCEVs in general need less frequent infrastructure, the service radius was doubled to 50 miles for this showcase. Similarly, this can be understood as cutting the 200-mile range of a fully loaded FCET in half to get 100 miles between stations or a 50-mile demand radius. See Figure 3.7 for a visualization of the service area of a random station as calculated by the model. It should be noted that most stations sited in the upcoming results serviced an area smaller than the 50-mile radius offered due to either stations running out of service capacity or other stations sharing service area such as in areas with dense traffic.

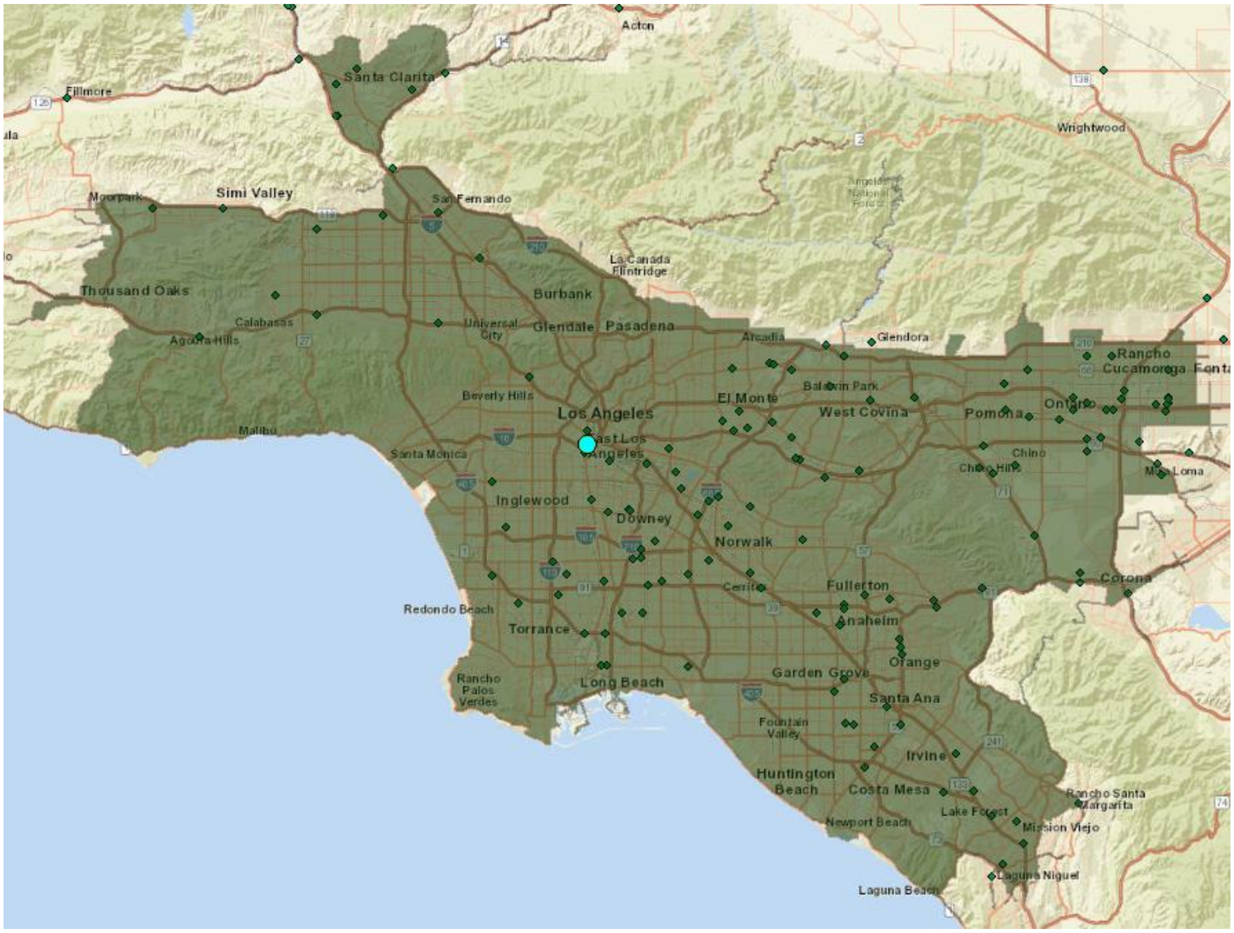

Figure 3.6: 50-mile service area of a candidate HDV HRS within Los Angeles

3.3 Truck Driving Network

In this section, the truck driving network used is detailed. A driving network is important because it is what establishes routes, travel distances, travel times, and station accessibility. Furthermore, having a driving network connects all demand points to roadways which otherwise were simply a grid of sqkm points and since demand points are supposed to represent on road vehicles requiring refueling, having them snap to roadways makes that representation more accurate. A driving network is also required for the network analyst feature of ArcGIS which is used to perform the siting optimization.

The STREET network developed by Stephens-Romero in [38] serves the same role that the truck driving network seeks to serve. It has every street and roadway within California including driving speeds and road junctions. However, this network could not be used for heavy-duty vehicles as not every roadway within California is truck legal nor does the network contain truck speeds. Therefore, a new network better suited for HDVs but with the same functionalities as the STREET network is needed.

The network that met these conditions was the Freight Analysis Framework 5 (FAF5) produced through a partnership between the Bureau of Transportation Statistics and the Federal Highway Administration. This network has every truck and freight highway and roadway throughout the entirety of the continental US and Canada. This means that the roadways in the network are all truck accessible, all proper truck junctions are modeled, and truck speeds are incorporated within the model for proper drive times. Using this network, proper drive routes can be established from refueling demand to sited stations. Figure 3.8 shows the network when reduced to be within the borders of California. Figure 3.9 compares the STREET network and the FAF5 network near the ports of Long Beach and Los Angeles.

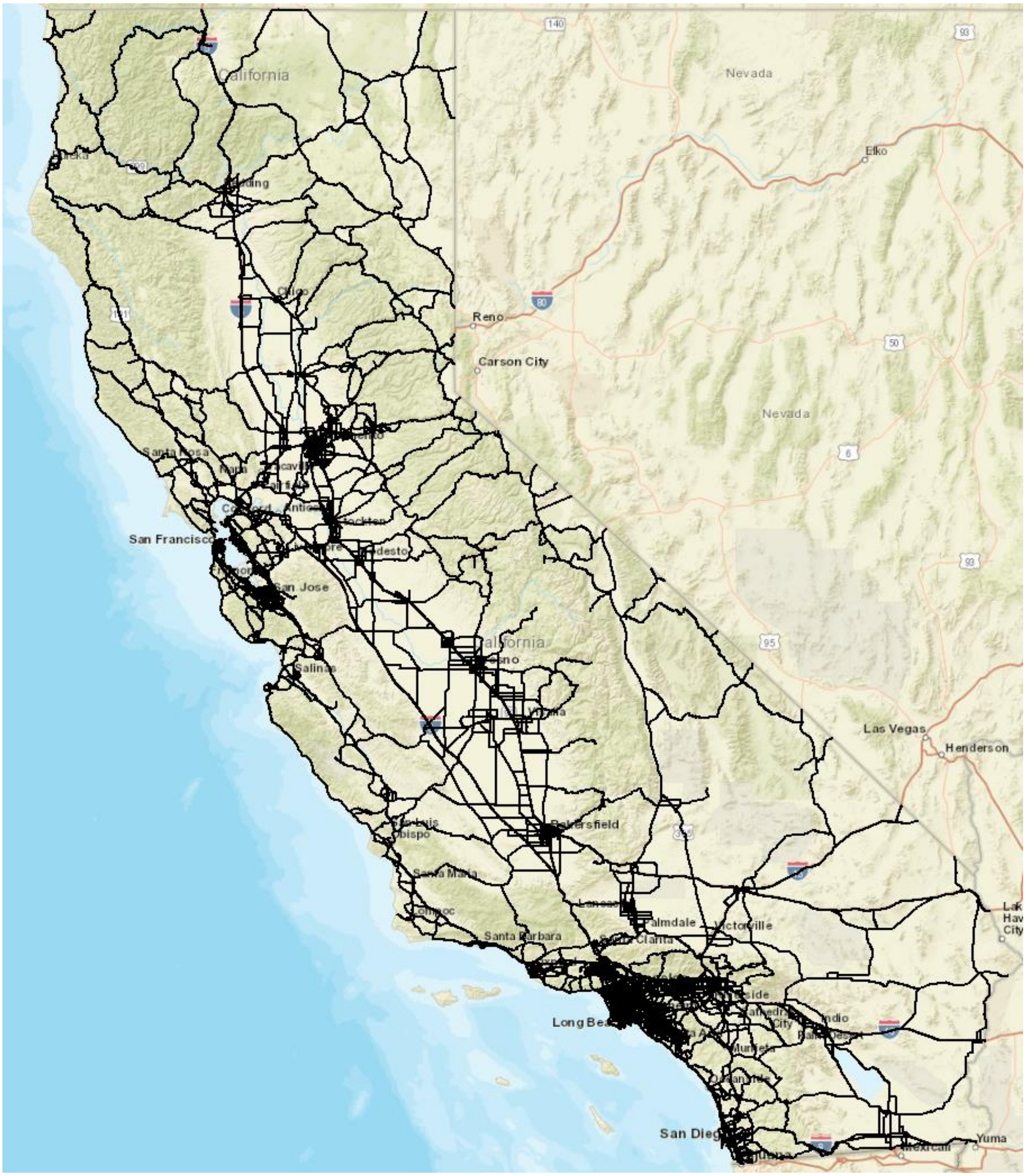

Figure 3.7: FAF network within California

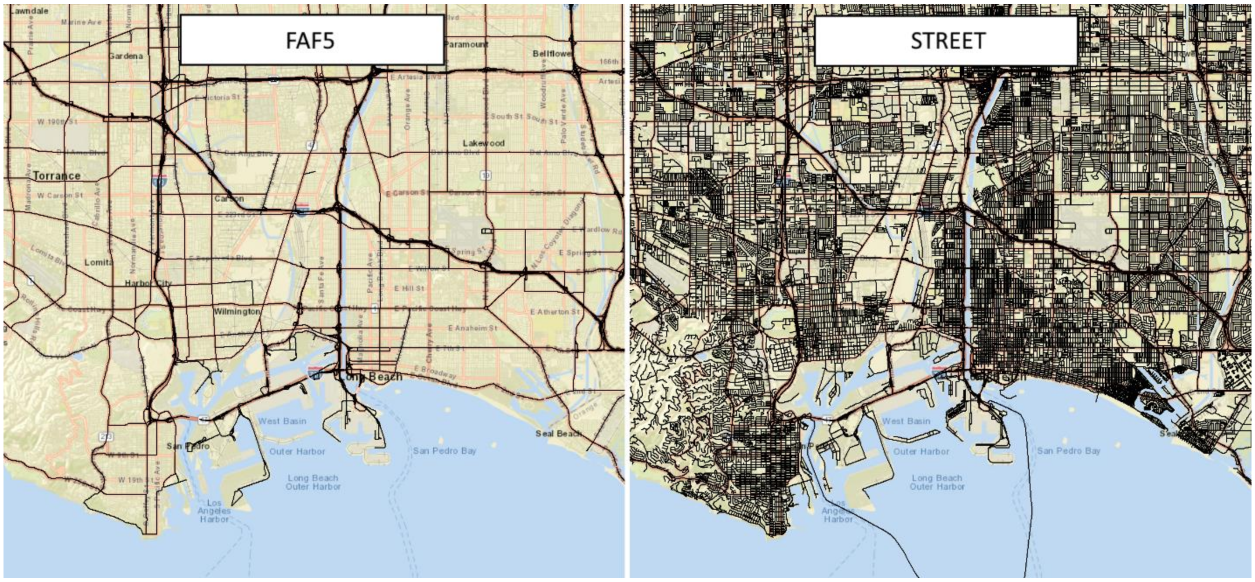

Figure 3.8: FAF5 HDV network (left) and STREET LDV network (right)

3.4 Network Analyst Model

The network analyst model is developed within the toolbox of ArcGIS. ArcGIS is a widely used GIS software developed by Esri. It has an extensive GIS database of land use data and a large array of tools that is crucial for many spatially resolved problems. The main toolbox used within ArcGIS for this thesis is the network analyst toolbox.

3.4.1 Creating the Network Analyst Model

This section details the combination of Sections 3.1-3.3 into one congruent station siting model. As with the methodology in STREET, the network analyst feature within ArcGIS is utilized to perform functions on the network such as “location allocation”, “route”, and “service area”. The primary functionality used with this model is the “location allocation" feature which will take a set of given demand points on the network and allocate them to a set of facilities points based upon factors such as the shortest or fastest route, or remaining demand capacity of the facility. The "route" feature can be used to analyze the shortest or fastest path along the network between two points which can be useful for testing specific use cases of the station network (i.e. the best route from the port to a nearby potential HRS). The "service area" feature gives a good representation of the geographic region a station can cover if it is not in competition with other stations and it has not reached its demand capacity.

The "location allocation" feature is the primary motivation of the model though as it allows a simulated demand to be allocated to the facilities. This feature can be used to take a set of existing or chosen facilities and analyze their coverage and utilization when local demand is allocated based on either shortest drive time or shortest route distance. Alternatively, this feature can be used to take a set of candidate facilities and the "location allocation" tool will optimize the location of each of the stations and subsequently allocated demand to these facilities as if they were the chosen facilities as mentioned before. Finally, this tool can take some required facilities that either already exist or have been chosen, and then take a set of potential stations. It will then allocate demand to the required facilities and then run the optimization for the remaining potential stations to build out the rest of the network and then allocate the remaining demand to the remaining stations.

In the case of this model, the term "facility" has been replaced with "HRS" and the demand is hydrogen demand. The candidate stations are the ones detailed in section 3.2.1, the current existing public diesel truck refueling stations. These are set as "candidate" stations although a select few can be denoted as “required” stations to specify stations that are planned, built, or being studied. The demand is simply the square kilometer hydrogen demand points generated within section 3.1. When loaded in, the stations and the demand points are snapped onto the network for calculations such that the routes are all along the FAF5 network. See Figure 3.10 for an example of both the 675 candidate stations in California and a set of example demand points being loaded onto the network in preparation of a “location allocation” simulation run.

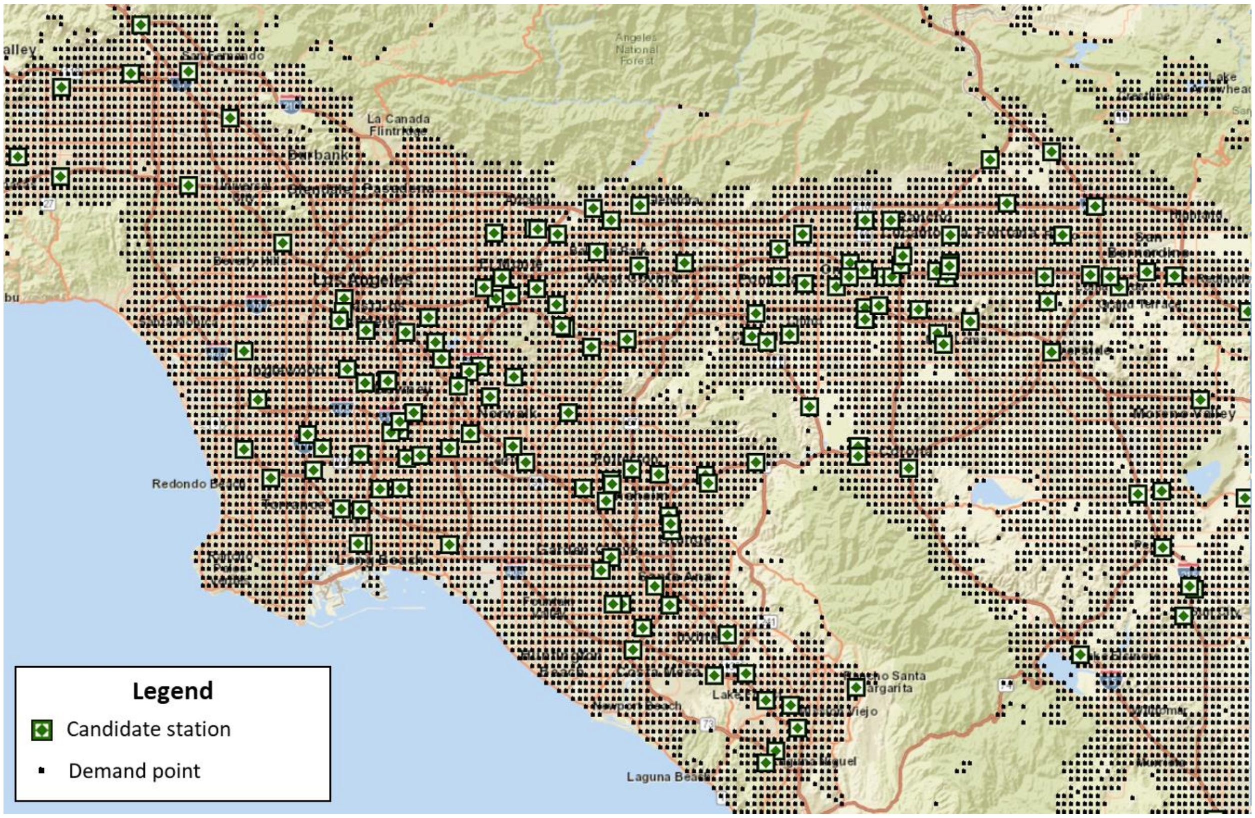

Figure 3.9: Candidate HDV HRSs and demand points as inputs for location allocation

3.4.2 Gathering Results from the Network Analyst Model

This section further details specific ways this model can be used to gather meaningful results for HDV HRS siting. This section will not include any specific results but rather describes the capabilities and tools provided by the model and how they could be used to garner future results.

“Location allocation” runs can be configured to have “max capacitated coverage” or “max coverage” as well as a few other options. “Max capacitated coverage” is the most important as it shows (1) how stations will perform with a given certain capacity and (2) if sited stations are underutilized or if they have reached their service capacity before local demand is fully serviced. Using this configuration allows station planners to see how stations will perform as well as help realize how many stations should be built to fully meet the spatial demand. It could also help station planners to properly size their station. If a “max capacitated coverage” run shows that a station designed to service 100 trucks a day is only being used to service 30 trucks a day, station planners could likely reduce the planned sizing of that station. Alternatively, if a station is servicing at its maximum capacity, station planners could think about adding more stations or building the station larger to handle more demand.

While “max capacitated coverage” is very important, “max coverage” simulation runs can also be useful conduct. “Max coverage” removes the capacity value from stations and allocates demand within the service area of stations to the nearest station. Performing these runs can reveal where demand wants to go if stations did not run out of capacity. These results can be particularly useful when comparing to “max capacitated coverage” results when stations are reaching maximum capacity. This can give insight into which stations are picking up the remaining demand and potentially where an additional station could be added to alleviate some of the excess demand on the over utilized station such that it reaches a healthier, more sustainable, utilization rate. Doing “max coverage” simulation runs alone to site stations is insufficient as it sites station density with no regard for demand density.

3.5 Summary of Assumptions

To support the rollout of FCETs, hydrogen refueling infrastructure must be strategically placed to efficiently service the desired routes and operations of FCETs. This model was developed using VMT projections, FCET adoption projections, a list of candidate stations, and a real driving network to simulate truck refueling and best provide a spatially resolved network of HRSs. The assumptions of the model are summarized below.

Model assumptions:

- There are no private truck HRSs, all stations sited for the projected demand are public.
- Current public truck stops offer valid locations for the construction and permitting of a HRS.
- Truck driving patterns will not change with the adoption of FCETs, all routes for a given vocation of current diesel trucks are assumed to be routes of

future FCETs. This means the demand does not spatially change in the transition of fuel types.

- Truck refueling happens evenly over any given 24-hour period, there are no time periods of increased or decreased refueling demand.
- Traffic and speed do not affect the efficiency of trucks. VMT is converted with flat efficiency.
- Truck weight and vocation are not considered for vehicle efficiency.
- Truck refueling demand is weighted more heavily onto zip codes where more vehicles are registered to provide a better sense of locating stations for fleet bases.
- Truck refueling demand is located more heavily in population dense zones where census data points exist, meaning some linehaul routes may be underrepresented.
- Hydrogen production and delivery is not considered a limiting factor for station deployment or performance.

CHAPTER 4: RESULTS AND DISCUSSION

The results presented are to be understood as examples of the capabilities of the model and station siting methodology developed. All results presented are for California in the projected year of 2025. See methodology section 4.1 for how these projections are made. The results were selected to demonstrate how the model is to be used in the process of station siting and the impact of varying the different parameters of the model. The goal of the model is to help transportation planners, fleet owners, and station owners effectively determine and predict the best locations for siting HDV HRSs. While the results presented here should be expanded upon both in years simulated and continue to have parameters adjusted as new information is garnered, they showcase a first usage of the model and highlight the capabilities of this methodology.

As discussed in section 4.1 of the methodology, both a high and low demand case were generated for 2025. These projections are based on California's targets for zero emissions vehicles and are therefore aggressive targets. Due to practical difficulty of reaching and servicing a high demand case by 2025, which is within 2 years of this work, only the low demand case was used for this results section. The lessons learned from the results would still apply to the high demand case as the spatial distribution of the demand does not change between the high and low demand cases. Thus, it can be assumed that simply scaling station size appropriately would net the same results. The primary focus of these results is in highlighting the capabilities of the model. Future work will be done to create a robust rollout plan for the future of California's FCET refueling demands using this methodology.

There are seven scenarios explored with varying number of stations, station capacity, and site requirements. The criteria that these scenarios are evaluated by are demand coverage and station utilization. Demand coverage is a percentage of the total demand that is allocated to hydrogen refueling stations. If a scenario has a demand coverage of 75%, then the remaining 25% of the demand in California is unable to be serviced in its normal operation by the provided stations. A low demand coverage means that either the fleet of hydrogen heavy duty vehicles must operate a limited set of routes as opposed to the current diesel network or the network of stations is not robust enough to support the anticipated number of vehicles. While there may be enough total hydrogen dispensing capability to support all of the predicted demand, demand coverage may still be low if the spatial distribution of stations is not effective. Achieving 100% demand coverage is ideal but will likely not occur until later years such as 2045 as California is large and may take 50-100 stations to provide the proper spatial coverage of the entire state while still meeting demand. However, a demand coverage of 90% or higher can be interpreted as a successful deployment of stations as at least 90% of normal trucking operations can be performed by FCETs. A demand coverage of less than 75% is seen as an ineffective network of stations as the operations of FCETs is too greatly limited and the network cannot likely support the daily operation of the anticipated number of FCETs.

The other parameter by which the scenarios can be understood is station utilization. Station utilization shows how much of a station's daily hydrogen output potential, or capacity, is being used to service the demand. Stations at 100% utilization are at risk of being overutilized and experiencing excess demand whilst stations below 50% utilization are not economically effective as the station was overbuilt or built in an area where there was not enough demand to warrant its existence. Due to the small amount of hydrogen refueling demand in 2025 it is difficult to justify stations in some of the more rural areas of California. While the station may provide a pivotal connecting refueling location for trucks in the future and help increase total demand coverage, it would likely experience such a low utilization in 2025 and in coming years that its deployment cannot be justified until future years. Hence optimizing the deployment scenarios means yielding the highest demand coverage while maintaining a high station utilization. It should also be noted that, while not analyzed within the scope of this work, HDV HRSs are expensive to construct. So optimized scenarios should also consider having a lower number of stations at the cost of coverage and utilization to optimize the scenario cost.

As discussed in section 4.2.2, there are three categories of station size considered by this methodology. However, large refueling stations are not being considered for 2025 due to the expensive cost and novelty of HDV HRSs. While these larger stations will likely see deployment in 2035 and beyond, the first rollout of stations are expected to be mostly small and medium sized stations as the first wave of fleet adopter buy into FCETs. It may be noted that stations deployed during the initial years of 2025 and 2030 may be upgraded in size and technology as the years progress and demand local to the station site increases.

4.1 Scenario 1: five stations with 10,000 kgH2/day service capacity

Scenario 1 explores the simplest solution to the station siting problem. To meet the total demand of 48,607 kgH2/day, this scenario sites five 10,000 kgH2/day (medium) stations. These five stations could service a maximum of 50,000 kgH2/day. The stations are therefore, in dispensing capacity, capable of servicing 1,393 kgH2/day more than the projected demand. However, due to the 50-mile service radius limitation these five stations would not be able to provide full coverage of California's FCET refueling demands. Therefore, this scenario informs the performance of the smallest feasible deployment of stations that could, in theory, meet 2025's FCET refueling demand.

This scenario has no site requirements meaning that no particular stations from the candidate set are required for the solution. The medium size of stations was chosen as this allows the least number of stations to be deployed to cover the total demand. The results are visualized in Figure 4.1 with one station near the ports of Oakland, one station north of Fresno on State Route 99, two stations within Los Angeles County, and one in Riverside County on Interstate 10. A subsection within southern California in the area of highest demand is visualized in Figure 4.2.

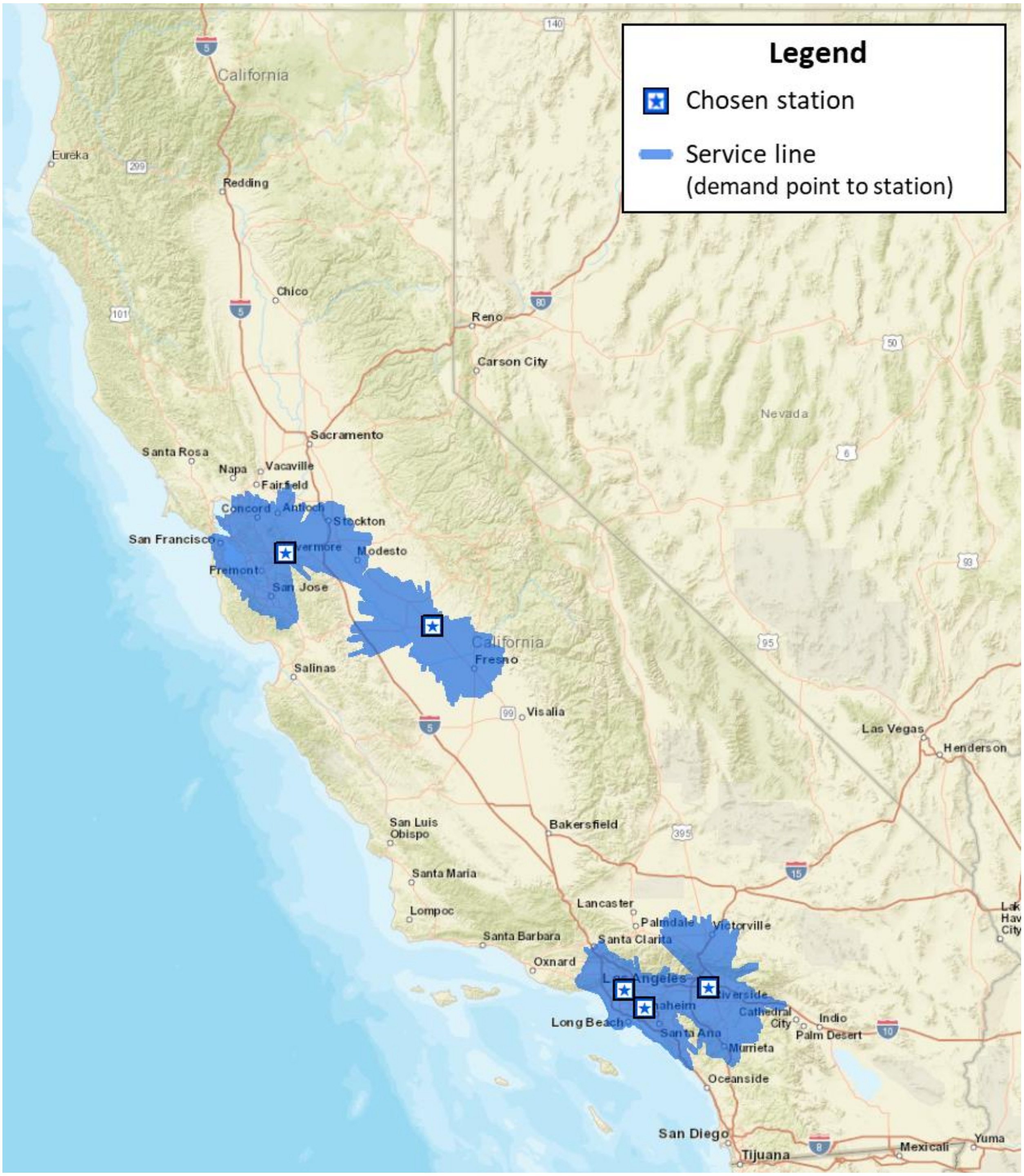

Figure 4.1: Scenario 1 - five medium stations (2025, low demand)

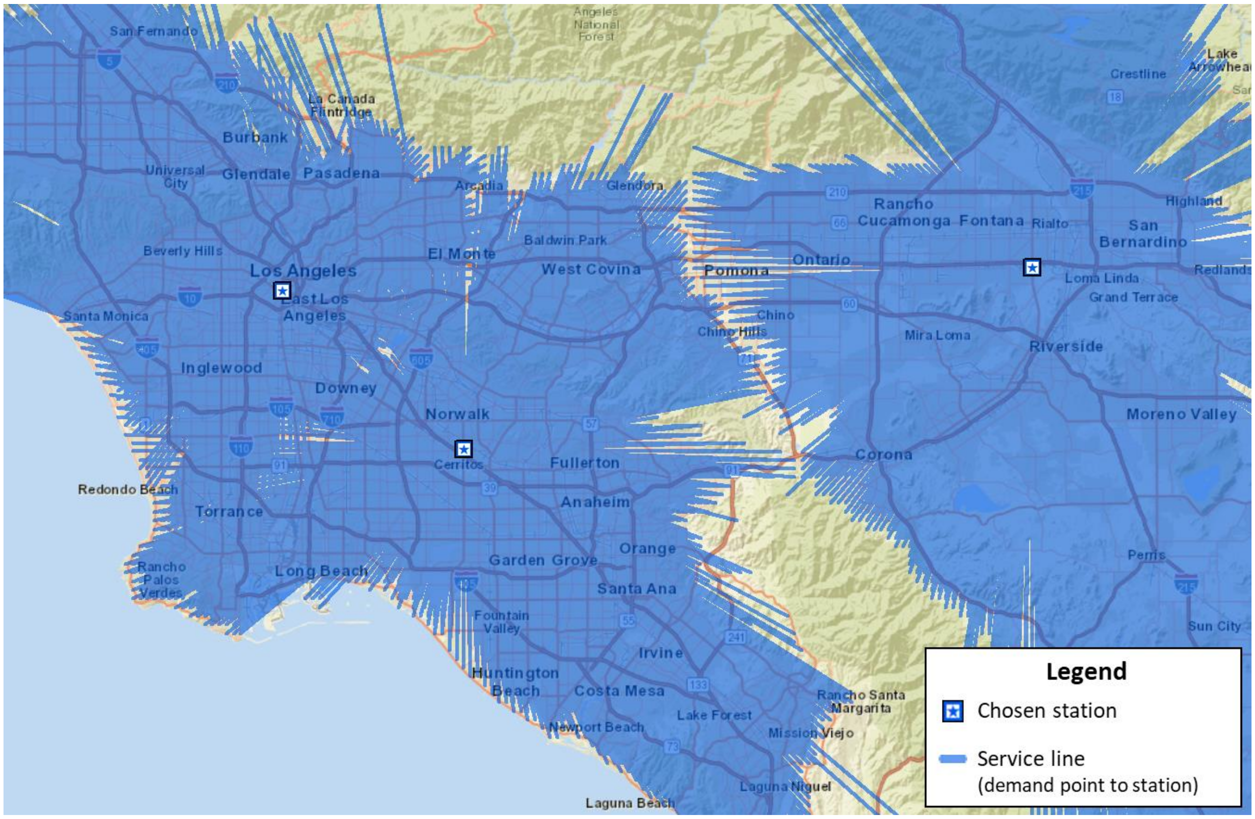

Figure 10: Scenario 1 zoomed to a southern California region

In this scenario, the five stations service a total of 39,510 kgH2/day which is 81.3% of the total demand and 79.0% of the stations' service capabilities. The least utilized station only serviced 3053 kgH2/day, operating at 30.5% of total efficiency. Three of the stations were operating at about 95% utilization. See Table 4.1 below for the station performance data.

Overall, these five stations create quite a successful HDV HRS network. As the total demand serviced is greater than 75%, this scenario creates a wide enough coverage to allow a substantial adoption of FCETs by fleet operators. The 18.7% of remaining unserved demand is largely outside of major urban zones and fleet owners could strategically adopt

FCETs only for job routes that lie within the service ranges of the deployed stations. The total utilization of this scenario of 79% is also quite high, however the Merced station falls below 50% utilization at 30.5% which fails the criteria for an economically successful station and the Downtown Los Angeles, Norwalk, and Bloomington stations all are above 95% utilization which heavy demands on their performances which creates concerns over station reliability.

As a first scenario, it is quite successful, however the five stations do suffer from total area coverage of California and are prone to many reliability problems. Scenario 2 explores how having more small stations can increase total coverage, increase individual station performances, and decrease network reliability risks.

Table 4.1: Scenario 1 station performances (2025, low demand)

Location	Adjusted Capacity [kgH2/day]	Demand Serviced [kgH2/day]	Utilization
Livermore	10,000	6,797.3	67.97%
Merced	10,000	3,053.5	30.54%
Downtown Los Angeles	10,000	10,000	100.00%
Norwalk	10,000	9,760.5	97.61%
Bloomington	10,000	9,898.5	98.99%
Total	50,000	39,509.8 (81.28% of total demand)	79.02%

4.2 Scenario 2: thirteen stations with 4,000 kgH2/day service capacity

This scenario differs from Scenario 1 by deploying thirteen small stations instead of five medium capacity stations. This means a station capacity of 4,000 kgH2/day instead of 10,000 kgH2/day. Similar to Scenario 1, this scenario attempts to meet the minimum number of stations needed by just enough stations to cover the 48,607 kgH2/day demand. In total the thirteen stations are capable of servicing 52,000 kgH2/day or 107% of total demand. This scenario should display how building out a HDV HRS network with many small stations differs in performance from a few larger stations as explored in Scenario 1. It is expected that distributing the demand load onto more stations will result in a higher coverage of the total demand and a decrease in the reliability risks of the network's performance. The results are visualized in Figure 4.3 with a subsection of southern California shown in Figure 4.4. Mostly the extra stations, as compared to Scenario 1, are used to fill out Southern California with more granularity, however a connecting station on the state route 99 is also sited as well as a station within San Diego.

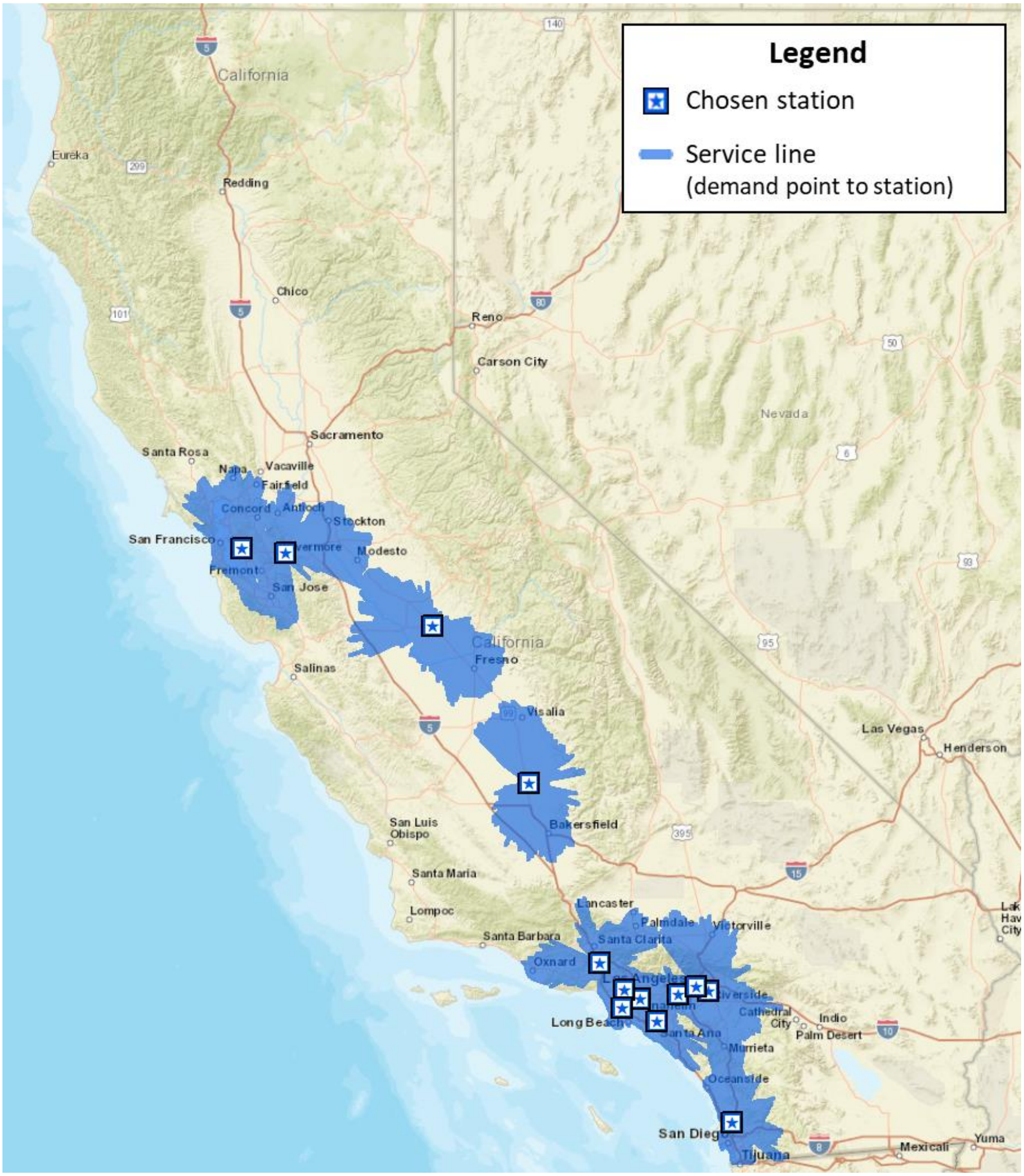

Figure 11: Scenario 2 - thirteen small stations (2025, low demand)

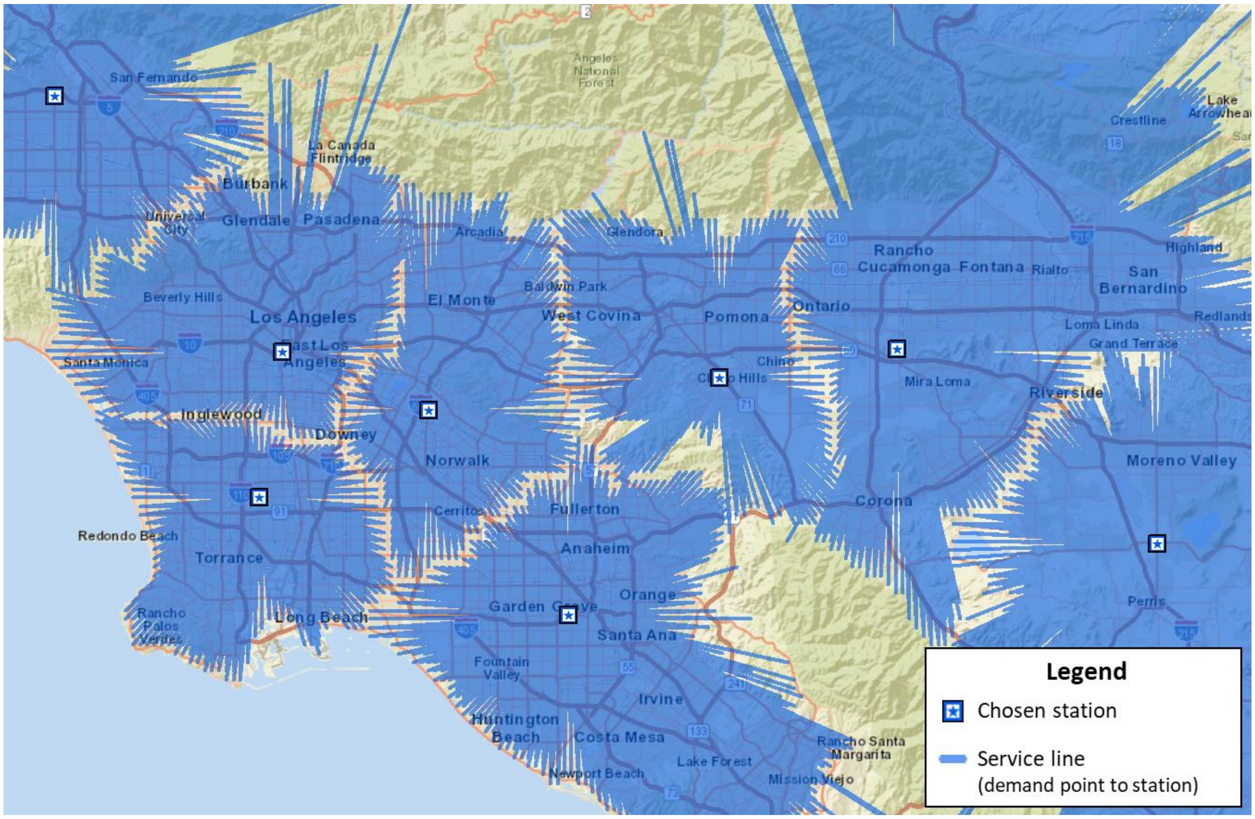

Figure 12: Scenario 2 zoomed to a southern California region

The thirteen stations service 44,940 kgH2/day to refueling trucks or 92.5% of the total hydrogen demand. As compared to the five medium stations in scenario 1, total coverage is 11.2% higher in this scenario and average station utilization is 5.4% higher at 86.4%. Additionally, with more stations, the demand is spread more evenly between stations with the lowest station utilization servicing 2301 kgH2/day or 57.5% utilization, which is still considered a successful station. Only two stations were under 70% utilization meaning efficient usage of refueling stations, however 6 stations experience over 95% utilization which could imply that some of these stations are at risk of being overburdened and having reliability issues. See Table 4.2 for individual station performance data.

Overall, this scenario performs well. It has a high total coverage for 2025 and the stations deployed are well utilized. If a state or private budget could fund the higher number of stations as well as hydrogen production properly sourced and delivered to each location then this scenario would be preferred over Scenario 1. An additional benefit beyond what the numbers show is that, especially within southern California, having a higher density of stations means higher network resiliency. If one station goes down FCET trucks can easily reroute to another local station. As opposed to Scenario 1 in which, if 1 station goes down, 1/5th of the network goes offline, or worse regionally.

Note, however, despite the success of this scenario, it leaves 7.5% of the demand within California for 2025 unserved and due to the number of stations at max utilization it does not support much room for growth and has resiliency issues. Scenario 3 and Scenario 4 look at increasing the number of stations or station capacity respectively from this scenario to understand the implications of overbuilding the network to improve coverage, resiliency, and leave room for unexpected increases in FCET refueling demand. It is expected that station utilization will decrease in those scenarios as total servicing capacity increases and demand remains unchanged.

Table 4.2: Scenario 2 station performances (2025, low demand)

Location	Adjusted Capacity [kgH2/day]	Demand Serviced [kgH2/day]	Utilization
South Oakland	4,000	3,973.1	99.33%
Livermore	4,000	3,078.5	76.96%
Merced	4,000	3,053.5	76.34%
Delano	4,000	2,301.5	57.54%
San Fernando	4,000	3,166.3	79.16%
Downtown Los Angeles	4,000	4,000	100.00%
Pico Rivera	4,000	4,000	100.00%
Gardena	4,000	4,000	100.00%
Garden Grove	4,000	3,428.5	85.71%
Chino Hills	4,000	3,742.3	93.56%
Rancho Cucamonga	4,000	3,816.9	95.42%
Bloomington	4,000	4,000	100.00%
San Diego	4,000	2,379.4	59.49%
Total	52,000	44,940.0 (92.46% of total demand)	86.42%

4.3 Scenario 3: fifteen stations with 4,000 kgH2/day service capacity

This scenario aims to expand upon Scenario 2 by adding an additional two stations. This will provide insight into how increasing the number of stations can help meet the remaining 7.5% of the demand that thirteen stations were unable to service. This is to understand how the model performs when potentially overservicing California's demand as well as to understand the tradeoff between station utilization and total statewide coverage within the early development of California's HDV HRS network. Aside from number of stations, all scenario parameters remain the same as Scenario 2. The results are visualized in Figure 4.5 and a subsection of southern California is shown in Figure 4.6.

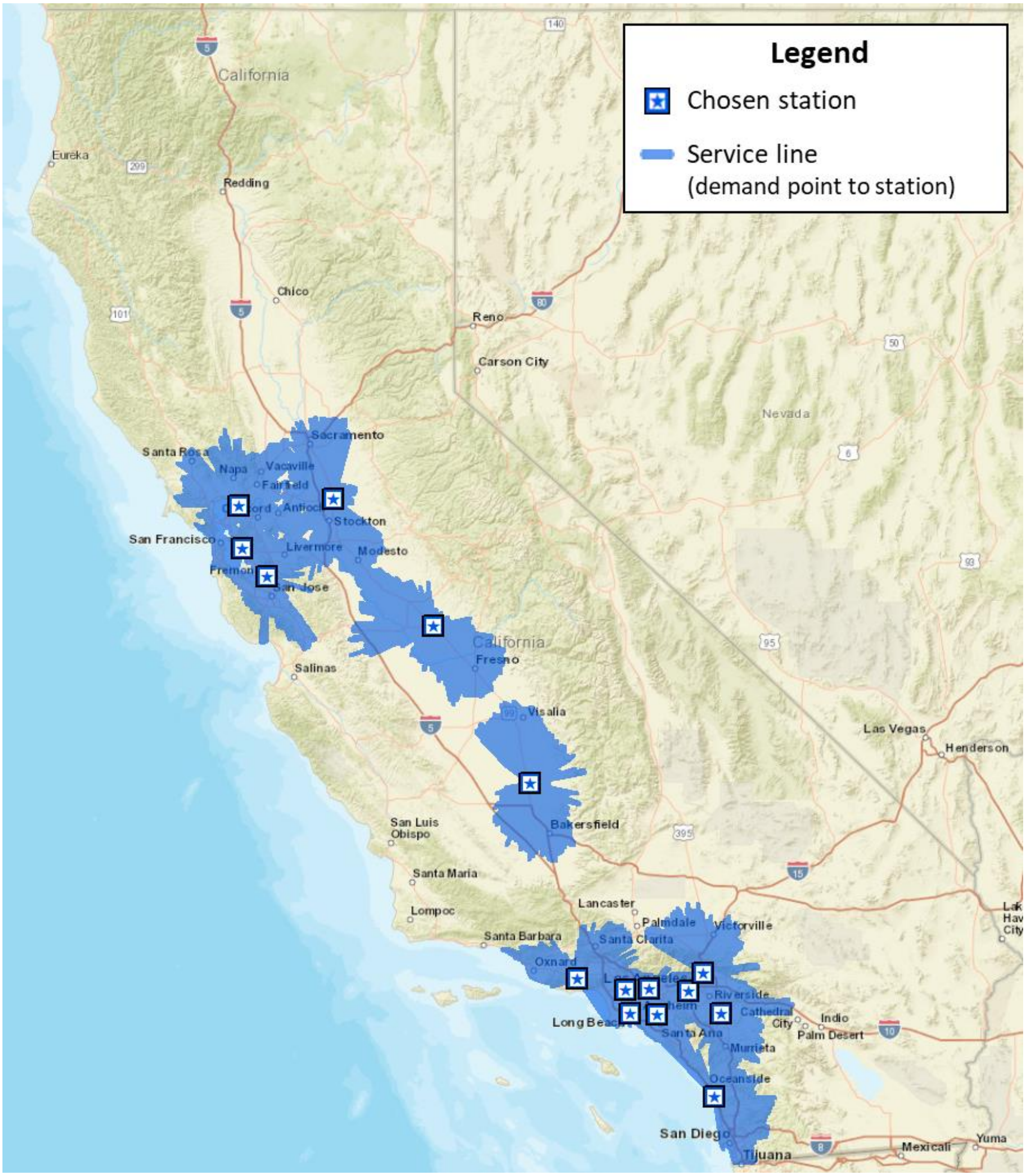

Figure 13: Scenario 3 - fifteen small stations (2025, low demand)

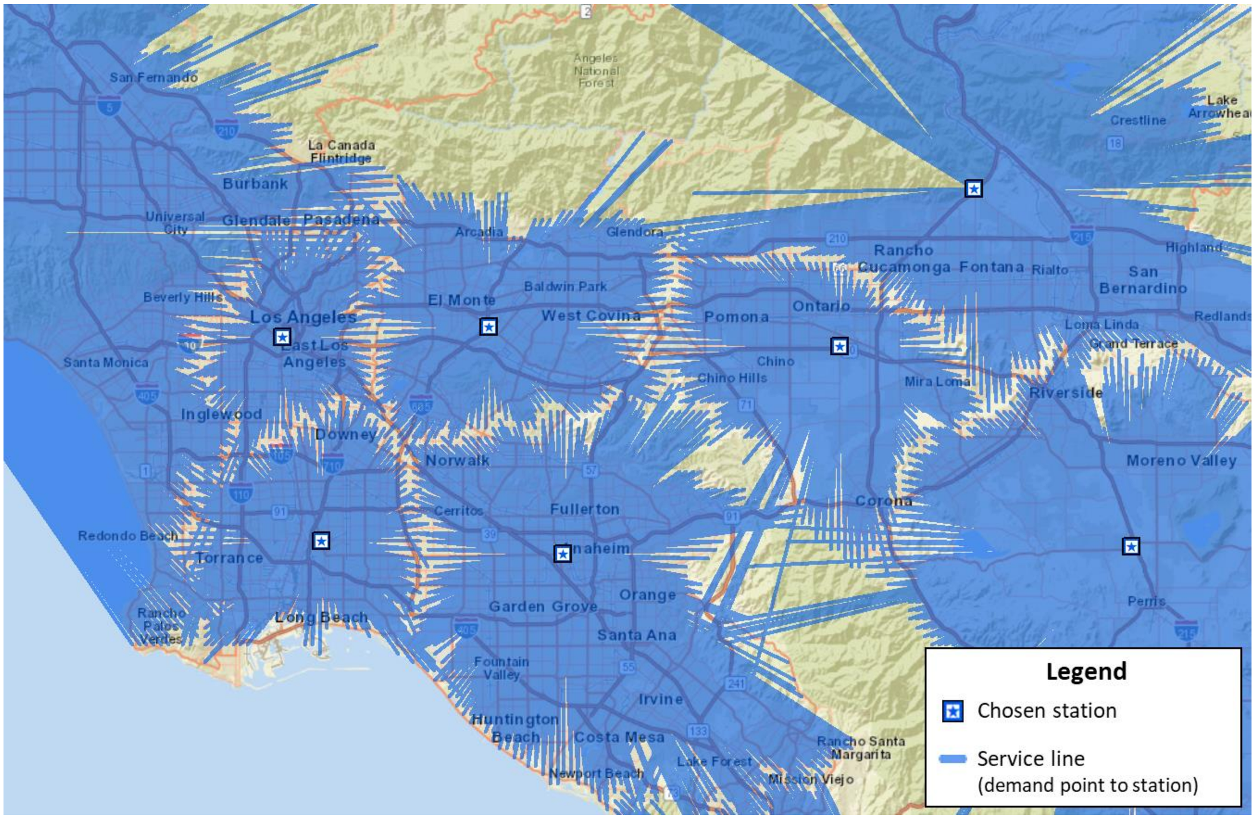

Figure 14: Scenario 3 zoomed to a southern California region

The fifteen stations were able to service a total of 46,011 kgH2/day or 94.7% of total demand which is up from 44,940 kgH2/day or 92.5% of total demand serviced by thirteen stations in Scenario 2. This time however, seven stations fell under 70% utilization which is up from only two stations. In total by building an additional two stations only 2.2% extra total demand was met, and average station utilization dropped from 86.4% to 76.7%. To this scenario's success, only one station fell below 50% utilization and now only five stations are being potentially overburdened at over 95% utilization. See Table 4.3 below for individual station data.

The resiliency of California's region of second greatest demand, the San Francisco Bay area, is greatly improved in this scenario as the two stations in the area in Scenario 2 are doubled to four. Also, meeting nearly 95% of total demand is extremely successful as an early solution. However, fifteen stations would likely be expensive and impractical for the state or any group that is deploying the stations. For an increase of only 2.2% of demand covered and an increase of resiliency within Northern California, this scenario is likely not worth the costs associated with the two extra stations, one of which (the Vallejo station) is under performing.

Table 4.3: Scenario 3 station performances (2025, low demand)

Location	Adjusted Capacity [kgH2/day]	Demand Serviced [kgH2/day]	Utilization
Vallejo	4,000	1,436.2	35.91%
South Oakland	4,000	2,454.6	61.37%
Fremont	4,000	2,448.0	61.20%
Lodi	4,000	1,884.0	76.96%
Chowchilla	4,000	3,043.7	76.09%
Delano	4,000	2,301.5	57.54%
Agoura Hills	4,000	3,647.2	91.18%
Downtown Los Angeles	4,000	4,000	100.00%
El Monte	4,000	4,000	100.00%
Long Beach	4,000	4,000	100.00%
Anaheim	4,000	4,000	100.00%
Ontario	4,000	4,000	100.00%
Fontana	4,000	3,688.7	92.22%
Perris	4,000	2,702.5	67.56%
Carlsbad	4,000	2,404.9	60.12%
Total	60,000	46,011.3 (94.66% of total demand)	76.69%

4.4 Scenario 4: thirteen stations with 10,000 kgH2/day service capacity

This scenario combines the number of stations from Scenario 2 with the medium station capacity of 10,000 kgH2/day used in Scenario 1. This scenario explores a few questions: how increasing number of stations, from five stations in Scenario 1 to thirteen stations, and increasing station capacity, from small stations in Scenario 2 to medium stations, affect total demand coverage and station utilization. In total, these thirteen stations can dispense a total of 130,000 kgH2/day whereas total refueling demand in the network is only 48,607 kgH2/day, so it will depict the impacts on performance in 2025 that greatly overbuilding a HDV HRS network will have. See Figure 4.7 for a visualization of the results of the model and Figure 4.8 to view a subregion of southern California with the greatest demand.

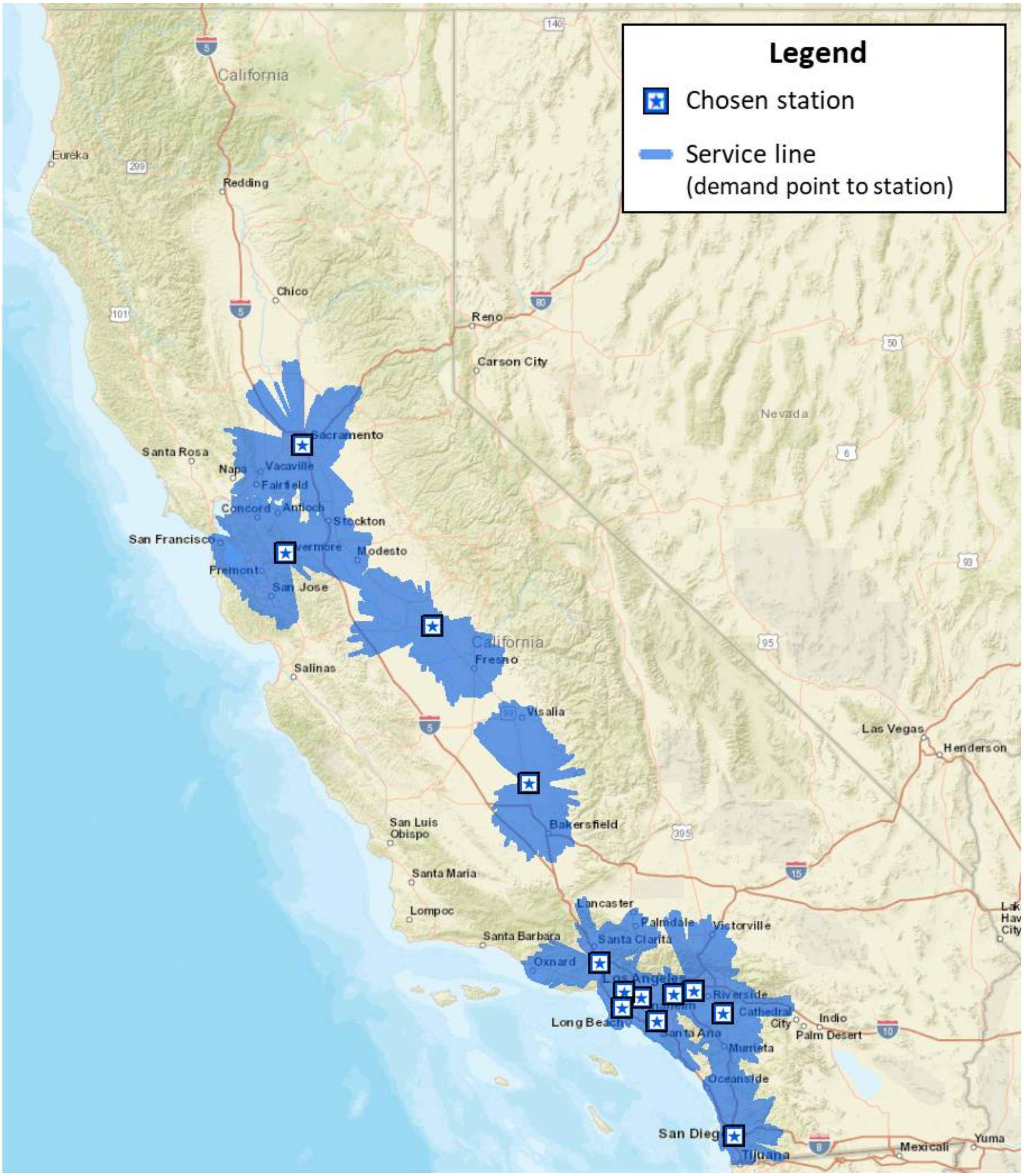

Figure 15: Scenario 4 - thirteen medium stations (2025, low demand)

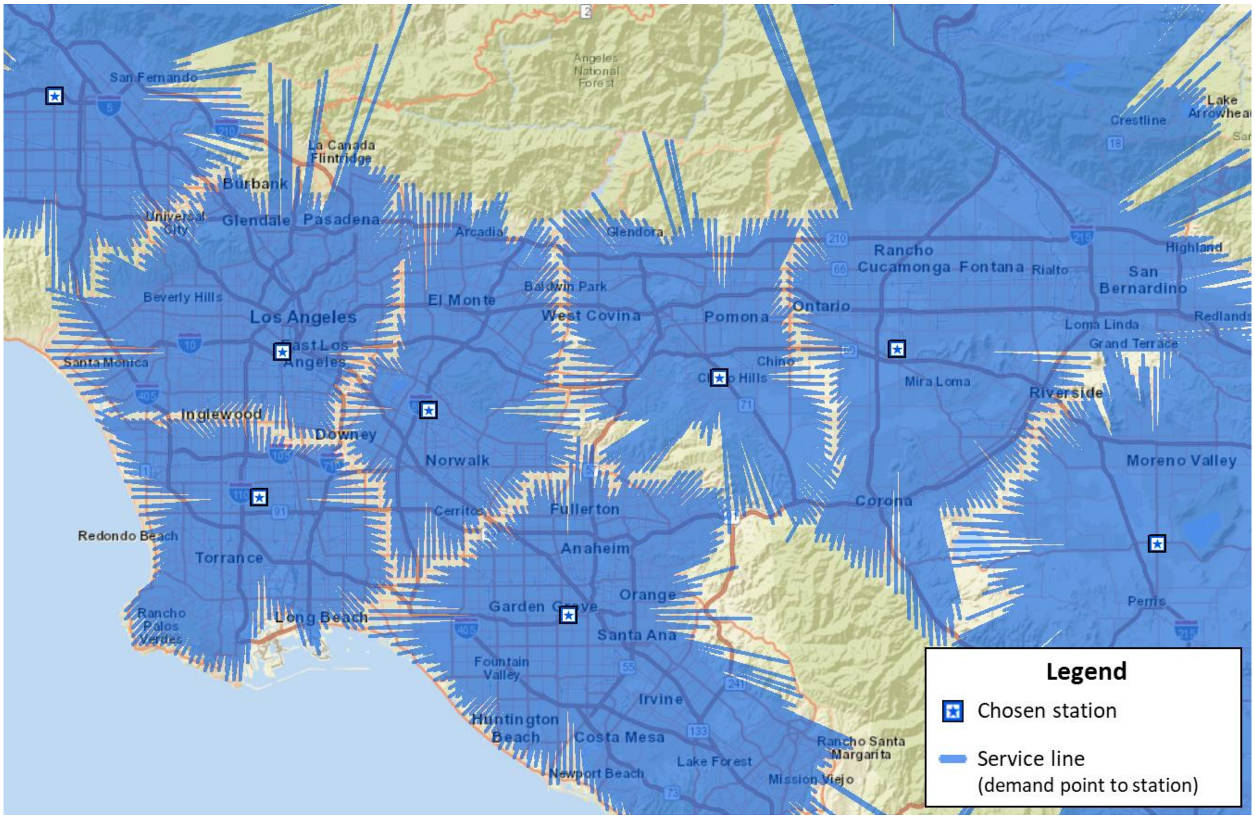

Figure 16: Scenario 4 zoomed to a southern California region

The thirteen stations were able to service a total of 45,822 kgH2/day or 94.3% of total demand which is a 13% increase in demand met from the five medium stations in Scenario 1, and a 1.8% increase in demand met from the thirteen small stations in Scenario 2. Reliability is up from both scenarios as no station is above 70% utilization, meaning stations struggling to perform likely will not affect the performance of the network unless they fully go offline for an extended period.

As expected though, there is an excessive amount of unutilized potential caused by the excessive total capacity of the stations. With a total serviceable demand of 130,000 kg/day, the thirteen-station network only dispenses 35.2% of its capacity. Ten out of the thirteen stations are below the 50% cutoff of utilization meaning that many of the stations cannot be justified to be built with the given capacity. See Table 4.4 for individual station data. Despite having so much underutilized capacity, this scenario still covers less of the total demand than the fifteen stations in Scenario 3. While making stations bigger will help meet more demand, building more stations is by far a better strategy, however it is the more expensive strategy. Upscaling station size should only be considered when either stations are struggling at above 95% capacity or cost/permitting limitations restrict the number of stations that can be deployed. Scenario 7 explores how mixing station capacities can be a more efficient solution to meeting demand aside from building excessively sized stations or an excessive number of stations.

Table 4.4: Scenario 4 station performances (2025, low demand)

Location	Adjusted Capacity [kgH2/day]	Demand Serviced [kgH2/day]	Utilization
Sacramento	10,000	1,198.2	11.98%
Livermore	10,000	6,721.0	67.21%
Merced	10,000	3,053.5	30.54%
Delano	10,000	2,301.5	23.02%
San Fernando	10,000	2,426.2	24.26%
Downtown Los Angeles	10,000	5,218.0	52.18%
Pico Rivera	10,000	4,873.5	48.74%
Gardena	10,000	3,772.9	37.73%
Garden Grove	10,000	2,731.8	27.32%
Chino Hills	10,000	2,559.7	25.60%
Wood Crest	10,000	6,582.9	65.83%
Perris	10,000	2,060.7	20.61%
San Diego	10,000	2,322.3	23.22%
Total	130,000	45,822.2 (94.27% of total demand)	35.25%

4.5 Scenario 5: five stations with 10,000 kgH2/day service capacity and site requirements

This scenario revisits Scenario 1 but seeks to force the position of some stations to locations with planned or discussed HDV HRS deployment. At least one station is already being built for demonstration projects and hydrogen fueled port operations at both the port of Long Beach and port of Oakland, so the existence of stations at both ports in 2025 is anticipated. Thus, one station at each location has been set as required in this scenario. Additionally, with insight from experts, a station within Fresno is also set as required due to Fresno's role as the largest city within the central valley and a huge destination and waypoint within the trucking and agricultural industry. This scenario will show how these real locations will compare to the optimized locations in Scenario 1 and how the remaining two stations get sited to meet the remaining demand. See Figure 4.9 for a visualization of the results and Figure 4.10.

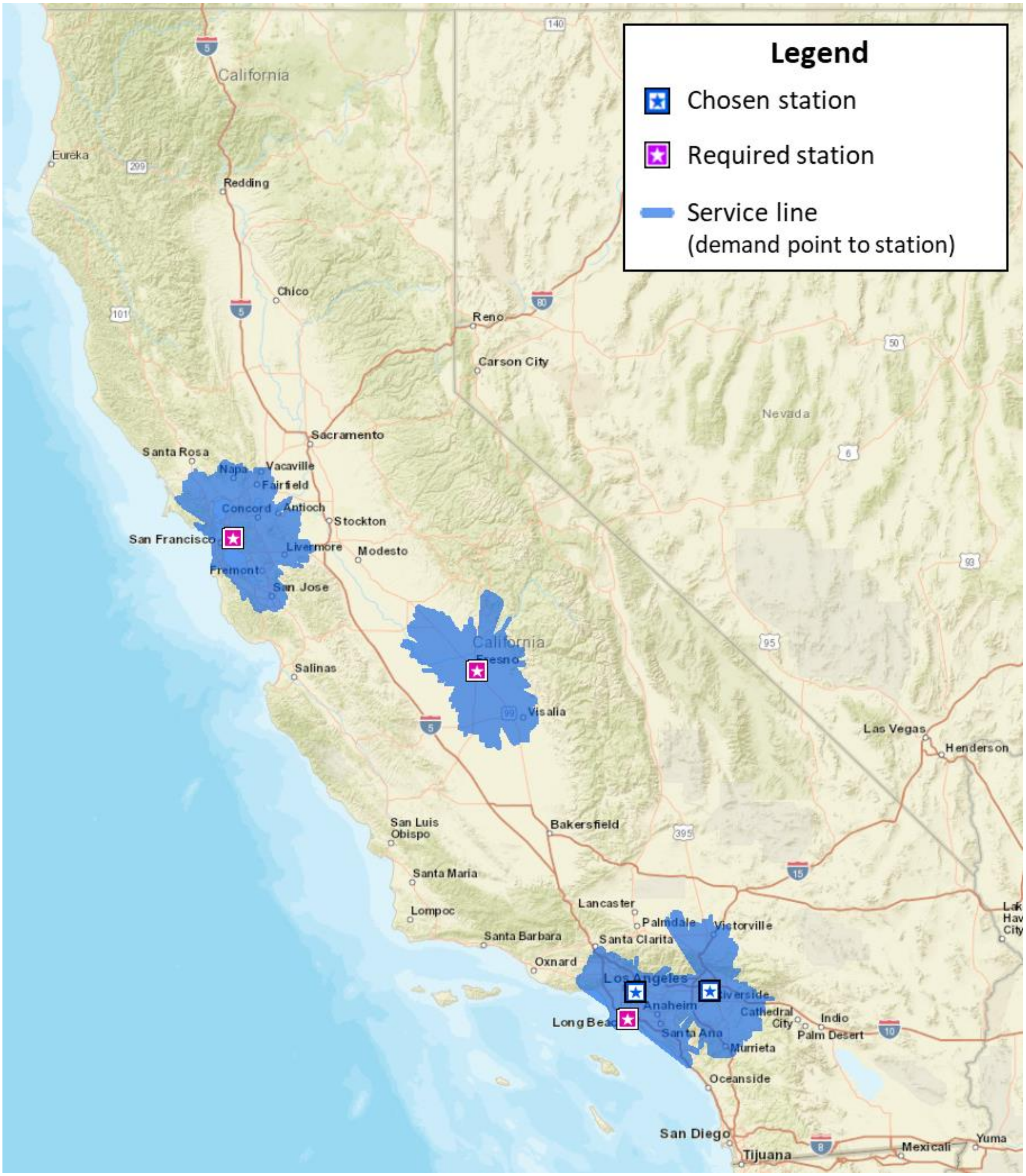

Figure 17: Scenario 5 - five medium stations with location requirements (2025, low demand)

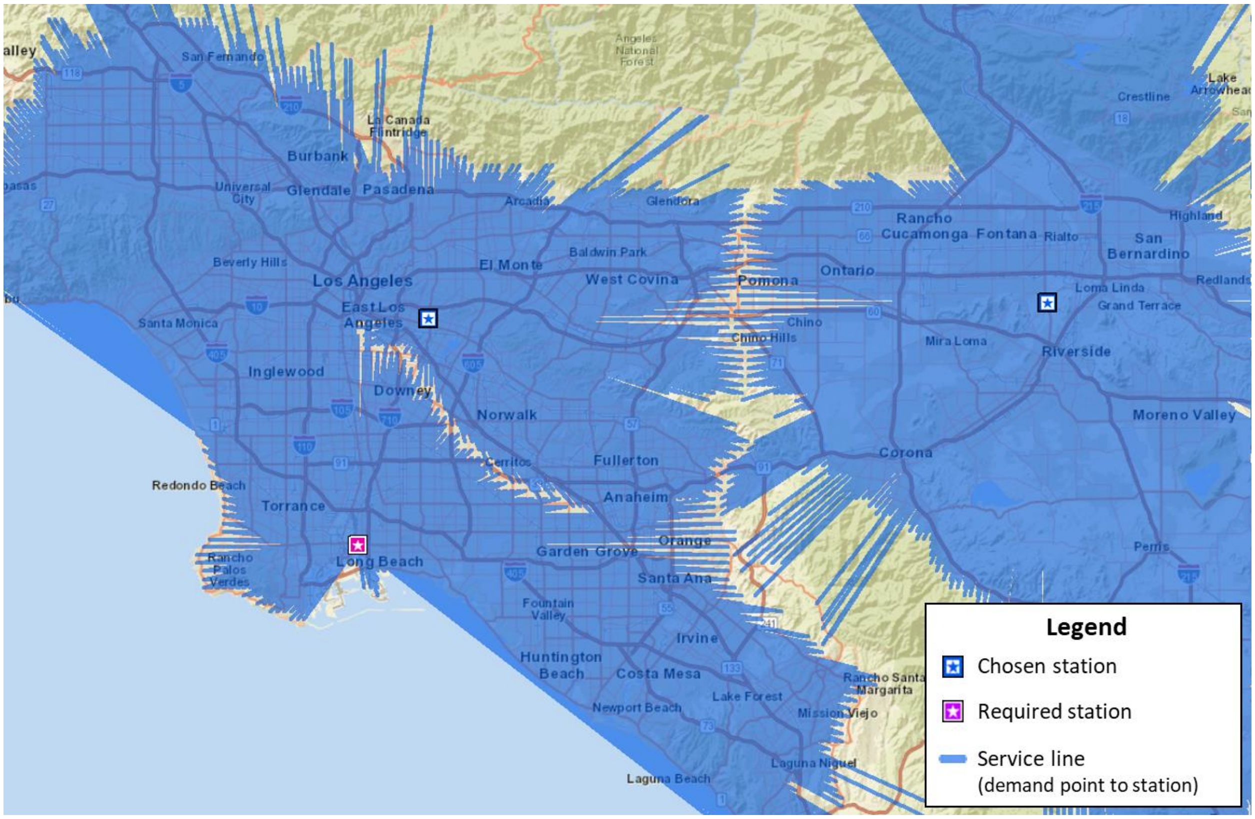

Figure 18: Scenario 5 zoomed to a southern California region

The five stations in this scenario were able to service 38,424.6 kgH2/day, or 79.1% of the total demand. This is a 1.8% decrease from the 81.3% of the total demand serviced by the stations in Scenario 1 which had no restrictions. Total utilization of the HDV HRS capacity is 76.9% which is 2.1% lower than Scenario 1. All three stations that moved saw a slight decrease in utilization due to their deoptimized positioning. Individual station results are in Table 4.5.

This scenario does confirm that using deoptimized locations decreases the total HDV HRS network coverage and utilization. The decreases are small though, but the required locations were not far from where the optimization originally located stations.

The fact that the decrease is small is important because it highlights that the general zone of a sited station is the most important factor when siting stations, and not the exact address location. This means a station developer using data from this model does not need to stress the exact placement of a station and can instead focus on finding the best accessible and affordable location which will aid in the rapid deployment of HDV HRSs in the coming years. Additionally, this shows that the model and its results are relatively stable and do not dramatically change based on a minor shift in the location of a few stations. This model can also be easily adapted for future deployment, for example using this model in 2025 after new stations have been deployed or planned with the intention of siting new stations for 2035 or 2045. Scenario 6 looks at applying this same methodology of required stations, but to the parameters of Scenario 2.

Table 4.5: Scenario 5 station performances (2025, low demand)

Location	Adjusted Capacity [kgH2/day]	Demand Serviced [kgH2/day]	Utilization
Port of Oakland*	10,000	5,942.0	59.42%
Fresno*	10,000	2,904.5	29.05%
Downtown Los Angeles	10,000	10,000	100.00%
Port of Long Beach*	10,000	9,686.7	96.87%
Riverside	10,000	9,891.3	98.91%
Total	50,000	38,424.5 (79.05% of total demand)	76.85%

* required station location

4.6 Scenario 6: thirteen stations with 4,000 kgH2/day service capacity and site requirements

This scenario applies the same site requirements from Scenario 5 to the thirteen-site scenario, Scenario 2. Unlike Scenario 5, which leaves only the two remaining stations of the five to be chosen, this scenario sites ten candidate stations after allocating demand to the three required stations. Like Scenario 5, this scenario demonstrates how site locations and HDV HRS network performance change when planned/built stations are sited in unoptimized locations. In this case, the greatest impact is on stations along California State Route 99 where the model now sites a Bakersfield station to compensate for the southern shift of the Fresno station in Scenario 2. The change in location of both the station at the port of Oakland and the station at the ports of Long Beach is a small shift, so stations within those regions are less greatly affected. The map of the stations can be seen in Figure 4.11 and a map of the stations within the subregion in Southern California is shown by Figure 4.12.

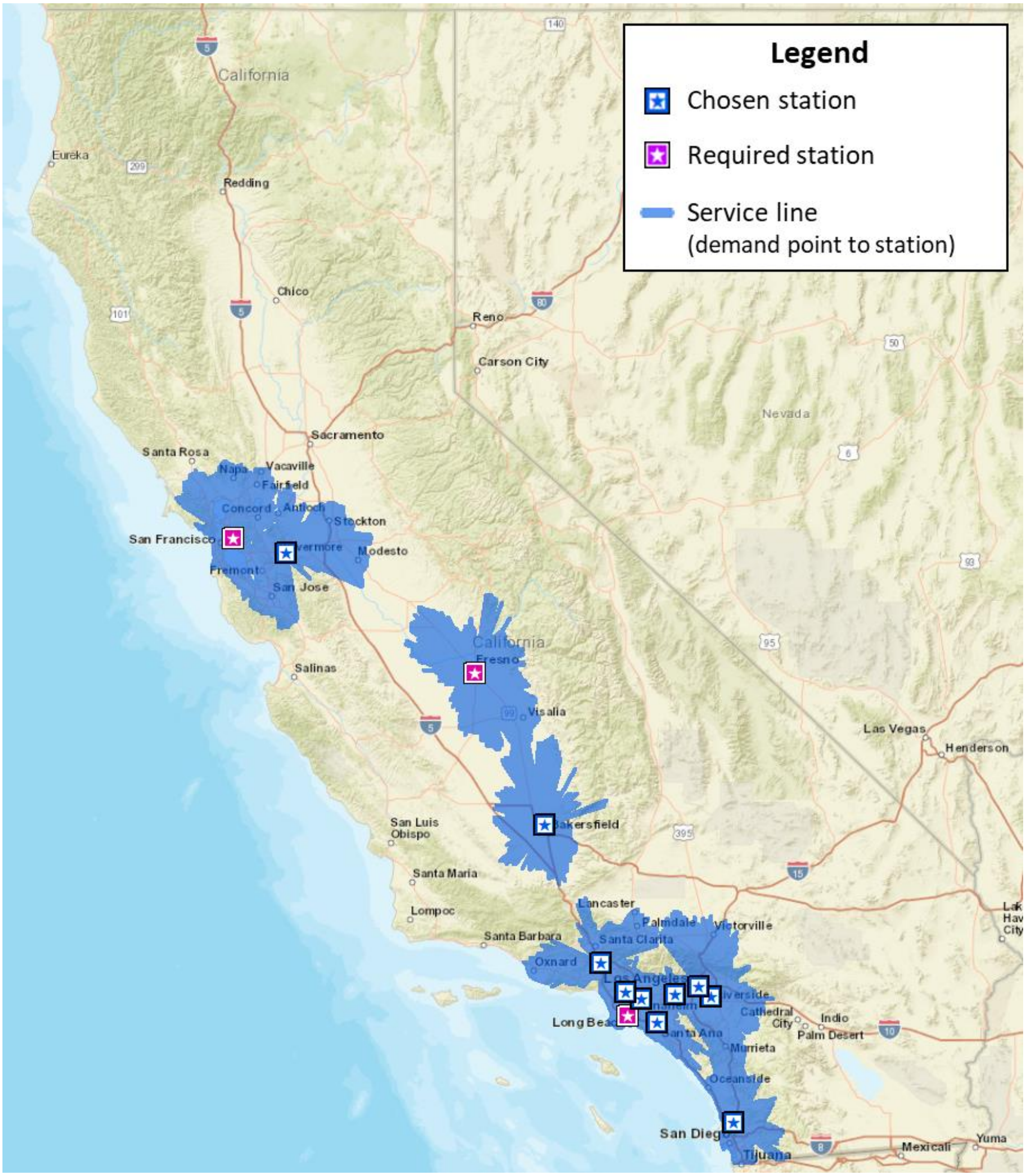

Figure 19: Scenario 6 - thirteen small stations with location requirements (2025, low demand)

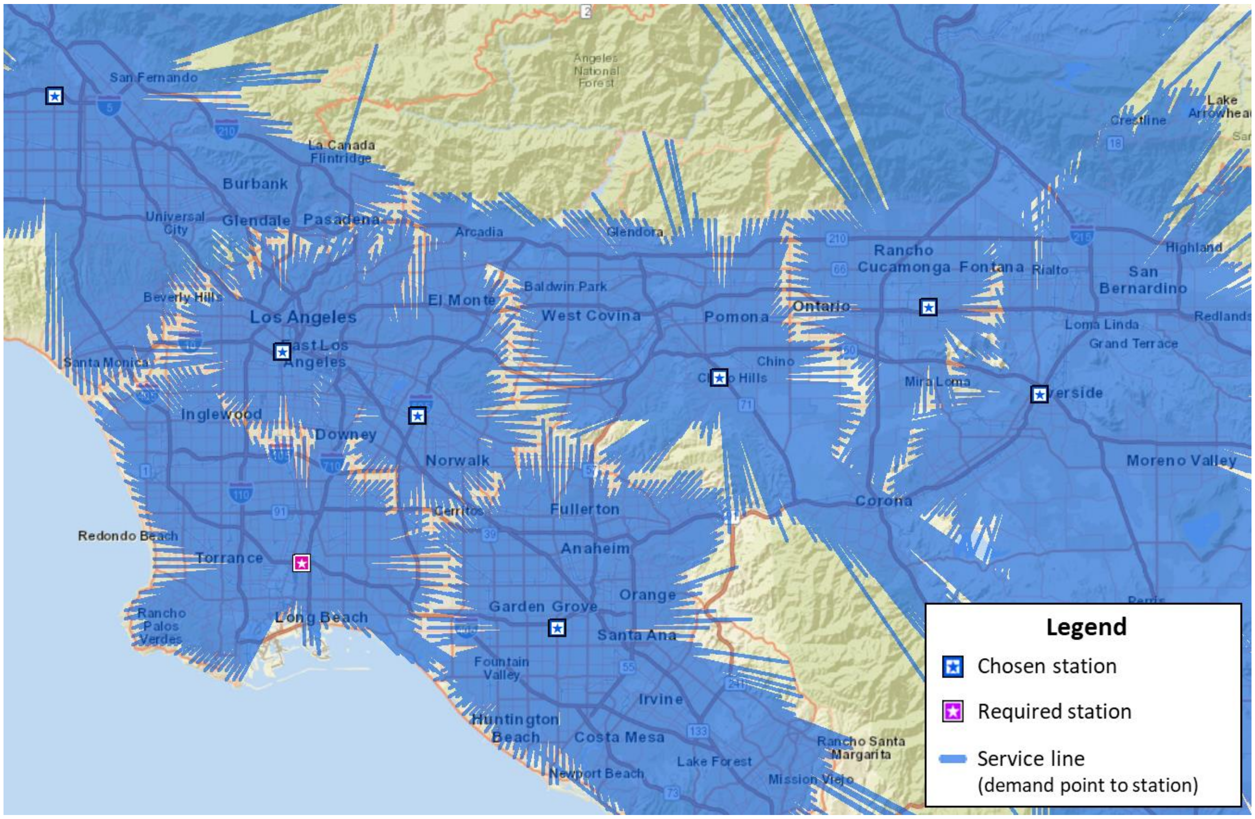

Figure 20: Scenario 6 zoomed to a southern California region

The thirteen stations in this scenario were able to service 44,623 kgH2/day of the total demand. This means 91.8% of the spatial demand was met, a 0.7% decrease from the thirteen unrestricted stations in Scenario 2. However, the least utilized stations saw a decrease in serviced hydrogen from 2301 kgH2/day to 2032 kgH2/day highlighting the largest effect of forcing unoptimized locations was on station utilization and not on total demand coverage. Some stations have increased burden and others have decreased demand implying that this scenario is slightly less reliable for refueling than Scenario 2. Individual results for stations can be viewed in Table 4.6. Despite the changes in utilizations, the stations remained performing well with no stations falling below 50%

utilization. Network performance is also adequate with over 90% of spatial demand being addressed. Similar to Scenario 5, this scenario showcases that the model responds well to built and planned stations, even if they aren't quite within optimal placements. This also again confirms that as long as stations are within the correct area (i.e. near the ports vs. at the ports or in Fresno vs. 50 miles north of Fresno), then they will likely service a similar amount of demand and perform quite well. This means the regions of the sited stations are more important than the specific sites where they were sited. The closer to the site the better, but the success of a HDV HRS network will not rely upon being placed at the correct highway offramp or street corner.

Table 4.6: Scenario 6 station performances (2025, low demand)

Location	Adjusted Capacity [kgH2/day]	Demand Serviced [kgH2/day]	Utilization
Port of Oakland*	4,000	3,806.8	95.17%
Livermore	4,000	3,347.9	83.70%
Fresno*	4,000	2,925.4	73.14%
Bakersfield	4,000	2,032.5	50.81%
Granada Hills	4,000	3,300.6	82.52%
Downtown Los Angeles	4,000	4,000	100.00%
Pico Rivera	4,000	4,000	100.00%
Port of Long Beach*	4,000	3,998.0	99.95%
Garden Grove	4,000	3,045.4	76.14%
Chino Hills	4,000	3,791.4	94.79%
Rancho Cucamonga	4,000	3,991.2	99.78%
Riverside	4,000	4,000	100.00%
La Jolla	4,000	2,384.6	59.62%
Total	52,000	44,623.8 (91.81% of total demand)	85.82%

* required station location

4.7 Scenario 7: eight stations with mixed service capacity and site requirements

This scenario is the final scenario and finally mixes the two station capacities seen in the previous scenarios. Three of the stations are medium stations that can service 10,000 kgH2/day and the remaining five stations are small stations that can service a total of 4,000 kgH2/day. This allows the network to have better coverage with more stations, but not need an excessive number of stations in areas of high demand such as southern California. Ideally this scenario should blend the performance of Scenario 1 and Scenario 2. The three top performing stations from Scenario 5 were utilized as the three 10,000 kgH2/day stations. These were the three Los Angeles stations, including the station that is required at the ports of Long Beach. The port of Oakland station and Fresno station were still required in this scenario; however, they were both sized down to 4,000 kgH2/day. This left three remaining small stations to be sited in this scenario. This process should yield better coverage than Scenario 5 due to an increase in number of stations and better utilization than both Scenario 5 and Scenario 6 due to sizing stations appropriately to match the demand that they service. The results of this process can be viewed in Figure 4.13 and a subregion of Southern California is also depicted in Figure 4.14.

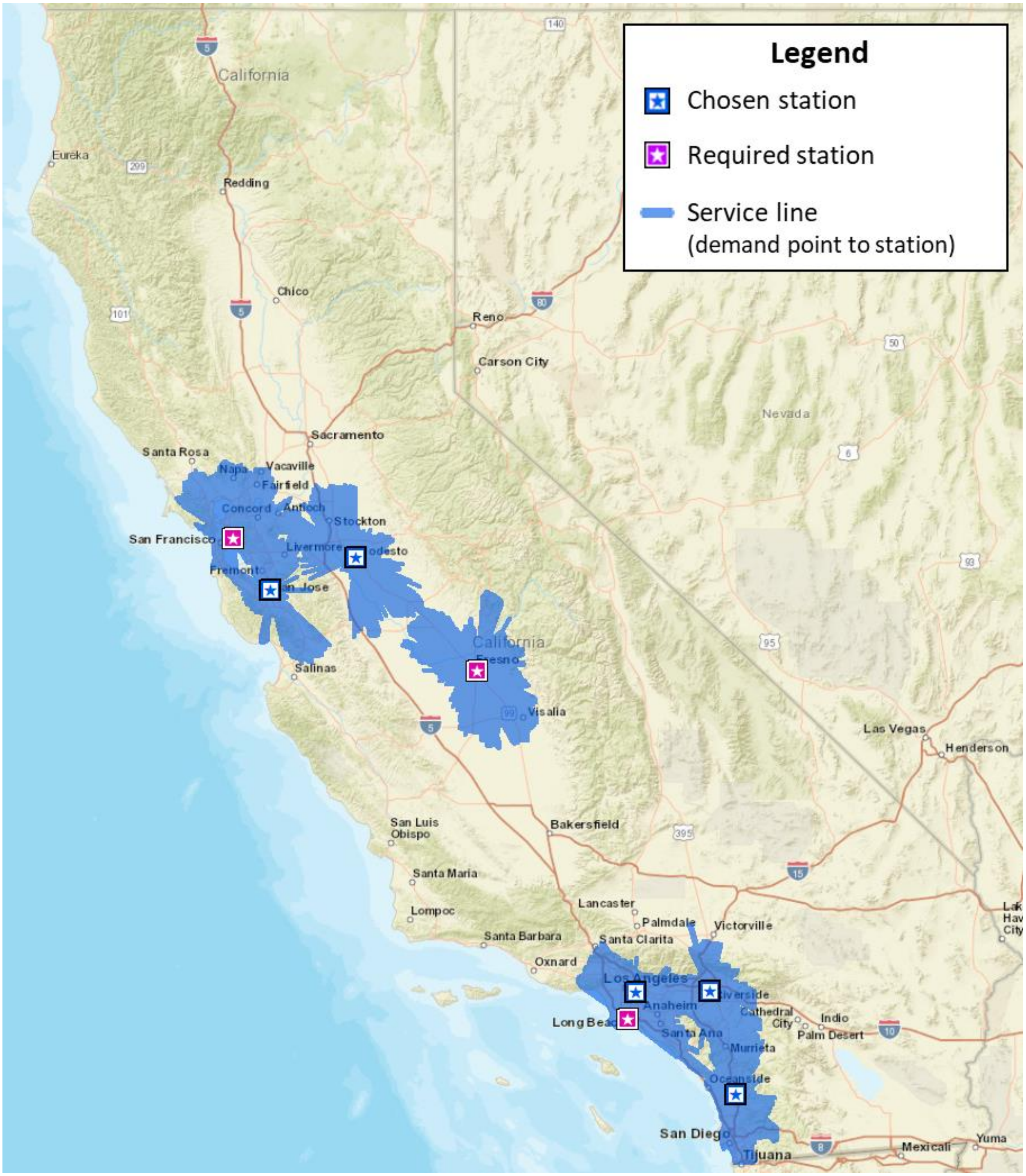

Figure 21: Scenario 7 - three medium stations and 5 small stations with location requirements (2025, low demand)

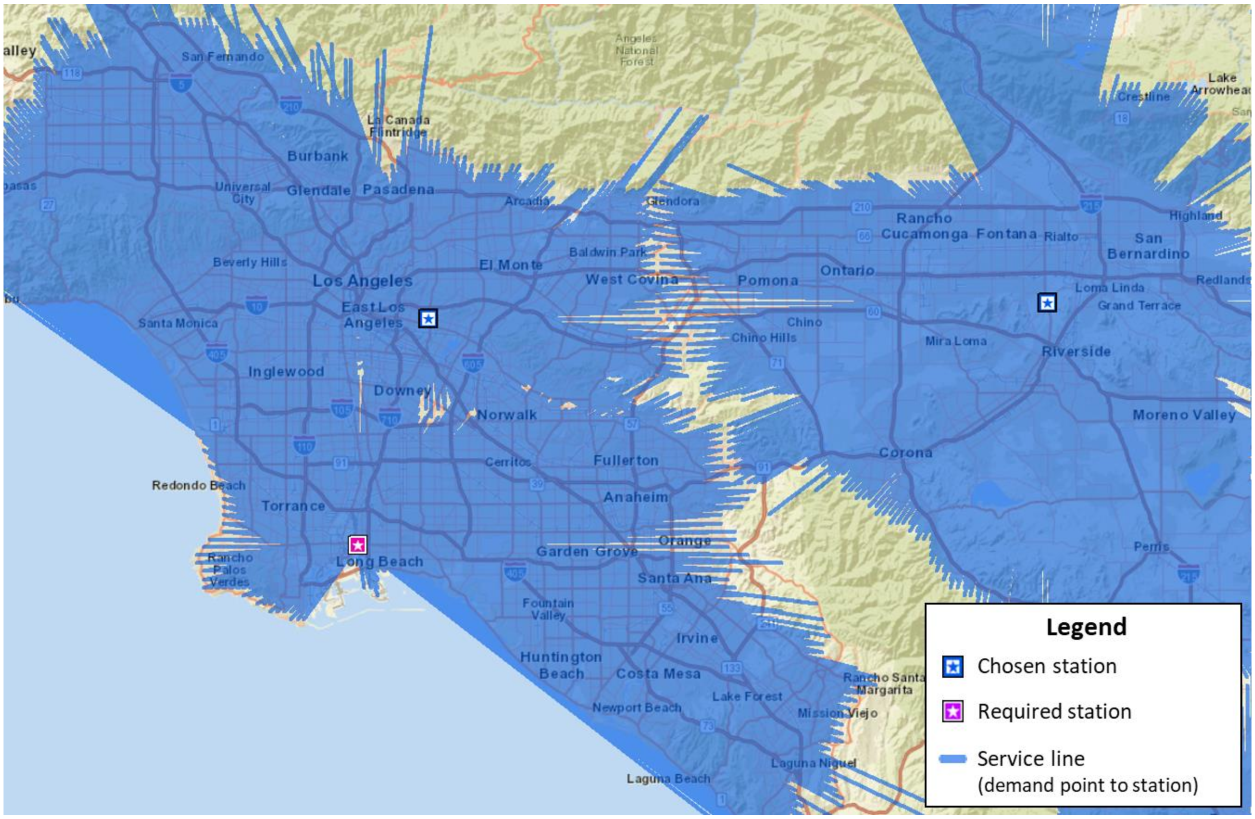

Figure 22: Scenario 7 zoomed to a southern California region

The eight stations were able to service 43,137 kgH2/day or 88.7% of the total demand. This is a 9.6% increase in total demand covered from the five stations in Scenario 5, and only a 3.1% decrease in demand met from the thirteen stations in Scenario 6. Additionally, station utilization is much higher in this scenario than in Scenario 5 considering the lowest operating stations operates at 60% utilization as opposed to the lowest station operating at 29% in Scenario 5. As predicted, it even sees better utilization than Scenario 6, seeing 60% utilization of the least utilized station as opposed to 50% and a total utilization that is ~1% greater. Individual station results are in Table .

While this scenario neither sees the highest demand coverage nor lowest station count which potentially could have cost implications. It does have the highest station utilizations while still maintaining a reasonable station count and high demand coverage. With only eight stations this scenario could provide hydrogen fueling for nearly 90% of all desired trucking routes within California in 2025. The largest flaw in this scenario potentially being the lack of a connection between northern and Southern California, creating instead two uniquely separate refueling networks. Furthermore, the low density of stations within Southern California which experiences the greatest trucking demand could pose reliability risks if any of the medium sized stations happen to experience reduced dispensing below the adjusted numbers or go offline entirely. This issue is exacerbated by both the East Los Angeles and Riverside stations already servicing 100% of their capacity. Positively, this represents the most efficient scenario when it pertains to the individual station performance.

Table 4.7: Scenario 7 station performances (2025, low demand)

Location	Adjusted Capacity [kgH2/day]	Demand Serviced [kgH2/day]	Utilization
Port of Oakland*	4,000	3,704.1	92.60%
San Jose	4,000	2,415.2	60.38%
Modesto	4,000	2,452.0	61.30%
Fresno*	4,000	2,901.4	72.54%
East Los Angeles^{P}	10,000	10,000	100.00%
Port of Long Beach^{*,P}	10,000	9,057.3	90.57%
Riverside^{P}	10,000	10,000	100.00%
Escondido	4,000	2,607.4	65.19%
Total	50,000	43,137.4 (88.75% of total demand)	86.27%

* required station location

P - sited medium station in Scenario 5 required for this scenario

4.8 Remaining Unserved Demand

With the highest amount of demand being met by the fifteen stations in Scenario 3 with 94.7% of total demand being serviced, it is of interest to note where the remaining 5.3% of demand is located to better understand why even overbuilt station networks have difficulty reaching 100% of the California's future refueling demands met. Figure 4.15 shows the unmet demand highlighted in red. While the red covers a large area, it only represents 5.3% of total demand. Note that most of the demand in these Scenarios comes from drayage with the remaining amount coming from in-state line haul. No demand comes from out-of-state line haul so unmet demand would likely increase in size in future years as other vocations and out-of-state line haul trucks come to more heavily adopt FCETs.

There are a few areas of unserved demand near sited stations. This is either due to the nearby station being at max capacity or not having an efficient or viable connecting route to the local station. Note that points with demand that can be interpreted as less than 1 truck a week are not represented here, however they account for <1% of the total demand.

The greatest areas of unserved demand that remain and would likely next require stations are connections along SR 99, extension of coverage on the I-5 in the central valley and northern California, and areas along highway 1.

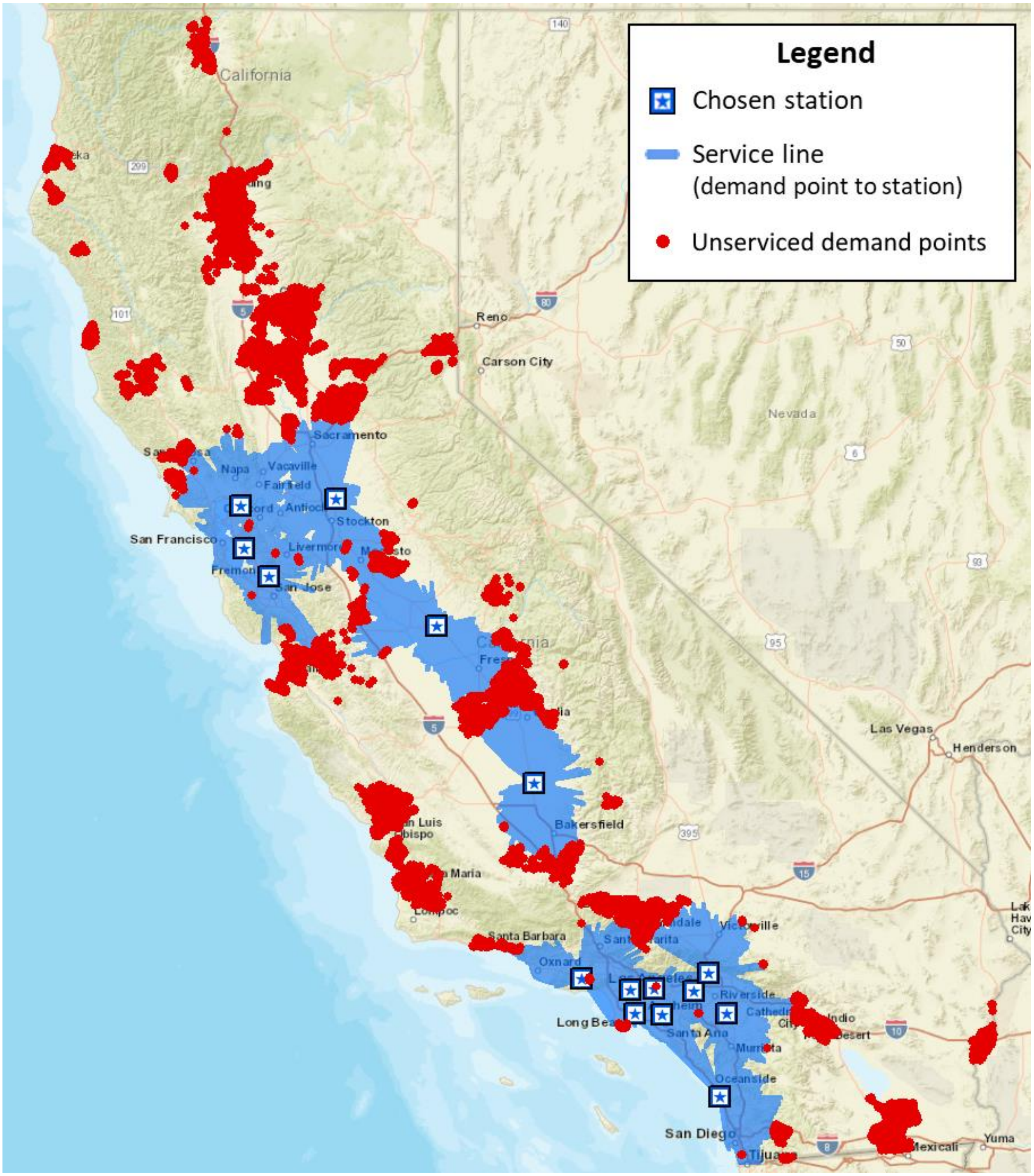

Figure 23: Scenario 3 with unmet demand visualized (2025, low demand)

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

- **A few HRSs is all California needs to enable the adoption of FCETs.**

California could provide a minimum function HDV HRS network for drayage and in-state line haul FCET refueling in 2025 with less than 10 stations and meet more than 85% of the potential demand. Even as few as five well placed stations can offer coverage to more than 75% of the state's growing hydrogen demand. While a few stations offer sufficient coverage, they do not necessarily offer the level of convenience and confidence needed to broadly engage FCET fleet owners. While more stations will be necessary for widespread adoption of FCETs, the few initial stations recommended will provide a minimum functional network by which early adopters are able to successfully deploy FCETs.

- **Use smaller stations to enhance refueling coverage in combination with larger stations to enable a more efficient and achievable HDV HRS network.**

Having many small stations instead of a few large stations greatly improves the spatial coverage of the fueling network. However, it is likely that fewer large stations will be more cost efficient and simpler to implement by 2025. Making use of varying station capacity can greatly improve the coverage and utilization of total station capacities when appropriately sized for the local demand. Depending on the budget, the greatest number of small HDV HRSs that can be deployed supported by a few medium sized HDV HRSs will be most effective in enabling the market. One medium station can potentially replace the coverage of two small stations. In this way, varying station capacities give optimal results when prioritizing station utilization, making it a cost-efficient solution.

- **Reaching 100% coverage <u>should not be</u> the target of California for 2025.**

It is unrealistic to offer total coverage of all of California's refueling demands by 2025. FCET fleet operators will have to be selective and dispatch FCETs on routes that best utilize the small number of stations that can be provided in the early years of adoption. As demand increases, offering more total coverage of the state of California will become more viable. No scenario for 2025, even when providing more than double the necessary dispensing capacity, could serve 95% or more of total hydrogen demand.

- **Planned and existing HDV HRSs can easily be integrated into station planning.**

As long as already planned and built stations are located within the target region that the model designates as high priority, including these stations in the methodology has little impact on network performance. While coverage and utilization will slightly decrease, the remaining stations of the network can be sited to compensate for the non-optimal station locations. This process is simple and can easily be repeated as station plans are announced to inform the next deployment.

- **A HDV HRS network does not need to be overbuilt to provide adequate fueling for FCETs within 2025.**

While overbuilding the network for 2025 aids little in reaching more demand (e.g., oversizing stations and creating more stations), the potential improvement in resiliency or convenience (due to factors such as station downtime or hydrogen shortages) was not factored into the current study and is a candidate for future work.

5.2 Recommendations

The HDV HRS siting methodology developed and applied in this thesis has been shown to be an effective tool at locating and assessing the performance of HRSs within California. Only results for 2025 have been showcased, but adoption is expected to increase as time progresses towards 2045 given California's zero emission goals. Scenarios need to be performed for 2030, 2035, 2040, and 2045 in addition to 2025. Additionally, these future scenarios will need to look at reducing assumptions as the network grows. Future scenarios will also gather more information on the network such as resiliency to stations going fully offline or functioning at reduced capacity.

Factors such as station costs, availability of hydrogen or hydrogen production, and disadvantaged community impacts need to be incorporated into the station siting optimization. The goal of this future work will create a roadmap that California can use as its guide to an effective deployment of HRSs throughout the years to optimally support zero-emission trucking.

Collaborative research is also required that addresses LDV HRS siting with HDV HRS siting, BET charging with FCET refueling, and bus refueling. The work is required to inform and aid California's overall growth towards sustainable energy and technology and while focused on HDVs it should also consider California's hydrogen, energy, and transportation economies at large.

REFERENCES

[1] United States Environmental Protection Agency, “Inventory of U.S. greenhouse gas emissions and sinks: 1990-2018,” 2020.

[2] California Office of Governor, “Governor Newsom Announces California Will Phase Out Gasoline-Powered Cars & Drastically Reduce Demand for Fossil Fuel in California’s Fight Against Climate Change,” 2020. https://www.gov.ca.gov/2020/09/23/governor-newsom-announces-california-will-phase-out-gasoline-powered-cars-drastically-reduce-demand-for-fossil-fuel-in-californias-fight-against-climate-change/ (accessed Aug. 02, 2021).

[3] D.-H. Nguyen *et al.*, “Tropospheric ozone and NOx: A review of worldwide variation and meteorological influences,” *Environ. Technol. Innov.*, vol. 28, p. 102809, 2022, doi: https://doi.org/10.1016/j.eti.2022.102809.

[4] I. B. Pollack, T. B. Ryerson, M. Trainer, J. A. Neuman, J. M. Roberts, and D. D. Parrish, “Trends in ozone, its precursors, and related secondary oxidation products in Los Angeles, California: A synthesis of measurements from 1960 to 2010,” *J. Geophys. Res. Atmos.*, vol. 118, no. 11, pp. 5893–5911, 2013, doi: https://doi.org/10.1002/jgrd.50472.

[5] D.-Y. Lee, A. Elgowainy, A. Kotz, R. Vijayagopal, and J. Marcinkoski, “Life-cycle implications of hydrogen fuel cell electric vehicle technology for medium- and heavy-duty trucks,” *J. Power Sources*, vol. 393, pp. 217–229, 2018, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378775318304737.

[6] B. Sen, T. Ercan, and O. Tatari, “Does a battery-electric truck make a difference? – Life cycle emissions, costs, and externality analysis of alternative fuel-powered Class 8 heavy-duty trucks in the United States,” *J. Clean. Prod.*, vol. 141, pp. 110–121, 2017, doi: 10.1016/j.jclepro.2016.09.046.

[7] A. Valente, V. Tulus, A. Galan-Martin, M. A. J. Huijbregts, and G. Guillen-Gosalbez, “The role of hydrogen in heavy transport to operate within planetary boundaries,” *R. Soc. Chem.*, vol. 5, pp. 4637–4649, 2021, doi: 10.1039/D1SE00790D.

[8] A. Ajanovic, “Economic and Environmental Prospects for Battery Electric- and Fuel Cell Vehicles: A Review,” *Fuel Cells From Fundam. to Syst.*, 2019, doi: 10.1002/fuce.201800171.

[9] K. Forrest, M. Mac Kinnon, B. Tarroja, and S. Samuelsen, “Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California,” *Appl. Energy*, vol. 276, 2020, [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S030626192030951X.

[10] T. Earl, L. Mathieu, S. Cornelis, S. Kenny, C. C. Ambel, and J. Nix, “Analysis of long haul

battery electric trucks in EU: Marketplace and technology, economic, environmental, and policy perspectives.," *8th Commer. Veh. Work.*, 2018, [Online]. Available: https://www.transportenvironment.org/wp-content/uploads/2021/07/20180725_T&E_Battery_Electric_Trucks_EU_FINAL.pdf.

[11] B. Nykvist and O. Olsson, "The feasibility of heavy battery electric trucks," *Joule*, vol. 5, no. 4, pp. 901–913, 2021, doi: 10.1016/j.joule.2021.03.007.

[12] J. Kast, G. Morrison, and J. J. J. Gangloff, "Designing hydrogen fuel cell electric trucks in a diverse medium and heavy duty market," *Res. Transp. Econ.*, vol. 70, pp. 139–147, 2018, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0739885916301639.

[13] P. Campbell and N. Thomas, "Tesla truck will need power of 4,000 homes to recharge, says study," *Financial Times*, 2017. https://www.ft.com/content/f5593480-d29a-11e7-8c9a-d9c0a5c8d5c9.

[14] P. Fairley, "Speed bumps ahead for electric-vehicle charging," *IEEE Spectr.*, vol. 47, no. 1, pp. 13–14, 2010, doi: 10.1109/MSPEC.2010.5372476.

[15] California Energy Commission, "Summary of California Vehicle and Transportation Energy," 2020. https://www.energy.ca.gov/data-reports/energy-almanac/transportation-energy/summary-california-vehicle-and-transportation.

[16] California Fuel Cell Partnership, "FCEV Sales, FCEB, & Hydrogen Station Data," 2020. https://cafcp.org/by_the_numbers.

[17] The Port of Los Angeles, "PORT OF LOS ANGELES ROLLS OUT HYDROGEN FUEL CELL ELECTRIC FREIGHT DEMONSTRATION," 2021. https://www.portoflosangeles.org/references/2021-news-releases/news_060721_zanzeff.

[18] B. Lane, "Alternative Light- and Heavy-Duty Vehicle Fuel Pathway and Powertrain Optimization," University of California, Irvine, 2019.

[19] P. G. Anselma and G. Belingardi, "Fuel cell electrified propulsion systems for long-haul heavy-duty trucks: present and future cost-oriented sizing," *Appl. Energy*, vol. 321, 2022, doi: 10.1016/j.apenergy.2022.119354.

[20] California Fuel Cell Partnership, "The California Fuel Cell Revolution: A Vision for Advancing Economic, Social, and Environmental Priorities," 2018. https://cafcp.org/sites/default/files/CAFCR.pdf.

[21] A. Saeedmanesh, M. Mac Kinnon, and J. Brouwer, "Hydrogen is essential for sustainability," *Curr. Opin. Electrochem.*, vol. 12, pp. 166–181, 2018, doi: 10.1016/j.coelec.2018.11.009.

[22] W. McDowall and M. Eames, “Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature,” *Energy Policy*, vol. 34, no. 11, pp. 1236–1250, 2006, doi: 10.1016/j.enpol.2005.12.006.

[23] U.S. Department of Energy, “DOE Launches Bipartisan Infrastructure Law’s $8 Billion Program for Clean Hydrogen Hubs Across U.S.,” 2022. https://www.energy.gov/articles/doe-launches-bipartisan-infrastructure-laws-8-billion-program-clean-hydrogen-hubs-across.

[24] T. D. Acharya, A. T. Jenn, M. R. Miller, and L. M. Fulton, “Spatial Modeling of Future Light- and Heavy-Duty Vehicle Travel and Refueling Patterns in California,” *UC Off. Pres. Univ. Calif. Inst. Transp. Stud.*, 2021, doi: http://dx.doi.org/10.7922/G2J67F7H Retrieved from https://escholarship.org/uc/item/1mf9r7g1.

[25] P. K. Rose, R. Nugroho, T. Gnann, P. Plotz, M. Wietschel, and M. Reuter-Oppermann, “Optimal development of alternative fuel station networks considering node capacity restrictions,” *Transp. Res. Part D Transp. Environ.*, vol. 78, no. 102189, 2020, doi: https://doi.org/10.1016/j.trd.2019.11.018.

[26] A. M. Fong, “Spatial Assessment of Tri-Generation Fuel Cells to Support Hydrogen Refueling Infrastructure in California Using Conventional and Renewable Feedstocks,” *Natl. Fuel Cell Res. Cent.*, 2020.

[27] H. Sun, C. He, K. Wang, Y. Zhang, S. Lv, and Y. Xu, “Hydrogen station siting optimization based on multi-source hydrogen supply and life cycle cost,” *Int. J. Hydrogen Energy*, vol. 42, no. 38, pp. 23952–23965, 2017, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319917330276.

[28] H. Sun, C. He, X. Yu, M. Wu, and Y. Ling, “Optimal siting and sizing of hydrogen refueling stations considering distributed hydrogen production and cost reduction for regional consumers,” *Int. J. Energy Res.*, 2019, doi: 10.1002/er.4544.

[29] J. Lindenmann, V. Matzi, N. Neuboeck, B. Ratzenhofer-Komenda, A. Maier, and F.-M. Smolle-Juettner, “Severe hydrogen sulphide poisoning treated with 4-dimethylaminophenol and hyperbaric oxygen.,” *Diving Hyperb. Med.*, vol. 40, no. 4, pp. 213–7, Dec. 2010.

[30] H. Dagdougui, A. Ouammi, and R. Sacile, “A regional decision support system for onsite renewable hydrogen production from solar and wind energy sources,” *Int. J. Hydrogen Energy*, vol. 36, no. 22, pp. 12324–14334, 2011, doi: 10.1016/j.ijhydene.2011.08.050.

[31] X. Wu, H. Li, X. Wang, and W. Zhao, “Cooperative Operation for Wind Turbines and Hydrogen Fueling Stations With On-Site Hydrogen Production,” *IEEE Trans. Sunstainable Energy*, vol. 11, no. 4, pp. 2775–2789, 2020, doi: 10.1109/TSTE.2020.2975609.

[32] M. Minutillo, A. Perna, A. Forcina, S. Di Micco, and E. Jannelli, “Analyzing the levelized cost of hydrogen in refueling stations with on-site hydrogen production via water electrolysis in the Italian scenario,” *Int. J. Hydrogen Energy*, vol. 46, no. 26, pp. 13667–13677, 2021, doi: 10.1016/j.ijhydene.2020.11.110.

[33] California Air Resources Board, “EMFAC: Emissions Inventory,” 2020. https://arb.ca.gov/emfac/emissions-inventory.

[34] J. Kast, R. Vijayagopal, J. J. Gangloff, and J. Marcinkoski, “Clean commercial transportation: Medium and heavy duty fuel cell electric trucks,” *Int. J. Hydrogen Energy*, vol. 42, no. 7, pp. 4508–4517, 2017, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S036031991633676X.

[35] R. Nugroho, P. K. Rose, T. Gnann, and M. Wei, “Cost of a potential hydrogen-refueling network for heavy-duty vehicles with long-haul application in Germany 2050,” *Int. J. Hydrogen Energy*, vol. 46, no. 71, pp. 35459–35478, 2021, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319921032833.

[36] H. Basma and F. Rodriguez, “Fuel cell electric tractor-trailers: Technology overview and fuel economy,” 2022. [Online]. Available: https://transport-online.de/sites/default/files/public/data-news/fuel-cell-tractor-trailer-tech-fuel-1-jul22.pdf.

[37] Federal Highway Administration, “National Electric Vehicle Infrastructure Formula Program: Bipartisan Infrastructure Law,” 2022. [Online]. Available: https://www.fhwa.dot.gov/environment/alternative_fuel_corridors/nominations/90d_nevi_formula_program_guidance.pdf.

[38] S. Stephens-Romero, M. Carreras-Sospedra, J. Brouwer, D. Dabdub, and S. Samuelsen, “Determining Air Quality and Greenhouse Gas Impacts of Hydrogen Infrastructure and Fuel Cell Vehicles,” *Environ. Sci. Technol.*, vol. 43, no. 23, pp. 9022–9029, Dec. 2009, doi: 10.1021/es901515y.