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Authors
Willette, Peter J
Shaffer, Brendan
Samuelsen, G Scott

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Systematic Selection and Siting of Vehicle Fueling Infrastructure to Synergistically Meet Future Demands for Alternative Fuels

Peter J. Willette
Advanced Power and Energy Program,
University of California,
Irvine, CA 92697-3550

Brendan Shaffer
Advanced Power and Energy Program,
University of California,
Irvine, CA 92697-3550

G. Scott Samuelsen
Advanced Power and Energy Program,
University of California,
Irvine, CA 92697-3550

In order to meet the increasing demand for low carbon and renewable transportation fuels, a methodology for systematically establishing build-out scenarios is desirable. In an effort to minimize initial investment costs associated with the development of fueling infrastructure, the analytical hierarchy process (AHP) has been developed and applied, as an illustration, to the case of hydrogen fueling infrastructure deployment in the State of California. In this study, five parameters are selected in order to rank hydrogen transportation fuel generation locations within the State. In order to utilize meaningful weighting factors within the AHP, expert inputs were gathered and employed in the exercising of the models suite of weighting parameters. The analysis uses statewide geographic information and identifies both key energy infrastructure expansion locations and critical criteria that make the largest impact in the location of selected sites.
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Introduction

Energy consumption continues to rise, and over the past two decades, California's foreign oil imports have steadily increased [1]. This is at least as important as California's air quality and greenhouse gas impact issues.

Persistent poor air quality in three primary air basins within the state of California underpins the motivation for a range of legislation. The three main air basins of concern are the South Coast Air Basin (SoCAB), San Joaquin Valley Air Basin (SJVAB), and the San Francisco Bay Area Air Basin (SFBAAB), which all are in nonattainment of either primary or secondary air quality standards [2]. The various air quality and climate change legislation enacted in order to counter this problem include: AB 32, AB 118, AB 1493, SB 375, SB 1505.

AB 32 was created as an overarching piece of legislation in order to combat California's contribution to climate change. The primary focus of this legislation is to reduce overall greenhouse gas emissions by 30% and 80% below 1990 levels by the years 2020 and 2050, respectively [3].

In order to attain these ambitious goals delineated by AB 32, California has set into motion a breadth of complimentary strategies. These climate change mitigation techniques range from holistic regional planning approaches (SB 375 [4]) to the reduction in carbon intensity of transportation fuels (AB 1493 [5], Low Carbon Fuel Standards [6]), all the way to private funding of hydrogen fueling infrastructure and research related to air quality impacts of renewable fuels (AB 118 [7,8]). Hydrogen has received special attention, with strategies for the construction of a hydrogen fueling network stemming from Executive Order No. S-7-04, in order to prepare for the demand that programs like the Zero Emissions Vehicle Action Plan intend to produce [9–11]. The carbon intensity of this hydrogen fuel will be checked by SB 1505 [12].

Air quality issues and climate change have motivated much alternative and renewable fuel legislation. In order to successfully implement these legislative directives, a clear delineation of where and how to best expand current fuel generation infrastructure must be created and set into place. Therefore, it is the aim of this work to show the facility of a tool capable of such a prescription for the future.

In order to understand and solve the problem of fueling infrastructure expansion, the general fueling supply chain needs to be understood. The first step in the fuel generation process is to extract the primary energy resource. This supply could be anything from crude oil to biomass. The raw product is then transported, in most cases, to a central plant, where it is processed, refined, and/or converted into a transportation grade fuel. This fuel is then transported from the central plant to its final dispensing location. It is at this dispensing location that the fuel is sold to the consumer.

In this study, the main focus is the location of the conversion facilities. Strategically locating these facilities will not only have an effect on reducing initial investment costs and increasing overall supply chain efficiency but also help to reduce the overall transportation distance of the finished fuel product. Therefore, it is the aim of this examination to locate fuel generation facilities on ideal land (least land cost (LLC), least populous (LP), along with being nearest to power generation facilities, exiting energy and water infrastructure), in order to reduce capital cost and overhead such as permitting, alongside locating these facilities near primary sources of fuel and finished product transportation routes. An additional step can also be taken to ensure that the least distance to a fuel dispensing location can be achieved.

In order to draw conclusions about where to best locate new fuel generation infrastructure, this study makes use of a method known as the AHP. This approach was decided upon mainly due to the ease in which it is able to break down complicated, multilevel and multicriterion decisions like the one in question. As an attribute to its merit, this technique has been widely utilized in industry and government for an array of complex decision making [13]. An additional key attribute is that this process has built in capabilities that ensure the validity of the solution that is produced. In the case of this study, the AHP methodology allows for many candidate fuel generation sites to be judged based on several criterion from which the best locations can be selected.

AHP: An Overview. The AHP is a tactical decision making process able to facilitate the decomposition of complex problems that consist of multiple criterion and often times have multiple

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level decisions to overcome in order to obtain an optimal conclusion. This process is used across many sectors (e.g., government, business and energy sectors [13]).

The AHP has been utilized in several studies that address hydrogen infrastructure. In Andalusia, the AHP was implemented in order to provide a preferential sequence for the build out of hydrogen dispensing locations [14]. This study supports the power of making a multicriterion based decision, along with the flexibility of the AHP in that it ranks all of the locations and does not solely provide an "optimal" solution [14]. This outputted set of ranking allows the decision makers to utilize the results as guidance, along with other exogenous information in order to come to a final conclusion. Another study examined the tradeoffs between several conversion technologies with the criteria being: cost of hydrogen, capital cost, feedstock cost, operations and maintenance cost, and carbon dioxide emissions [15]. This methodology has also been applied not only to current hydrogen conversion technologies but also to future projections, along with scenario analysis tools [16]. This study accredits the AHP with showing facility in discerning weighting criterion from an inventory of expert inputs in addition to being able to utilize both quantitative and qualitative criteria [16]. A hybrid AHP approach study combines a fuzzy decision-making methodology with the AHP in order to take into account varied human perceptions and uncertainties [17]. This study evaluated six of the most industry ready hydrogen production methods for a region in Korea [17].

In addition to pure hydrogen-related implementations, others that are worth noting are those that optimally site central manufacturing facilities. An improved, integrated, AHP methodology has been recently utilized to solve the multicriteria decision-making problems consisting of production facility siting that businesses often encounter when trying to expand production [18–20]. The AHP was utilized in these studies in order to develop the relative importance of the weighting criterion for each of the decisions. Other methods were then utilized in conjunction to determine the best set of alternatives. The selection of plant locations is a pivotal decision as it heavily effects the overall supply chains efficiency [18]. This approach holds potential in siting future hydrogen generation facilities.

In summary, the AHP has several defining attributes that make it ideal for this study and are as follows: (1) capable of comparing multiple criterion that may vary greatly in unit and magnitude, (2) decomposes complex multicriterion and multilevel decisions, (3) collects and aggregates expert inputs on an equivalent basis, (4) implements a consistency ratio (CR) in order to ensure results are meaningful, and (5) ranks results so as to provide guidance to decision makers.

Through the exercising of the AHP, the objectives of this paper are to: (1) examine the AHP as a fuel generation facility siting tool, (2) exercise the AHP tool in a case study for hydrogen fuel focusing on both Northern and Southern California that remains independent of overall projected hydrogen demand, (3) examine the robustness and resolution of the analysis results through the exploration of anomalies in the results to verify its utility in complete modeling of hydrogen fuel cell vehicle roll out planning.

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

Several metrics are utilized in order to create a mesh grid of potential hydrogen generation locations over the entire state. The first step is to generate a rectangular mesh grid of a desired spatial resolution that covers the state. Two metrics are then utilized in combination with a filtering function. The two metrics determine if the point lays within the border of the state and then if the point falls within the boundaries of California's many parks, preserves, or large water bodies. A map of candidate locations with a spatial grid of about 10 km^2 (12,000 $\times$ 10,250 m) can be viewed in Fig. 1. The exact spacing of the candidate locations is adjustable. For this case study, 10 square kilometers is used due to the resolution versus modeling time tradeoff. The grid areas generated in this step are then passed off to the decision making portion of the code in order to analyze geographical metrics for each individual point of interest.

AHP Decision-Making Methodology. The following generalized AHP approach is a methodology adapted from Bushan and Rajkumar [13]:

Step 1: Decouple the problem "into a hierarchy of goal, criteria, subcriteria, and alternatives" [13]. A general overview of a hierarchical structure used in this type of decision making can be seen in Fig. 2. In Fig. 2, the "Goal" is the overall decision to be made. The main "Criterion" is smaller decisions that can be made in order to facilitate an overall decision. The "Sub Criterion" is the factors that the smaller decisions depend on in order to draw a conclusion.

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

Step 3: The pairwise comparisons are organized into matrices in order to display all criteria of each decision. The matrix diagonal values are all unity, signifying that equal criteria have equal importance. Values above and below the diagonal are both mirrored and inverted, or $a_{ij} = 1/a_{ji}$. Values in the matrix vary from 1/9 to 9 due to the rating system. Therefore, when there is a value of less than one in any particular cell, the criteria represented by the corresponding column have more weight than the criteria in the row. If the value is greater than one, the row criterion is deemed to be more important than the column.

Step 4: Each of the matrices must be checked for consistency in order to ensure a meaningful solution will be reached. In the case of small matrices, a standard CR is generated as in the below equation:

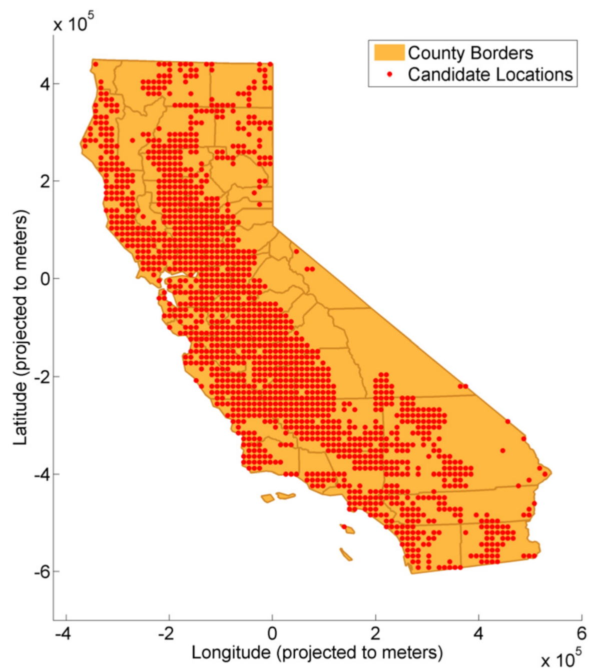

Fig. 1 Candidate fuel generation locations

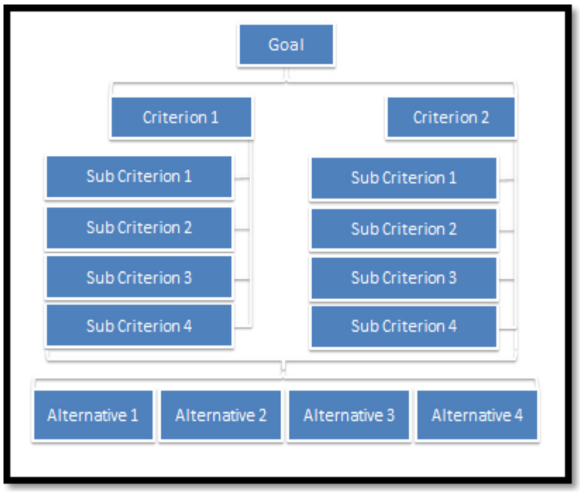

Fig. 2 General AHP hierarchy

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \tag{1}$$

In order to obtain such a ratio, first a consistency index (CI) must be derived for each particular matrix. This index is obtained via Eq. (2), by utilizing $\lambda_{\max}$ or the maximum eigenvalue along with n, the order of the matrix

$$\mathrm{CI} = \frac{(\lambda_{\max} - n)}{(n-1)} \tag{2}$$

The next step is to look at the random index (RI), or the consistency of a set of random matrices with the same order as the considered matrix. There are well-known values for matrices up to the order of 15. With orders of greater than 15, Alonseo and Lamata [21] suggest a method for estimating the CR as seen in the below equation:

$$\mathrm{CR} = \frac{(\lambda_{\max} - n)}{(\bar{\lambda}_{\max} - n)} < 0.1 \tag{3}$$

where they calculate a least square fit for the mean maximum eigenvalue as shown in the below equation:

$$\bar{\lambda}_{\max} = 2.7699n - 4.3513 \tag{4}$$

The combination of Eqs. (3) and (4) yields an expression that is a good estimate for determining the consistency of the matrix under examination, and is presented in Eq. (5). This expression is utilized in this study for the estimation of the CR for all of the matrices corresponding to the input datasets

$$\mathrm{CR} = \frac{(\lambda_{\max} - n)}{(1.7699n - 4.3513)} \tag{5}$$

Table 1 Definition of pairwise rating criteria for AHP (adapted from Ref. [13])

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

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

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

AHP Case Study: Hydrogen Generation Locations. The five metrics used in the AHP case study were power plant proximity (PPP), LLC, LP, energy infrastructure proximity (EIP), and water infrastructure proximity (WIP). PPP is the distance to the closest electricity generation locations (e.g., solar farms, wind farms, natural gas power plants). LLC are current median dollars per square foot values extracted from Zillow™ [22], LP is the lowest population based on LandScan™ data, EIP is the distance to current energy infrastructure (highways, railroads, natural gas pipelines, and electrical transmission lines), and WIP is the distance to the nearest major lakes, rivers, and water ways in California. In order to gather data on the weighting parameters for each metric as applied to the case of hydrogen generation locations, a survey was performed that asked each participant to rank each metric. Several hydrogen fueling supply chain experts were surveyed.

The metrics were chosen based on their relevance to the generation of transportation fuels in general and correspondingly the selection of optimal generation sites. Near distance to electrical generation facilities was selected in order to give a priority to the colocation of fuel and electrical generation. By colocating these facilities, much of the commercial permitting process would not need to be undertaken due to the previously zoned land. Additional benefits from colocation exist, such as utilizing a portion of the generation facilities feedstock for fuel production (e.g., wind or solar for the production of hydrogen). The average housing value was utilized as an estimate of land cost in the area. Preference should be given to areas with low land cost in order to reduce the initial capital investment for the facility. The lowest population metric was utilized for two reasons: (1) an area with fewer people is more likely to have open space available for development and (2) an area with fewer residents is less likely to receive resistance from an esthetic point of view. The next metric is the least distance to eligible transportation infrastructure. This is a key metric for two reasons. The first is that many times previously installed infrastructure can become the primary energy supplier for fuel generation. Second, once the fuel is created, it needs to be transported to the dispensing location. All of the considered infrastructure will allow for previously zoned energy transmission corridors to be utilized in conjunction with new pipelines or trucking routes for the transportation and delivery of transportation fuels. The final metric considered is WIP. Water is an important resource to consider as it has become a scarce and greatly underestimated energy utilization component. Demand has rapidly been increasing, while supply has fallen. This water metric adds a great deal of value when citing fuel generation locations, due to the inherent need of process water. This parameter becomes even more germane when considering the generation of hydrogen, due to the fact many of the process to generate such a fuel require a large magnitude of water, for example, hydrogen via steam methane reformation requires about 0.06 gallon/mile [23].

In this study, the AHP methodology implemented a site selection tool for the generation of hydrogen as a transportation fuel. The overall goal of this decision is to rank each location for its overall appeal to siting a hydrogen generation facility, which will

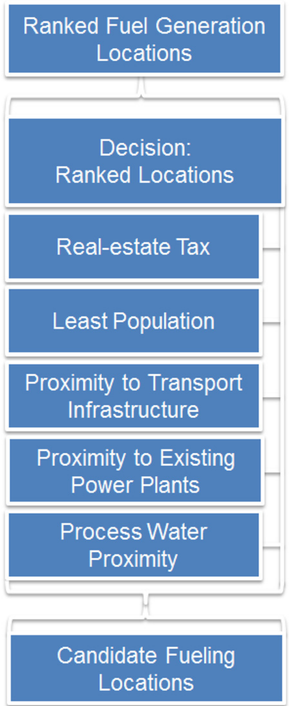

Fig. 3 Spatial AHP decision-making process

inform government officials and other prominent leaders. This tool is intended to delegate suggestions over wide swaths of land. As will be pointed out, there are some limitations and anomalies due to dataset resolution when looking at highly focused results. This tool is intended to highlight areas of interest and not to be taken as absolute. A visual outline of the decision making process is displayed in Fig. 3.

Results

Survey. The survey contained the previously mentioned five criterion (PPP, LLC, LP, EIP, and WIP). The experts were asked to rank each criterion in a pairwise fashion based on the previously described weighting scale, while maintaining a CR of 10% or less. Data were collected from five field experts with the results displayed in Table 2. These criteria maintained a CR of 9%, which satisfies the consistency constraint.

Observations should start with the results of the expert survey. Going back to Table 2 and taking the normalized principal eigenvector of each row, the general importance of the ranked criterion can be seen (displayed in the last column). At the conclusion of this step, it can be noted that the experts as a whole put a large amount of emphasis (43.8% more than the other criterion) on the importance of EIP relative to the fuel generation locations. This shows that the location of existing energy infrastructure is critical in dictating future fuel generation facility siting decisions. The other four criteria were ranked significantly less important. In order to explore how these criteria played into the ranking of generation locations, each one will be examined individually later in this paper.

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

AHP Ranking Results. Statewide results generated from the AHP can be viewed in Fig. 4. The first observation likely made from Fig. 4 is to note the low ranking areas since many areas received a high-priority ranking. Examining these low-ranking areas can provide some insight. Focusing on the corners, it can be seen that the areas of low rank exist far from installed energy infrastructure locations. However, other areas that display low rankings (i.e., the San Francisco, Los Angeles, San Diego metropolitan areas) are very near much energy infrastructure and power plants. The low rankings in these areas result from the high populations in these areas, causing an intensification of the weight on population. The final, somewhat low scoring location is settled into the northwestern corner of San Bernardino County. This low ranking is also correlated to its large distance from candidate energy infrastructure and power plant locations. These results are broad generalizations and are the aim of this study. These results are reasonable given the input weighting of the different criteria. These results can also be useful for decision makers interested in locating hydrogen generation sites in certain regions or areas. In order to further investigate how these results would affect calculations in a complete hydrogen supply chain planning tool, it is necessary to look at some of the air districts with degraded air quality in more detail to ensure that there are no pockets of high ranking within these areas.

To do this, the three main air districts that continually do not attain compliance with national standards are concentrated upon. Some general observations of these districts will be highlighted. The first noteworthy aspect is the high ranking of almost all points within the SJVAB. This could cause problems when considering the addition of hydrogen generation technologies that emit greenhouse gasses and criteria pollutants. Another overarching conclusion that can be drawn is the effect that infrastructure proximity has on the overall decision. It can be seen that areas both in the Bay Area and the Port of Los Angeles are ranked high mainly due to their proximity to energy infrastructure and oil refineries. The effect of other criterion is hard to judge at this scale. Therefore, two subsections of the state have been chosen for closer analysis.

Southern California Focus. The AHP results for Southern California are displayed in Fig. 5. The SoCAB region was chosen as a focus because this area has been noted for degraded air quality [2] while also having some interesting results. In this region, several locations have been ranked high for the siting of hydrogen generation facilities. Of particular interest are the four highly ranked locations circled in Fig. 5, as many of the locations surrounding them are ranked much lower overall. This becomes of

Table 2 Aggregate expert rankings

Spatial candidate location weighting matrix						
	Power plant proximity	Least land cost	Least populous	Infrastructure proximity	Process water proximity	Normalized principle eigenvector (%)
Power plant proximity	1	5/4	1	3/8	3/2	16.50
Least land cost	4/5	1	7/8	1/4	1	11.97
Least populous	1	8/7	1	2/7	8/7	14.30
Infrastructure proximity	8/3	17/4	31/9	1	17/7	43.84
Process water proximity	2/3	1	7/8	2/5	1	13.39

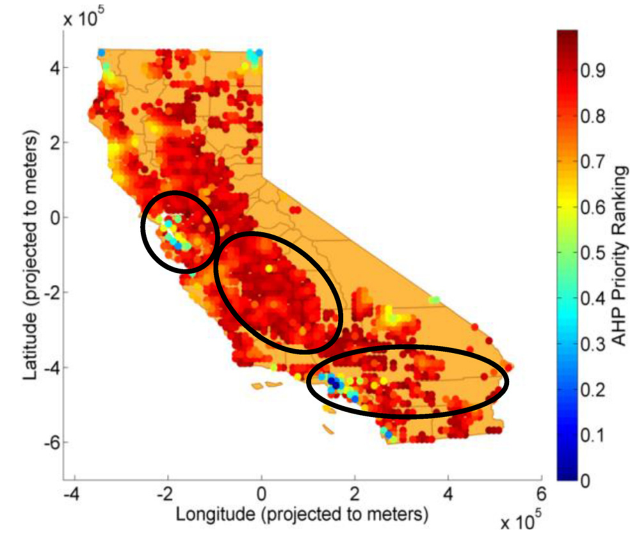

Fig. 4 Candidate generation location rankings for the entire state of California

particular interest when taking into account that large hydrogen generation facilities would not be sited there given the proximity to residential areas and that some hydrogen generation methodologies may still contribute to air quality problems. However, if the hydrogen technologies of interest were to be distributed in nature, environmentally sensitive, and acoustically benign, then these locations near residential areas might be of interest, and it is necessary for the AHP designed here to resolve distributed as well as centralized generation possibilities.

To further evaluate why these sites scored high while sites near them scored low, it is important to consider the proximity to infrastructure criterion given its high weighting relative to all other criterion. The energy infrastructure is shown in Fig. 5. On average, almost every considered point in this region is near some sort of infrastructure as evident in Fig. 5. This shows that a high weighting on proximity to infrastructure by the experts places a large, yet similar weighting on all candidate locations. The only difference between the locations is the distance they are located from the nearest infrastructure. Therefore, it is of interest to determine why some areas in the SoCAB are ranked markedly higher for the siting of a hydrogen generation facility.

In order to better understand where the locations of focus are geographically, Fig. 6 is displayed and can be compared to Fig. 5. These locations will be the concentration of the remainder of this section.

In order to continue to interpret the rankings determined by the AHP, a map of the SoCAB with AHP results and power plant locations are overlaid in Fig. 7. Power plants are chosen next due to their relative importance (see Table 2). The first thing to note about Fig. 7 is the apparent power plants in the ocean near the Port of Long Beach. This aberration is most likely due to the resolution of the dataset incorporating the power plants and the lack of resolution utilized by the base map. From viewing this figure, it can be seen that all of the candidate locations are relatively close to power plant locations. Therefore, it is assumed that the priority assigned due to this criterion is similar for the different points. The question still remains as to why some of the surrounding locations are ranked much lower, while being just as near if not closer to power plant locations.

The next step is to examine population data, which is next in the priority of the weighting criterion. After looking at Fig. 8, it can clearly be seen there is a large amount of fluctuation in the data within the areas of consideration. Populations near the generation locations that were ranked high overall are clearly low. This is most likely not the sole reason for the high rankings of these four locations due to the low overall priority of the population criterion.

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

The final criterion of consideration becomes the relative cost of land. It can be seen from Fig. 9 that the land costs in the areas of consideration are very near in magnitude. This raises some concern when looking at the candidate sites circled in red in Fig. 10 because these candidate sites are in locations with high real estate value and communities that would not be receptive to the construction of an industrial hydrogen energy generation facility. However, distributed, environmentally sensitive and quiet systems would be possible. This anomaly shows two important facts. The first is that the tool is designed to provide guidance to industry and state officials in decision making and is not intended to be a deterministic approach. Such instances of highly ranked generation locations would need to be manually removed by local authorities with a more detailed knowledge of the local land

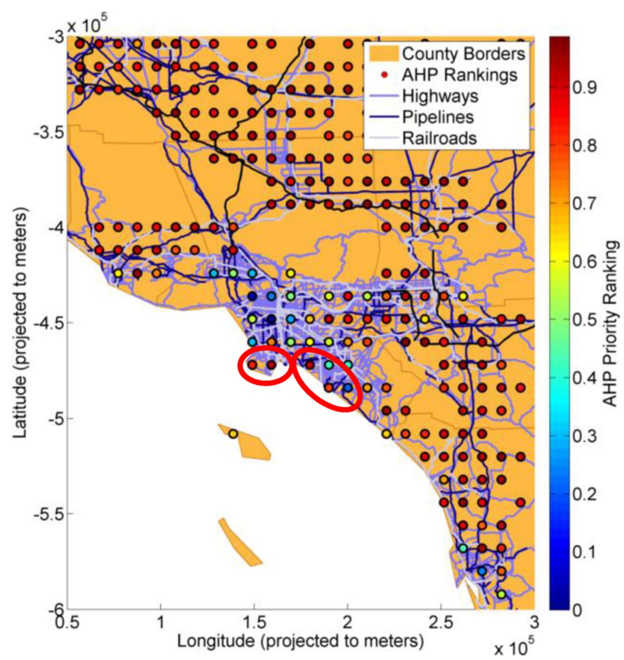

Fig. 5 SoCAB AHP priority rankings for fuel generation locations and infrastructure map [24]

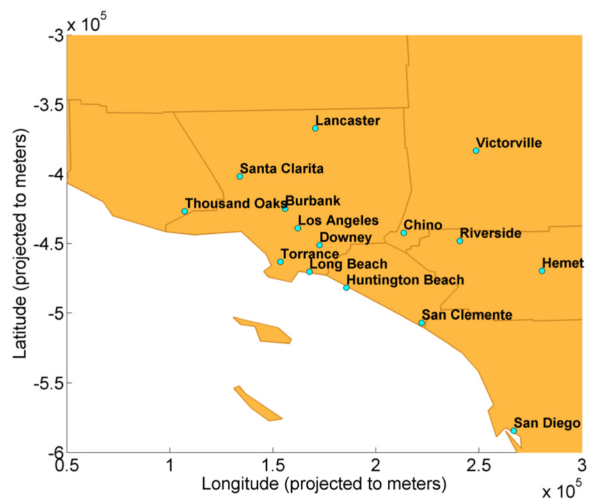

Fig. 6 Detailed view of cities in the SoCAB area of study

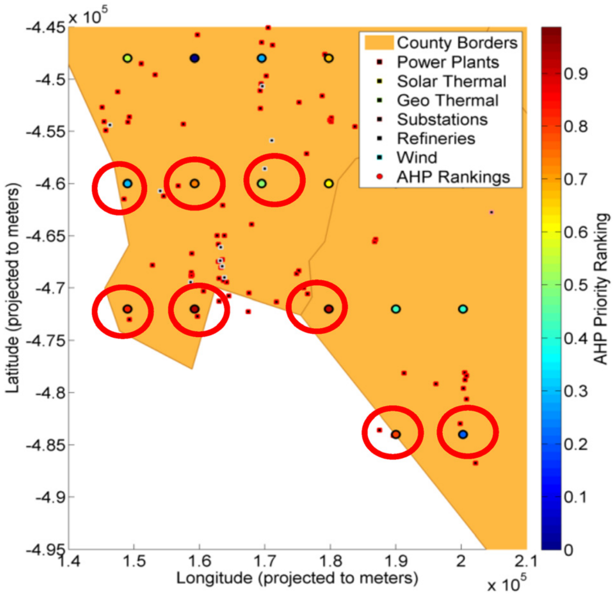

Fig. 7 SoCAB AHP priority rankings for fuel generation locations and power plants map [24]

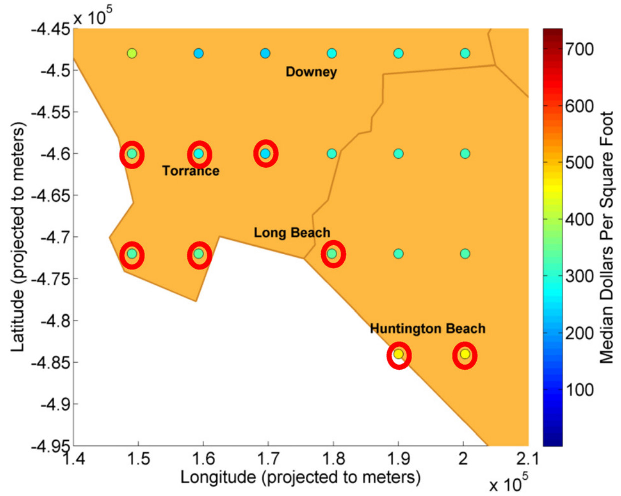

Fig. 9 SoCAB Zillow™ real estate data correlated to candidate fueling locations

appraisals and zoning if centralized hydrogen generation strategies were the only ones being considered by these decision makers. Second, this anomaly shows the critical nature of understanding the resolution of the datasets being utilized in such a study. Going back to Fig. 10, it can be seen that there is a lack of data in the region circled in red, which is assumed to be a missing, yet large magnitude data point. This data point is nonexistent in that location mainly because the data set was generated for all major cities in California and within the marked region exist no cities. Therefore, this tool would benefit greatly from acquiring land cost data with a greater spatial resolution.

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

Northern California Focus. A similar investigation is carried out on the San Francisco Bay Area. There are 12 locations encircled in red in Fig. 11. This set of locations has low overall rankings and are of interest because the other nearby sites have high rankings. For clarity with regard to proximity to cities, Fig. 12 is provided. Figure 12 is an equivalent spatial view to Fig. 11.

It can be seen from Fig. 11 that all of the circled areas sit directly adjacent to existing infrastructure, which has the highest weighting. This indicates that all of the candidate points should have an equivalent and high ranking when it comes to this criterion, however, they do not.

The next most heavily weighted criterion is the proximity to power plants. In Fig. 13, the ranked candidate locations and power plants within the state of California are displayed. A first observation in Fig. 13 is that the power plants appear to be in the water near the legend. This was addressed in the previous section, Southern California Focus, and has been correlated to a lack of costal resolution utilized by the base map. With respect to ranking of the candidate locations, all of the points are close to or on top of existing power plant locations, except for the two locations circled in light blue. This is likely partially responsible for the sites' low rankings.

The next criterion to investigate due to its weighting is the population. In Fig. 14, it can clearly be seen that the points of interest

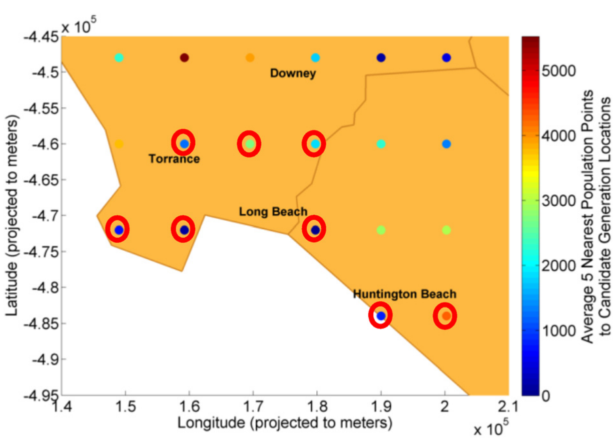

Fig. 8 SoCAB average five nearest population points from landscan data relative to candidate fuel generation locations

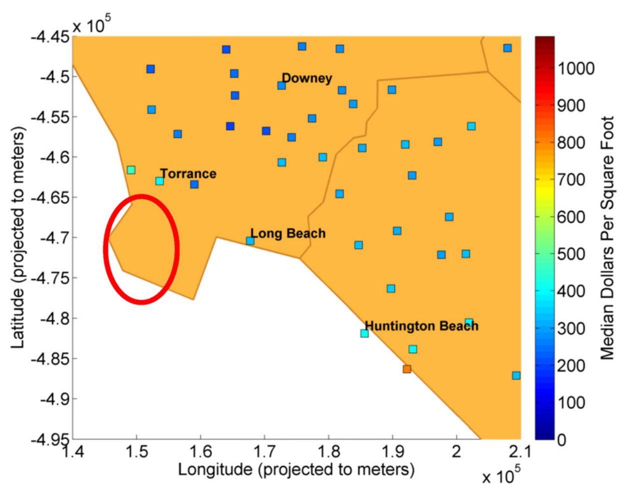

Fig. 10 Zillow™ raw real estate data for cities in the SoCAB

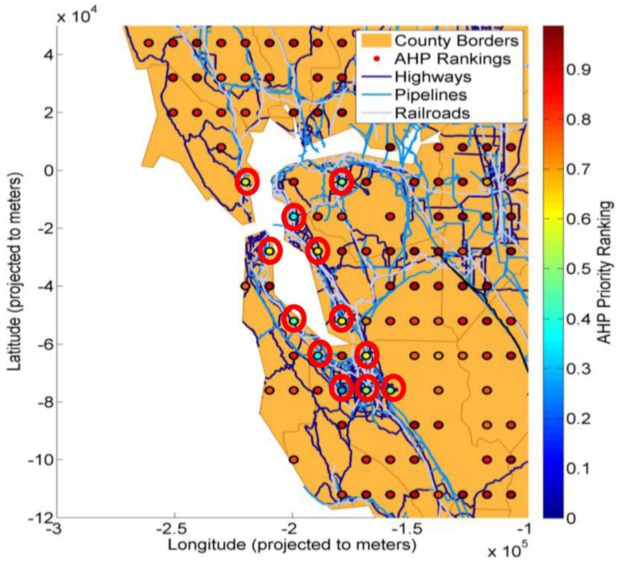

Fig. 11 SFBAAB AHP priority rankings for fuel generation locations and infrastructure map [24]

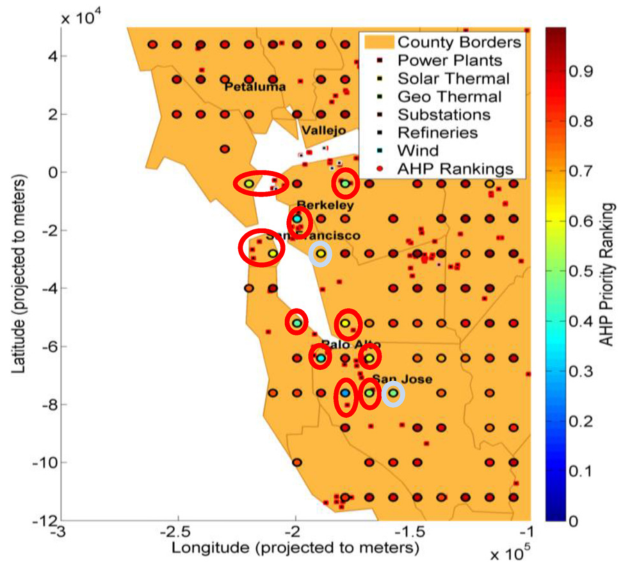

Fig. 13 SFBAAB AHP priority rankings for fuel generation locations and power plants map [24]

fall into the category of moderate to high populations. An interesting facet is that the two locations circled in light blue only have moderate population values. This goes to show that the proximity to power plants, energy infrastructure and population criterion cannot be the cause of the rankings of these two outstanding points.

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

The final criterion to consider then becomes the surrogate land cost data. The raw data extracted from Zillow™ can be seen in Fig. 15 and values assigned to the candidate locations based on the nearest Zillow™ data point can be observed in Fig. 16. First, as a general observation all of the housing data surrounding the San Francisco Bay are moderate to high values. This fact, in and of itself, is most likely a contributing factor to the low ranking assigned to the nearby candidate generation locations. However, an extremely interesting artifact circled in red, can be observed in Fig. 16. The three locations circled have some of the highest home values assigned to them, however, when observing Fig. 11, it can be seen that these same locations receive a high overall AHP score. This solution can only be justified by observing Fig. 14 and noticing that these three points have an extremely low population value. This makes sense due to the greater weighting assigned to low populations as compared to low land cost, in addition, if proximity to power plants and infrastructure are about the same, these three points would logically obtain a high ranking.

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

Summary and Conclusions

In this paper, the AHP was utilized to rank candidate fueling locations for potential as hydrogen generation sites in order to: (1)

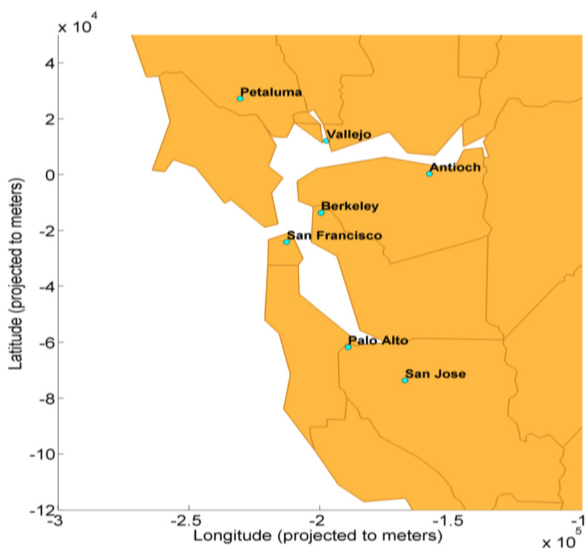

Fig. 12 Detailed view of cities in the SFBAAB

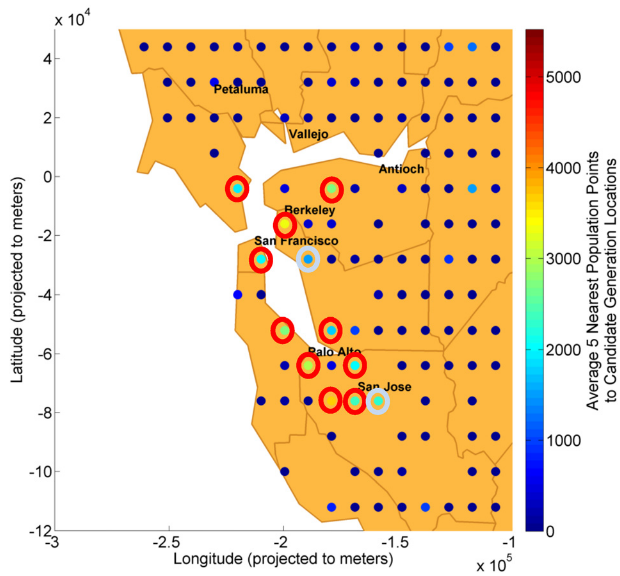

Fig. 14 SFBAAB average five nearest population points from landscan data relative to candidate fuel generation locations

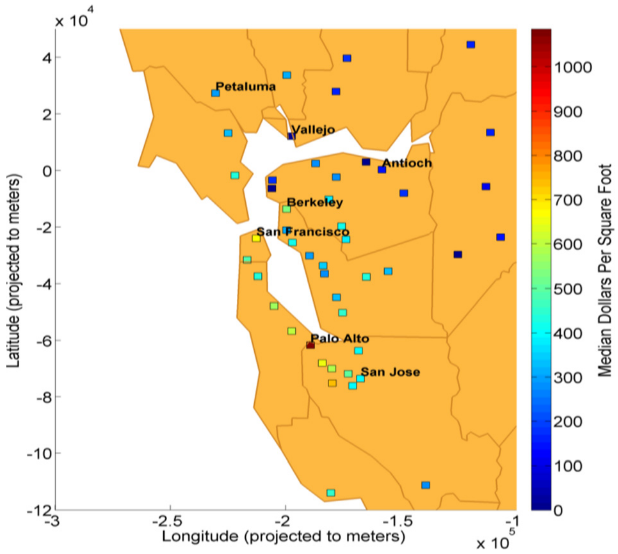

Fig. 15 Zillow™ raw real estate data for cities in the SFBAAB

examine the AHP as a fuel generation facility siting tool, (2) exercise the AHP tool in a case study for hydrogen fuel production focusing on both Northern and Southern California that is independent of overall hydrogen demand, and (3) examine the robustness and resolution of the analysis results through the exploration of anomalies in the results. The identification of anomalies allows for the verification of the model's utility in complete representation of hydrogen fuel cell vehicle roll out planning. In order to systematically rank these locations, five criteria were chosen: (1) proximity to power generation facilities, (2) lowest land cost, (3) LP, (4) proximity to existing energy infrastructure, and (5) WIP. In order to generate the weighting metrics for each of these criteria and to carry out a case study on hydrogen production, five hydrogen fueling supply chain experts were surveyed.

The AHP tool reasonably demonstrated its capability to rank various candidate generation sites. There were some apparent abnormalities that upon further inspection revealed that the results indeed made sense given the rankings applied to the selected criteria. The multiparameter approach to the overall decision exemplifies the power of the AHP.

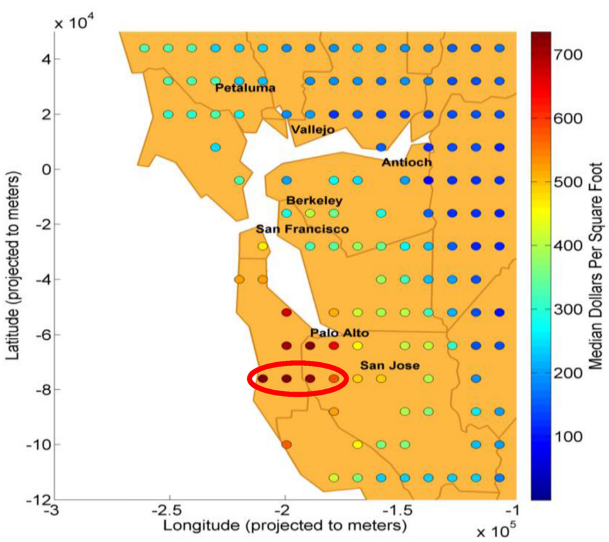

Fig. 16 SFBAAB Zillow™ real estate data correlated to candidate fueling locations

Major conclusions from this study are:

- The AHP tool reasonably demonstrated its capability to rank various candidate generation sites.
- The rankings showed high variability in certain locations that led to further investigation.
- These investigations allowed the following conclusions:
  - Spatial resolution of different data sets can lead to some of this variability
  - Criterion with low weighting can actually become significant drivers in the overall ranking if the other criteria are nearly equal.

Future Work

One shortcoming of this study is a carbon intensity and air quality signal. In order to prevent emissions intensive technologies from being installed in areas with degraded air quality, a parameter should be introduced that accounts for emissions that occur in certain areas. The AHP is versatile enough to accommodate such a signal through any sort of air quality and emissions data. In future studies, this criterion(a) will be included.

The AHP was chosen due to its flexibility in the decomposition of complex problems. Therefore, future studies will decompose the decision in Fig. 3 into several more subdecisions. For example, the EIP metric could be broken down into subcriterion based on the type of infrastructure (highways, railroads, natural gas pipelines, and electrical transmission lines). Each of these subcriteria would receive a different weight when considering the generation of different fuel types. Finally, this AHP-based model will be expanded to span the entirety of the fuel generation, distribution and dispensing process. The AHP will be applied to choosing the type of fuel generation technology (e.g., steam methane reformation versus electrolysis) at the various sites as well as the storage, delivery, and dispensing of the fuel.

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