SERA Scenarios of Early Market Fuel Cell Electric Vehicle Introductions

Modeling Framework, Regional Markets, and Station Clustering

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Technical Report
NREL/TP-5400-56588
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Acknowledgments

Funding for this report came from the U.S. Department of Energy's Fuel Cell Technologies Office. The SERA model has been developed at NREL over the course of the past five years, and builds upon earlier development of the Hydrogen Deployment System Modeling Environment, the HyDS-ME model, by Keith Parks. During this time many improvements have been made to the SERA model, including revisions based upon feedback received in response to presentations made at the U.S. Department of Energy Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting. Jon Svede and David Thompson made major contributions to the SERA software architecture, design, and implementation.

Acronyms and Abbreviations

ADOPT	Automotive Deployment Options Projection Tool
AEO	*Annual Energy Outlook*
CaFCP	California Fuel Cell Partnership
FCEV	fuel cell electric vehicle
H	hydrogen
H2A	hydrogen analysis models (developed by NREL)
HDSAM	Hydrogen Delivery Scenario Analysis Model (developed by Argonne National Laboratory)
HEV	hybrid electric vehicle
HYDRA	Hydrogen Demand and Resource Analysis Tool
IRS	Internal Revenue Service
kg	kilogram
MA3T	a vehicle choice model (developed by ORNL)
NAS	National Academy of Sciences
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
ReEDS	an electric sector market expansion model (developed by NREL)
REF	Renewable Electricity Futures
SERA	Scenario Evaluation, Regionalization and Analysis (developed by NREL)
STREET	a fueling station placement model (developed by University of California at Irvine)
TEF	Transportation Energy Futures
UCD	University of California at Davis
VISION	a vehicle stock model (developed by Argonne National Laboratory)
VMT	vehicle-miles traveled

Abstract

The availability of fueling infrastructure has become a major barrier to the early market success of hydrogen fuel cell electric vehicles (FCEVs). Various models have addressed infrastructure development during the early transition phase, but few long-term models have captured development dynamics in a manner that is consistent with real-world planning activities. This report describes the development and analysis of detailed temporal and spatial scenarios for early market infrastructure clustering and vehicle rollout using the Scenario Evaluation, Regionalization and Analysis (SERA) model. The scenarios reconcile nationwide scenario dynamics from a National Academy of Sciences study (NAS 2008) with observations and lessons learned from California's early market strategy and planning activities (CaFCP 2012). The report provides an overview of the SERA scenario development framework and discusses the approach used to develop the nationwide scenario. The capability to focus on detailed infrastructure rollout dynamics within particular regions and states is then discussed with reference to Northeast Corridor states. The report also provides a description of the enhanced station placement algorithms developed to simulate both urban area network coverage and station clustering in neighborhoods with high densities of early adopters. Results from the national scenario analysis suggest that long-term levelized delivered costs for hydrogen tend toward \$6.00/kg nationally, and zero cumulative cash flow is achieved in about 2018 or 2025 if hydrogen is priced at \$11.00/kg and \$6.75/kg, respectively. The capability to focus on dynamics within particular regions and to articulate detailed station placement strategies within urban areas adds realism and a planning perspective to these national scenario results.

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1 Introduction

Hydrogen fuel cell electric vehicles (FCEVs) offer significant social and environmental benefits, and can contribute to long-term goals to reduce greenhouse gas emissions, petroleum imports, and urban air pollution. With major automakers planning vehicle introductions in the 2015–2017 timeframe, the availability of hydrogen refueling stations has become a major market barrier to the commercialization of FCEVs. In addition to progress in California, through the efforts of the California Fuel Cell Partnership (CaFCP 2012) and the California Energy Commission's Alternative and Renewable Fuel and Vehicle Technology Program (CEC 2013), the U.S. Department of Energy has recently announced H2USA, a public-private partnership to support hydrogen infrastructure development on a national scale (DOE 2013a). These activities will contribute to international efforts to prepare markets for FCEV commercialization in Japan, Germany, Scandinavia, Korea, the United Kingdom, and elsewhere (ICCT-BTI 2012; UK H_2Mobility 2013).

A wide range of analytic models have addressed different challenges associated with the commercialization of FCEVs and hydrogen infrastructure development, including the recent market and policy analyses from the National Academy of Sciences (NRC 2013) and a study of zero emission vehicle markets in California (Greene et al. 2013). Both studies emphasize the importance of hydrogen infrastructure for successful market growth. The present study builds upon a series of infrastructure analysis activities supported by the U.S. Department of Energy (DOE 2013b), and contributes to previous analytic insights revealed through a number of studies addressing particular issues associated with the early market transition to FCEVs (Struben 2006; Melaina 2007; Greene et al. 2008; NAS 2008; Lin et al. 2008; Meyer and Winebrake 2009; Ogden et al. 2010; Stephens-Romero et al. 2010). In particular, this report reviews updated capabilities of the Scenario Evaluation, Regionalization and Analysis (SERA) model with respect to clustering hydrogen stations as a means of reducing early market infrastructure capital requirements (Ogden and Nicholas 2011). The capability to assess detailed regional developments has benefited from planning efforts in California (CaFCP 2012). The SERA model, originally developed as the HyDS-ME model, has been in development since 2005 to support infrastructure analysis studies for the DOE's Fuel Cell Technologies Office (Bush et al. 2011; Bush et al. 2010).

This report presents an updated national scenario and focuses on several new capabilities recently incorporated into the SERA model. Section 2 provides an overview of the general analysis framework used to develop scenarios of hydrogen infrastructure build-out. Section 3 provides an example of a national "hydrogen success" scenario, and Section 4 demonstrates how detailed scenario metrics can be developed for a particular region, in this case the Northeast Corridor states. Updates and enhancements to the station placement algorithms in SERA are presented in Section 5. Section 6 gives a brief summary of the report.

2 Scenario Analysis Methodology

The SERA model fills a unique and important niche in the temporal and geospatial analysis of hydrogen infrastructure build-out for production and delivery. SERA complements other hydrogen analysis tools and is well suited to contribute to scenario analysis involving the temporally specific geospatial deployment of hydrogen production and delivery infrastructure. For example, the SERA model can be easily configured to assess investment and market growth dynamics in a particular state or region, such as California, Texas, or the Northeastern States. Its key capabilities are:

1. Optimization of the physical build-out of hydrogen infrastructure
2. Unified treatment of production, delivery, and dispensing
3. Ease with which new technologies can be added to an analysis
4. Consistent physical and economic computations
5. Ability to estimate costs, cash flows, financing and incentives
6. Spatial and temporal resolution of hydrogen infrastructure networks, including refueling stations
7. Regional specificity
8. Allowance for exogenously specified urban hydrogen demands.

SERA's internal architecture is flexible, and it is compatible with geographic information systems and various hydrogen analysis (H2A) case studies (DOE 2009; DOE 2012a; DOE 2012b), as well as H2A or Fuel Cell Power Model case studies developed to explore unique infrastructure scenarios, such as incorporation of tri-generation stationary fuel cells that produce heat, hydrogen and power (Steward et al. 2012). SERA is designed to answer questions such as the following:

- Which pathways will provide least-cost hydrogen for a specified demand?
- What network economies can be achieved by linking production facilities to multiple demand centers?
- How will particular technologies compete with one another?
- How does clustering of refueling stations and FCEV garaging affect infrastructure requirements and costs?

To answer such questions, SERA supports analyses aimed at identifying optimal infrastructure to meet specified annual urban hydrogen demands, perhaps coupled to other multiple objectives and constraints. Cash flows are computed, detailed by infrastructure component, city, and region, and these provide insights into the components of hydrogen costs, which are determined by year, volume, and locality. Four methods of long-distance hydrogen transport are considered: pipeline, gaseous truck, liquid truck, and railroad. The major use of SERA is for studying potential turning points in infrastructure build-out via sensitivity analysis on infrastructure, feedstock, and fuel cost inputs in the context of the complex transient and transitional interactions between increasing hydrogen demand and hydrogen infrastructure construction. With carefully constructed input data sets representing the relative cost and performance characteristics of different infrastructure components and pathways, SERA can also weigh tradeoffs between investments in various infrastructure types, given policy constraints (e.g., regulations on greenhouse gas emissions). Figure 1 shows the interrelationship between the input data for SERA and the algorithms applied to them to compute the delivered cost of hydrogen. The infrastructure networks are optimized using a simulated-annealing algorithm that explores the large set of potential build-out plans that meet the input requirements for hydrogen delivery at cities over time. The hydrogen transport computations are based on graph-theoretic algorithms for determining optimal flows in networks. The cash flow computations rely on standard discounting approaches. See reports by Bush et al. (Bush et al. 2011; Bush et al. 2010) for details on the algorithms, data flows, and assumptions within the individual SERA submodels.

SERA consists of six interlinked submodels generating final outputs, as shown in Figure 1. Input data sources are indicated in red for each submodel and outputs from the final results module are shown in blue. A typical study that utilizes the SERA submodels would follow the workflow sequence shown in Figure 2: (1) scenario generation, (2) vehicle choice, (3) vehicle stock, (4) infrastructure cost, (5) intra-regional refueling-station placement, and (6) inter-regional production and delivery optimization. More complex studies may involve feedback between the estimated delivery cost and availability of hydrogen for FCEVs and consumer choices of vehicle types (e.g., FCEVs vs. non-FCEVs).

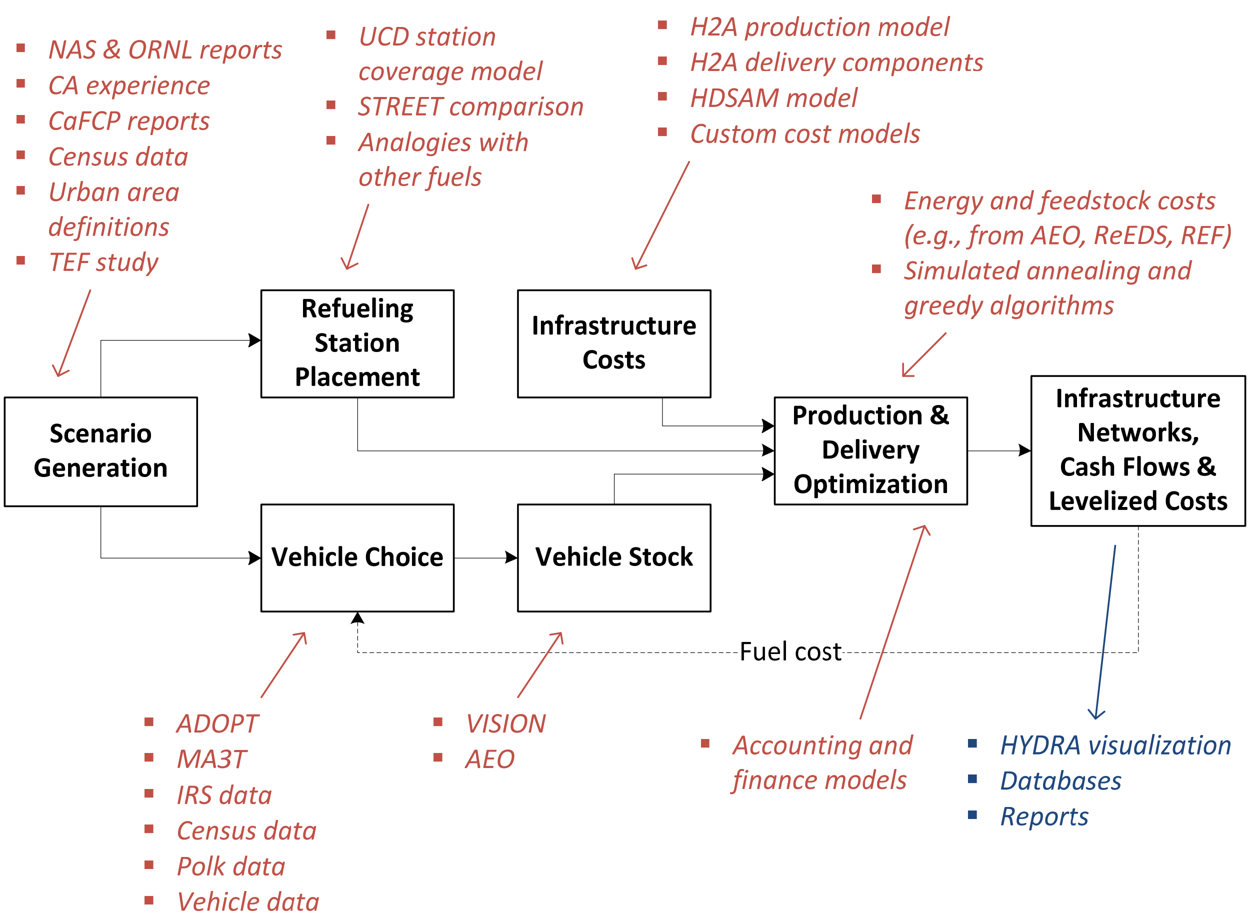

Figure 1. Interrelationships between SERA modules, their input data, and their outputs.

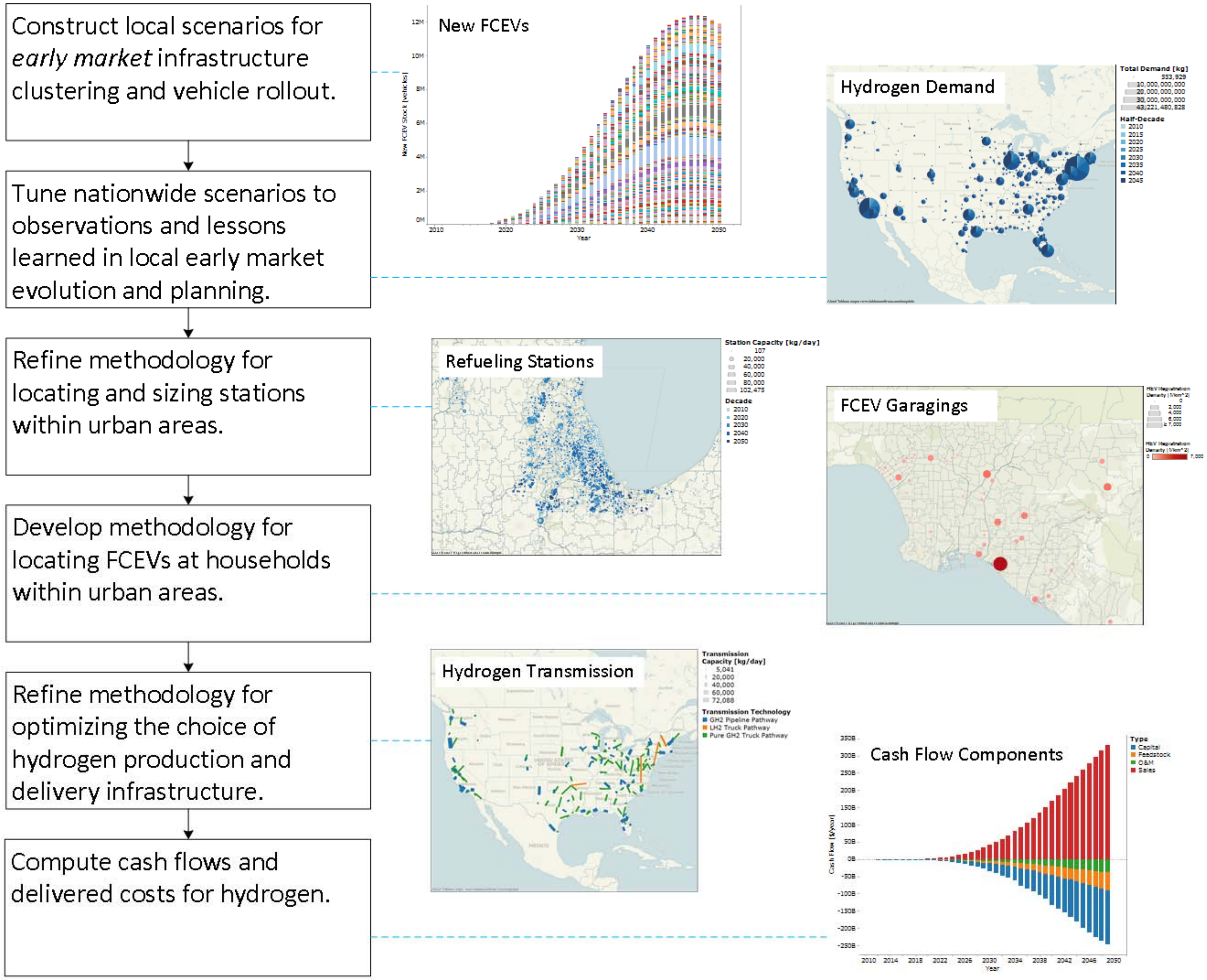

Figure 2. Workflow for a typical SERA study.

3 Early Market "Hydrogen Success" Scenario

3.1 Demand Characteristics

Three nationwide reference scenarios for FCEV infrastructure rollout, sizing, and placement have been constructed, based on a combination of near-term matched with recent stakeholder rollout plans in California and longer-term high-penetration conditions of NAS scenarios (NAS 2008). These scenarios are calibrated to the early market adoption rates anticipated by stakeholders within CaFCP (2012), and comparable (but later) infrastructure rollout patterns are extended to all major U.S. urban areas. This is an attempt to generalize the quantitative characteristics of observed and planned FCEV refueling station rollout and vehicle adoption in California to urban areas nationwide. To accommodate the time lag that mimics California adoption and sequential adoption among urban areas, the early years of market share growth in the NAS scenarios for FCEV station rollout and vehicle adoption were adjusted downward by approximately 50%. The later years of the new scenarios match the high-penetration conditions of the NAS scenarios, while the middle years of the new scenarios gradually transition between California-like early market growth and the NAS-like growth in later years. This is accomplished by applying a smoothing function $\frac{1.064248}{1+e^{-(\text{year}-2022.55)/10}}$ to the year-by-year NAS hydrogen demands: we assume an S-shaped transition (i.e., a logistic function of the general form $\frac{A}{1+e^{-(\text{year}-B)/C}}$ where A, B, and C are unknown parameters) between the early market and mature market hydrogen demands, and then compute the precise shape of the transition (e.g., the values of the logistic parameters) given the numerical values for the early and mature hydrogen demands. This adjustment of demands effectively delays the introduction of new FCEVs in the early years of the NAS "hydrogen success" scenario so that the overall hydrogen demand and FCEV introduction rate approximately match the California forecasts. In the middle and long term, these scenarios approach the standard NAS scenarios ("accelerated," "success," and "partial success" scenarios). Once the NAS specification of demand over time is disaggregated (see Figure 3), all of the vehicle stock and hydrogen demand computations are performed using the SERA Vehicle Stock submodel, under vehicle-miles traveled (VMT) per year profiles consistent with the NAS scenarios. The Vehicle Stock submodel is comparable in structure and underlying data to Argonne National Laboratory's VISION model (Ward 2008).

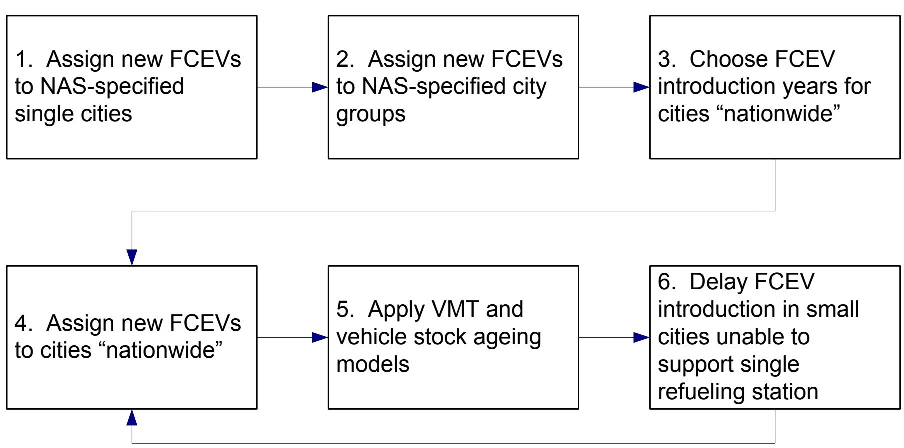

Figure 3. Process for disaggregating and sequencing FCEV introductions for NAS-like scenarios applied to individual urban areas.

We apply the aforementioned smoothing technique to hydrogen demands in the approximately 600 largest urban areas in the United States (see Figure 4). This technique has the advantage of maintaining rigorous self-consistency between scenario parameters such as FCEV vehicle introduction, stock turnover, VMT, and the demand for hydrogen fuel. Figure 5 shows the resulting vehicle stock introductions and total stock for the early market “hydrogen success” scenario, while Figure 6 illustrates the implications of that scenario for incremental and annual hydrogen demand. Finally, Figure 7 demonstrates how these assumptions play out geographically.

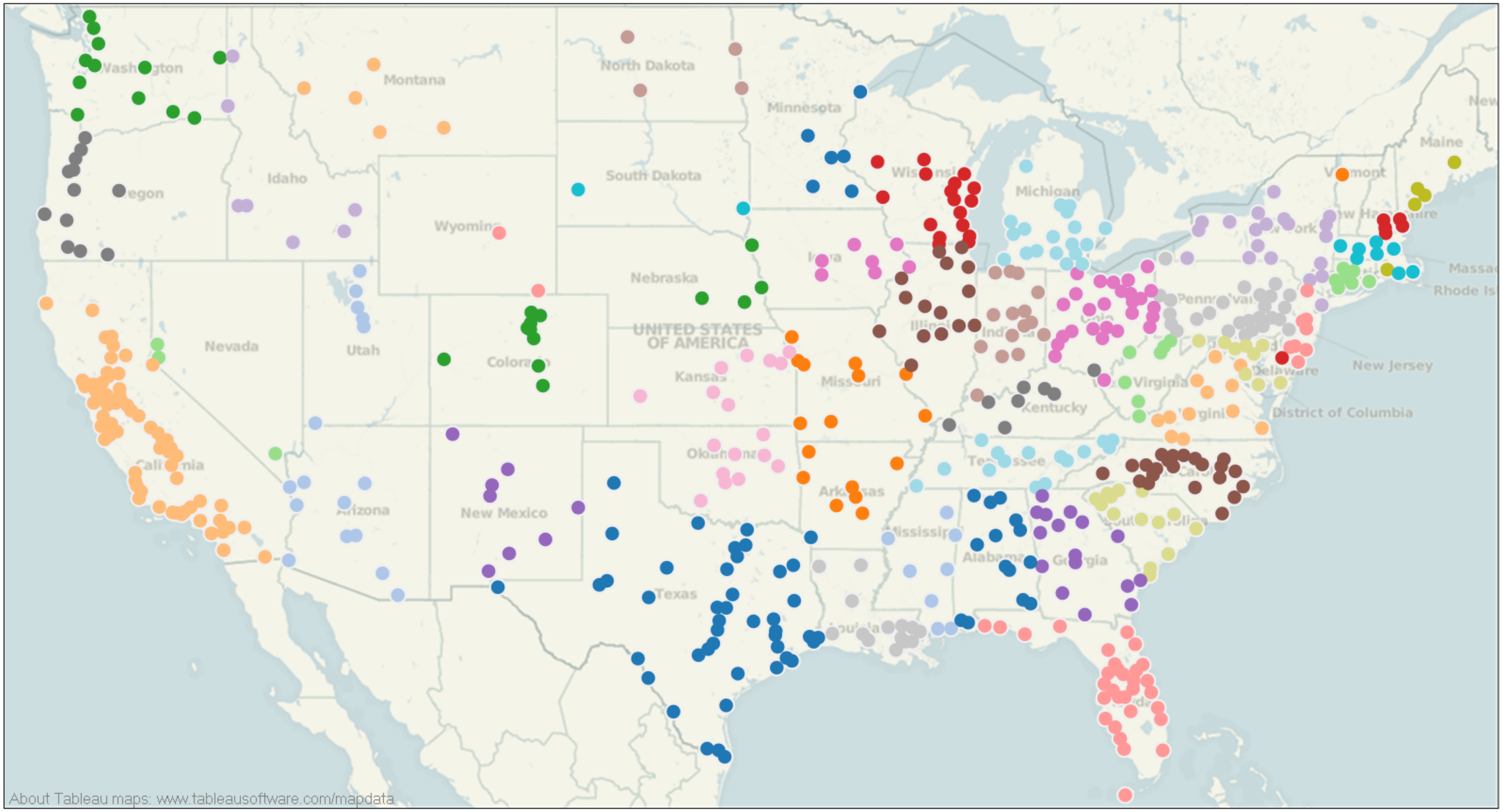

Figure 4. Locations of the approximately 600 urban areas considered in the early market "hydrogen success" scenario.

Urban areas are color-coded by state.

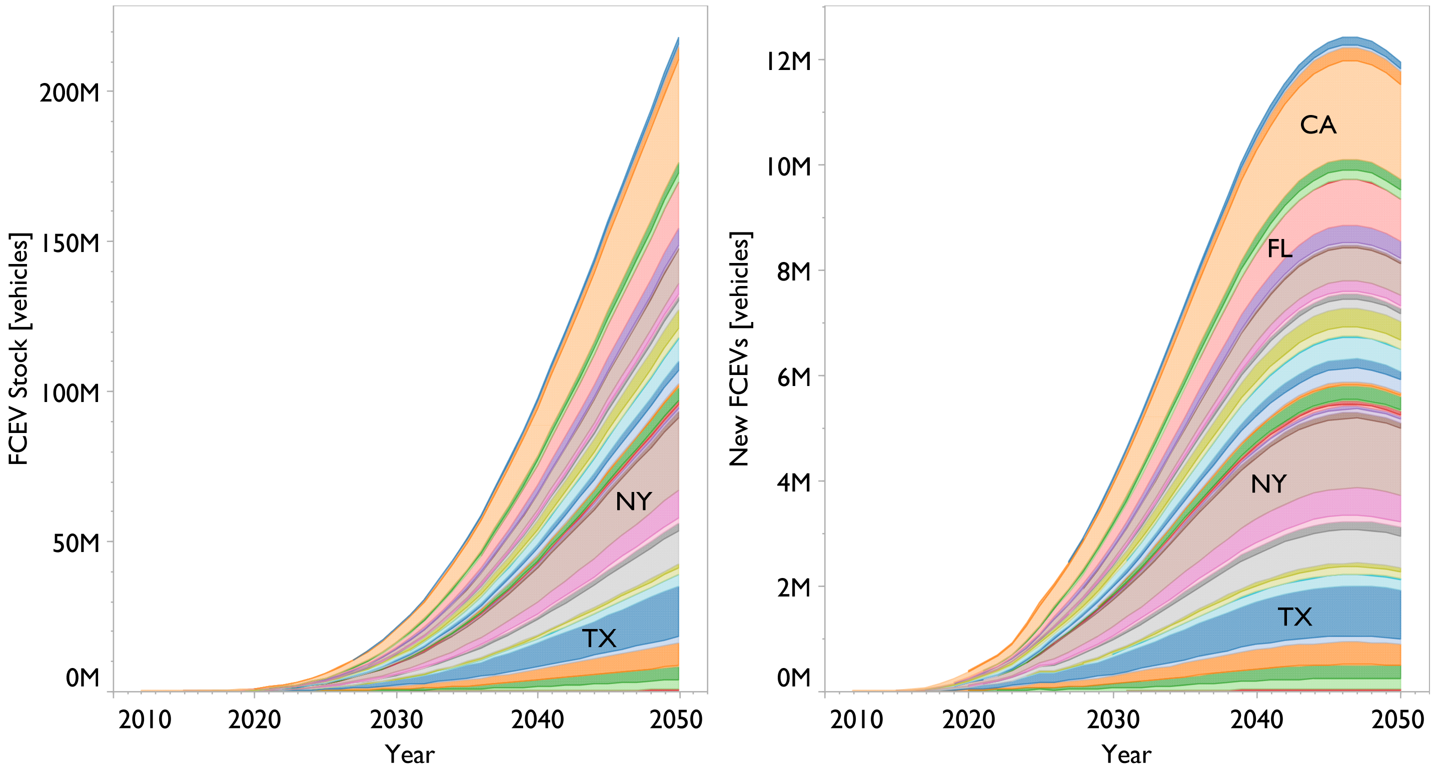

Figure 5. FCEV stock (left) and new FCEV stock (right) in the early market "hydrogen success" scenario.

The colors correspond to the urban areas in Figure 4. Note that vehicle sales level off and decline slightly in the last five years of the scenario because the underlying NAS scenario on which those years are based indicates a slowdown in the rate of FCEV adoption as target FCEV stock levels are realized.

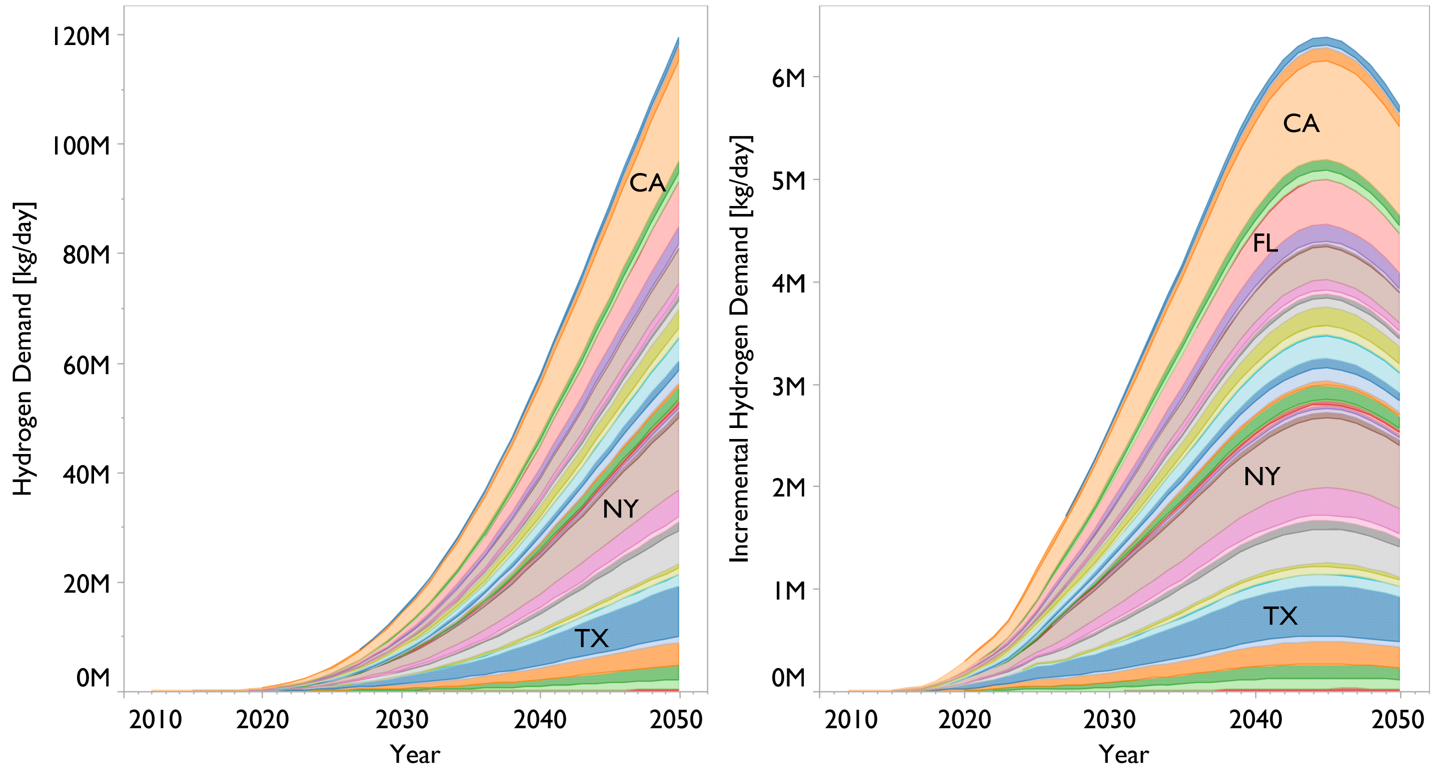

Figure 6. Hydrogen demand (left) and incremental hydrogen demand (right) in the early market "hydrogen success" scenario.

The colors correspond to the urban areas in Figure 4.

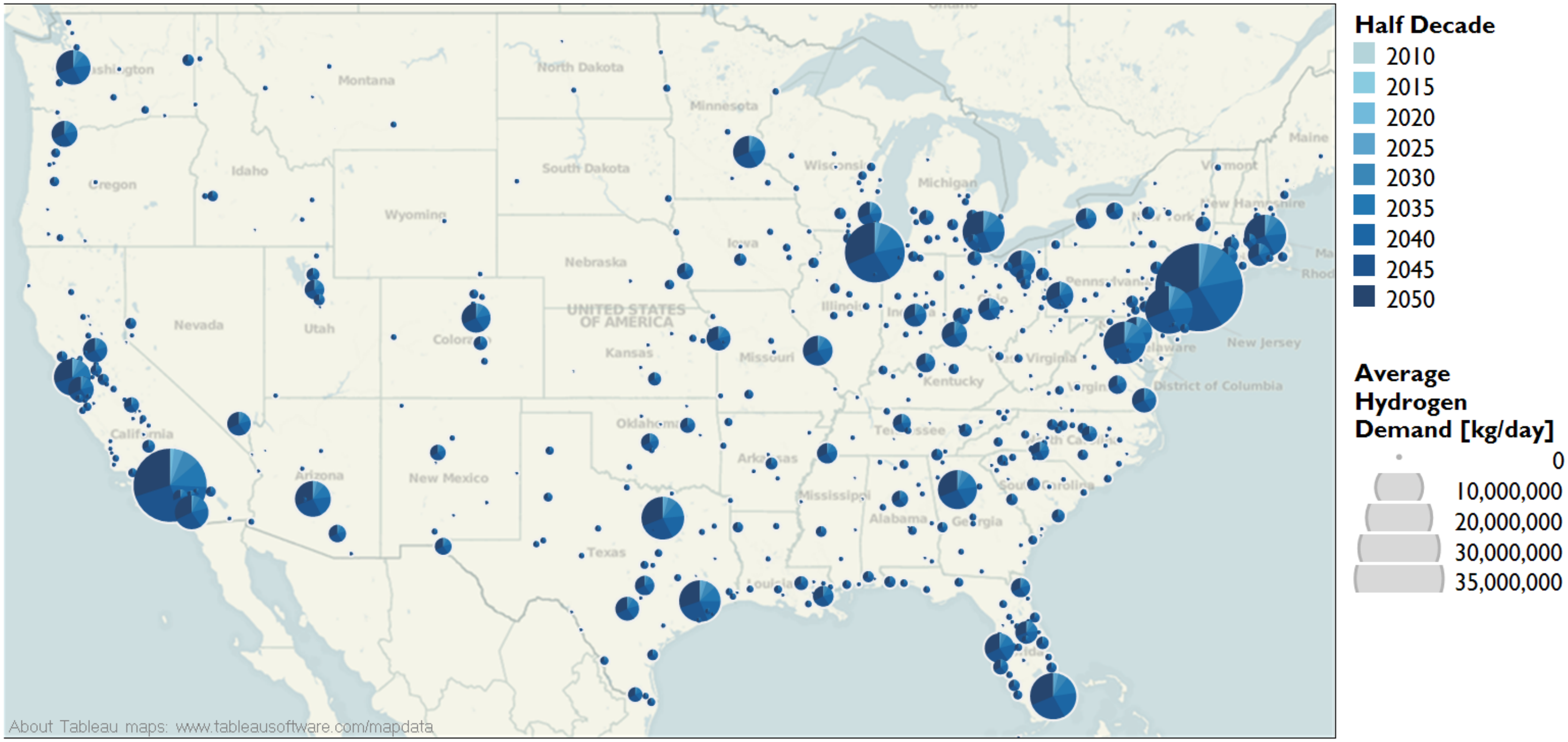

Figure 7. Geographic distribution of hydrogen demand in the early market "hydrogen success" scenario, by half decade.

3.2 Local Infrastructure

Given the forecast of hydrogen demand over time for each urban area, the local FCEV infrastructure can be generated using SERA's station placement and sizing submodel. This submodel assumes the generic distribution of fueling capacities shown in Figure 8 and gradually increases the average station capacity over time as the demand in the urban area and the density of stations increase. The horizontal axis indicates the fraction of total stations in any given urban area, and the vertical axis indicates the rank order of stations by size as the percentage of the average station size in the urban area. These empirical relationships are based on a study of the evolution and distribution of gasoline fueling stations (Melaina and Bremson 2008; Melaina and Bremson 2006). The spatiotemporal station placement technique relies on four algorithms that are applied in sequence. First, the time-dependent hydrogen demand for the urban area is used to estimate the number of stations that would be built in each year. Based on those station counts and on an average station capacity for the year, the stations are randomly sized according to an empirically determined capacity distribution. Finally, the stations are randomly located within the urban area of interest (however, see Section 5). The station-count algorithm is deterministic, whereas the station sizing and location algorithms are stochastic. The mathematical details of the algorithms follow.

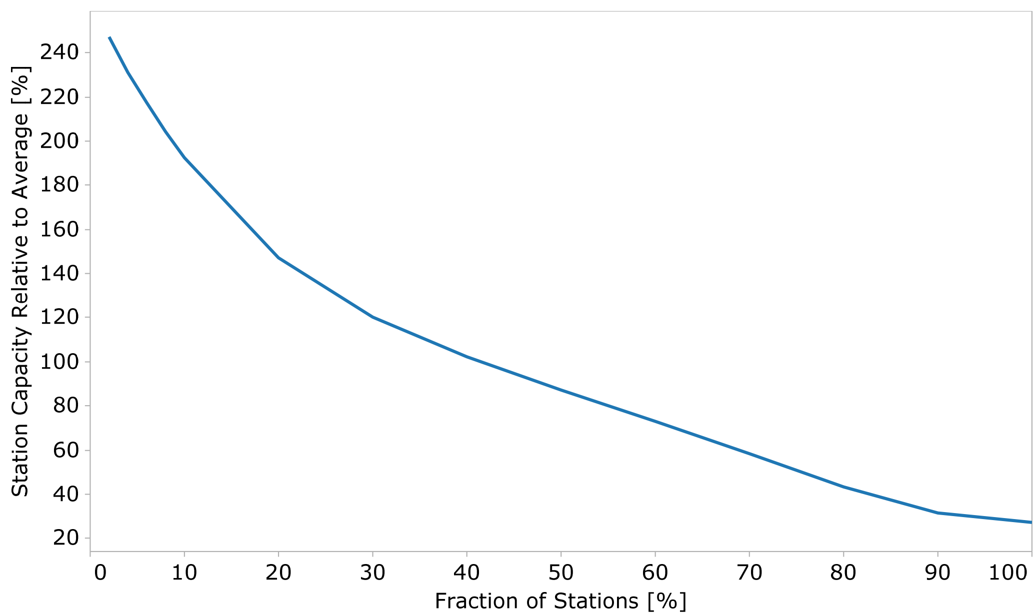

Figure 8. Generic distribution of station capacities relative to the average station size and as a function of the percent of stations in any urban area.

Figure 9 indicates the trend towards larger station capacities over time, while Figure 10 shows that the distribution of capacities includes a mixture of small stations, introduced in the early years of FCEV presence, and much larger stations (equivalent to the dozen or more fueling pumps that are found in the largest gasoline refueling stations present today). It is important to note that the NAS scenarios stage FCEV introductions from larger cities to smaller ones, and this trend toward the appearance of small demand centers over time somewhat counteracts the competing trend toward the construction of higher-capacity stations in areas where FCEVs are well established. This is why Figure 10 indicates the continued construction of small stations in the later years of the scenario. The sequencing of stations by urban area size is somewhat apparent in Figure 11, which maps the count of stations over time in urban areas.

Once the counts and sizes of fueling stations have been estimated, they can be located within urban areas using several alternative algorithms available in SERA. For the purposes of these nation-level scenarios, we use the simple option, which allocates FCEV fueling stations to ZIP codes as a function of the prevalence of hybrid electric vehicle (HEV) registrations (acquired from Polk), which are assumed to be an adequate surrogate for early adopters of FCEVs and therefore the proximity of initial fueling stations to early adopter households. Results from a detailed survey of driver refueling behavior support the assumption that refueling events tend to occur near consumer households (Kitamura and Sperling 1987; c.f. Kelley and Kuby, forthcoming). ZIP codes within the urban area are sorted in order of decreasing HEV density, and those are assigned sequentially to the list of FCEV fueling stations, but with a bias toward assigning multiple stations to the highest density ZIP codes; stations are placed uniformly at random within the ZIP codes. Recent enhancements to the station placement algorithms are discussed in Section 5.

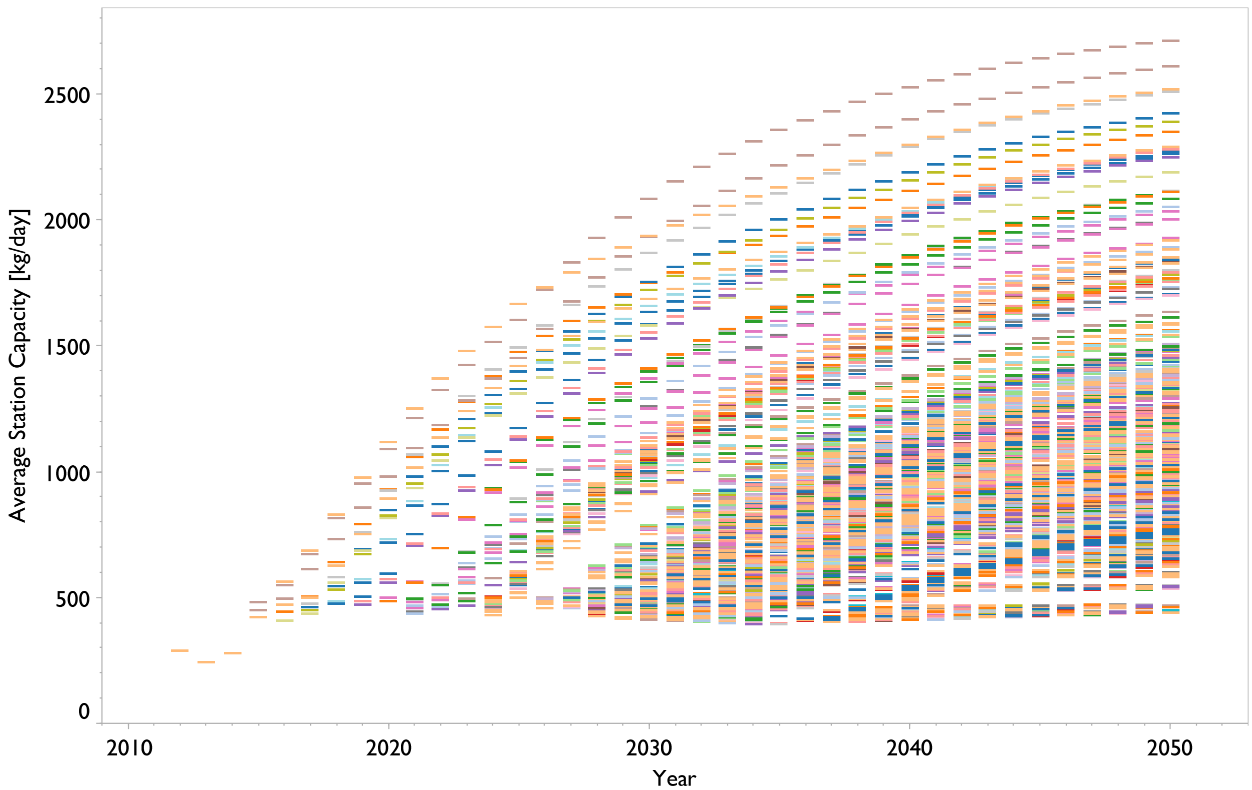

Figure 9. Distribution of the average capacity of new FCEV fueling stations, by urban area and year of construction in the early market "hydrogen success" scenario.

The colors correspond to the urban areas in Figure 4.

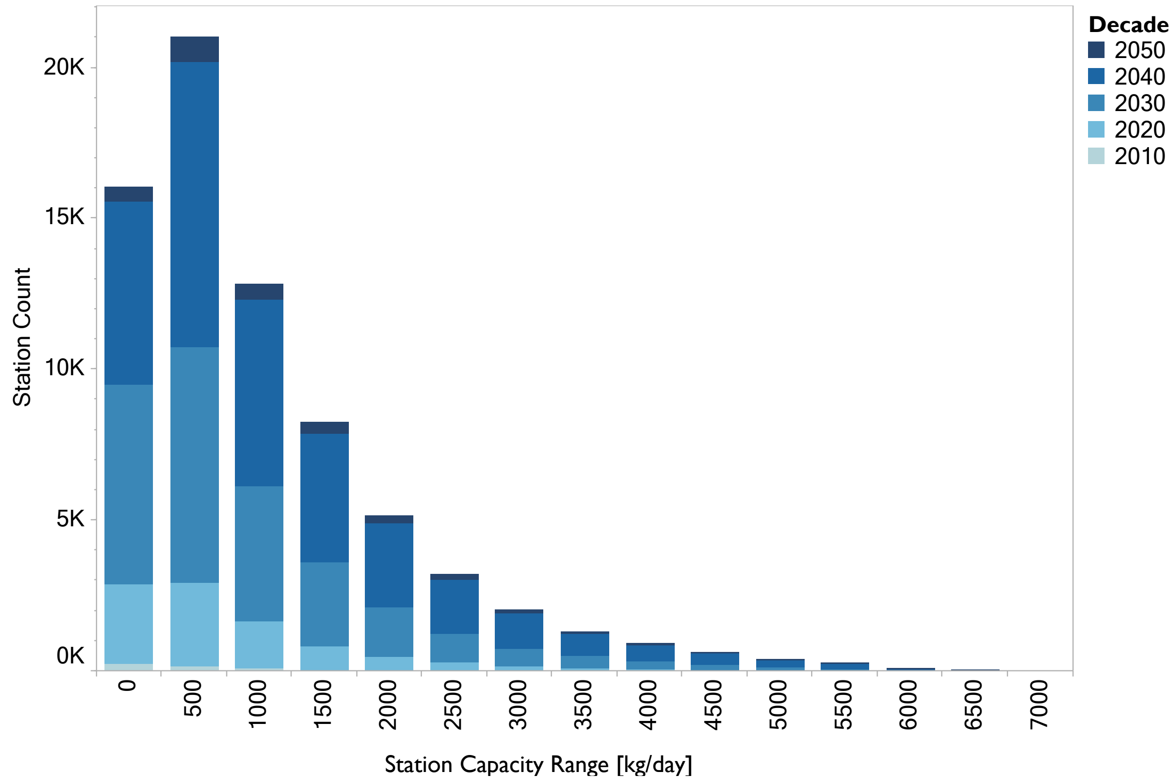

Figure 10. Distribution of capacities of FCEV fueling stations, by decade of construction, in the early market "hydrogen success" scenario.

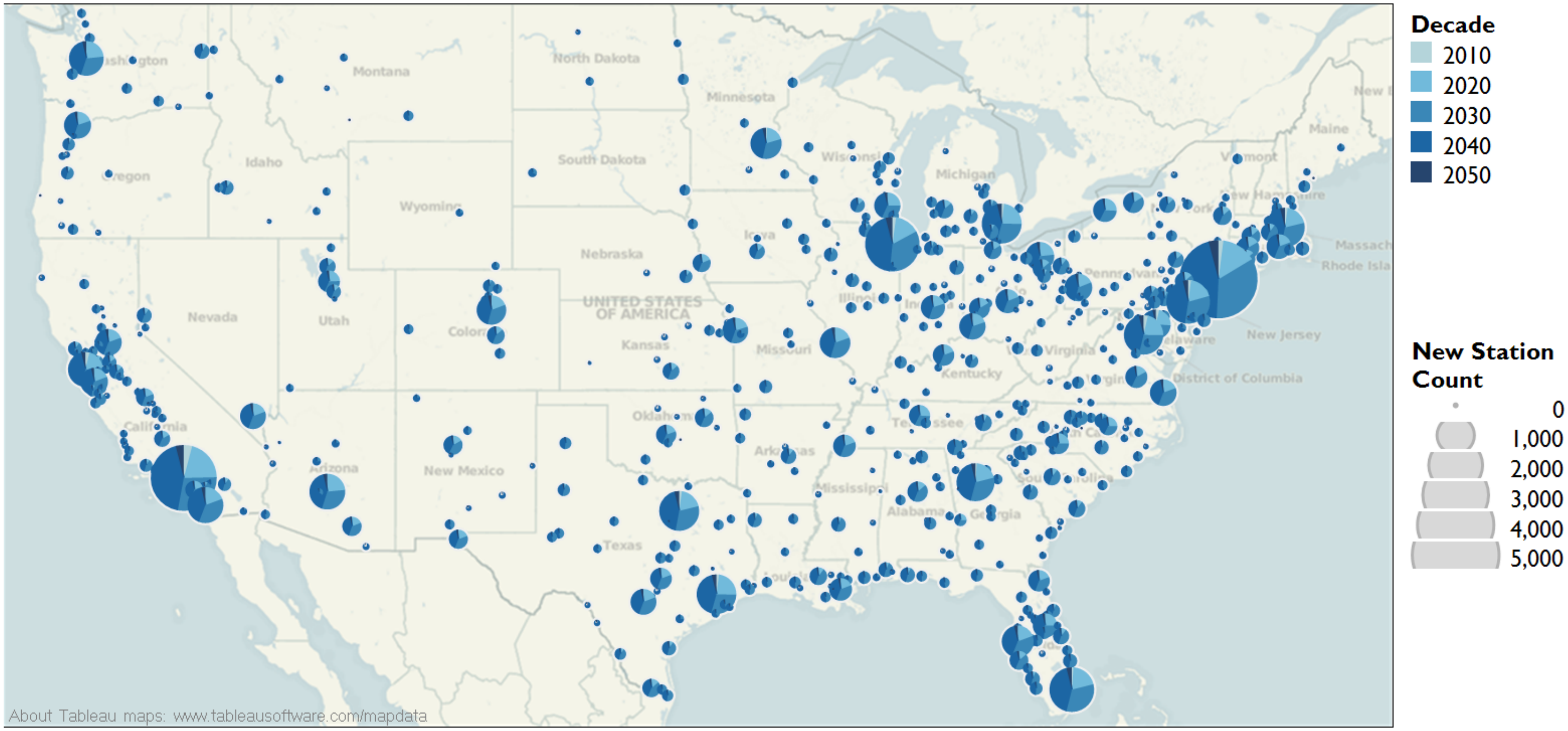

Figure 11. Geographic distribution of new FCEV fueling stations, by decade of construction, in the early market "hydrogen success" scenario.

3.3 Regional Infrastructure

Once the demand over time and urban area has been specified, it is possible to apply the SERA regional infrastructure submodel to estimate the hydrogen production and delivery infrastructure constructed each year to meet those demands. Given annual city-by-city hydrogen demands, feedstock cost forecasts, and a catalog of available hydrogen production, storage, and delivery technologies, the model generates "blueprints" for hydrogen infrastructure build-out that minimize the overall net present value of capital, operating, and feedstock costs for infrastructure networks that meet the specified demand profiles. The model represents production facilities and pipelines at the level of individually geolocated components, while it treats truck and rail transportation at an aggregate level. The nodes in the blueprint networks are characterized by their location, activities that occur there (e.g., production or consumption of hydrogen), and the quantity of hydrogen produced or used. The links between those nodes are characterized by their location, the type of delivery occurring, their capacity, and the actual flow of hydrogen. The objective function that is optimized (minimized) by SERA is the total discounted cash flow for the entire hydrogen infrastructure, equivalent to minimizing the weighted average of the levelized hydrogen delivery cost over the demand centers and years under consideration. The objective function can be changed to suit any particular study requirements. In this study we optimize infrastructure piecewise in five-year increments, while previous SERA studies have optimized over a 40-year time period. The shorter optimization time period is more likely to generate realistic build-out decisions, especially during the early market growth phase.

Figure 12 maps the geographic distribution of new production capacity by year, whereas Figure 13 maps it by technology type. The years in which different technologies are added are shown in Figure 14. Because we are using *Annual Energy Outlook 2011* energy costs for this study, natural gas production technologies predominate (EIA 2011). There are predominantly centralized production facilities, rather than onsite production stations, because of the cost advantage of industrial over commercial natural gas. For the largest demand centers, however, there is some use of central coal gasification, and for the smallest demand centers grid electrolysis is a viable niche. (Once again, the difference in cost between industrial vs. commercial electricity tips the balance toward centralized production technologies.) Four key conclusions are:

1. Low natural gas costs in most regions and the favorable economies of scale for large coal plants lead to the predominance of central natural gas reforming and coal gasification.
2. Central grid electrolysis has niches in areas of low electricity prices.
3. Onsite natural gas reforming is optimal in low-demand conditions.
4. The price differential between industrial and commercial natural gas or electricity is sufficient to overcome the cost of deploying a centralized production technology instead of an onsite one.

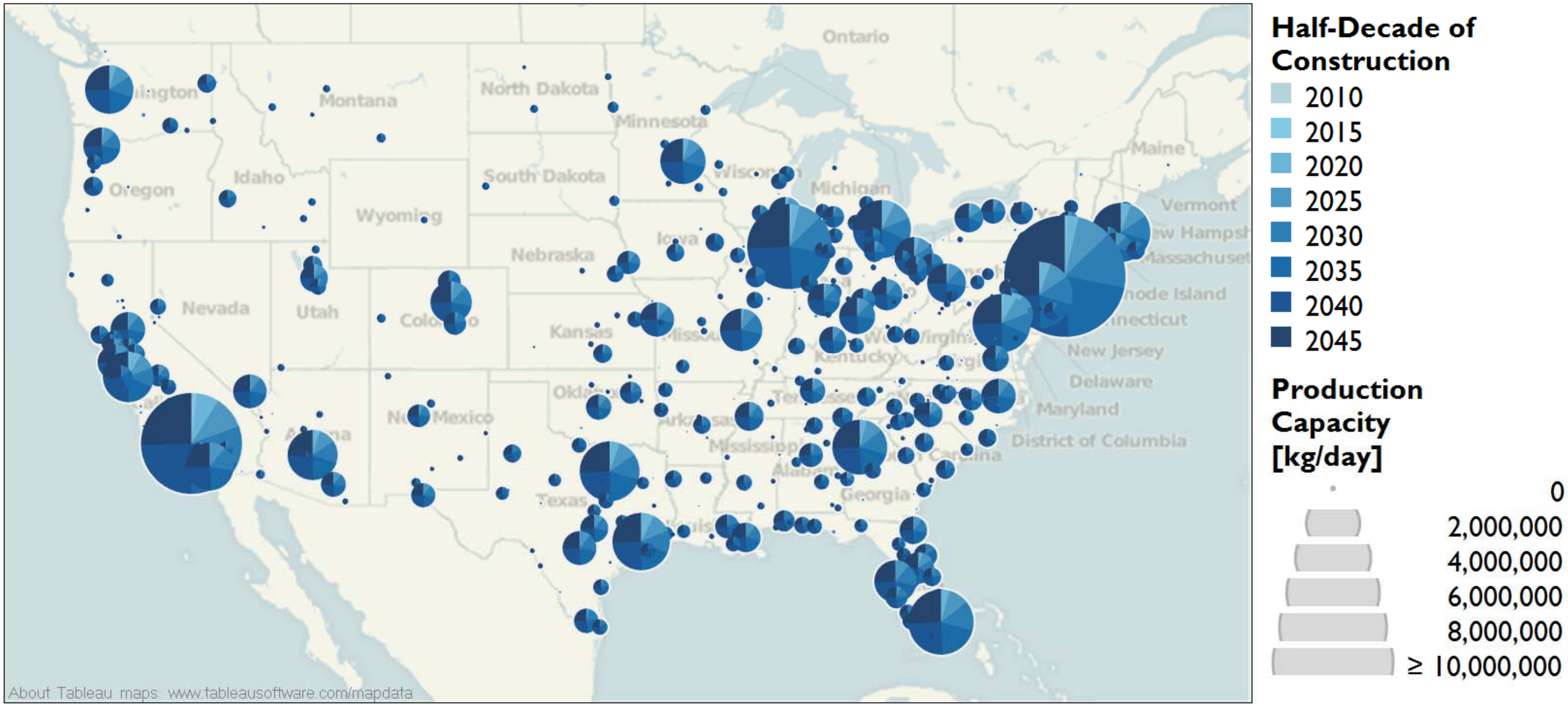

Figure 12. Geographic and capacity distribution of new hydrogen production capacity in the early market "hydrogen success" scenario, by half-decade of construction.

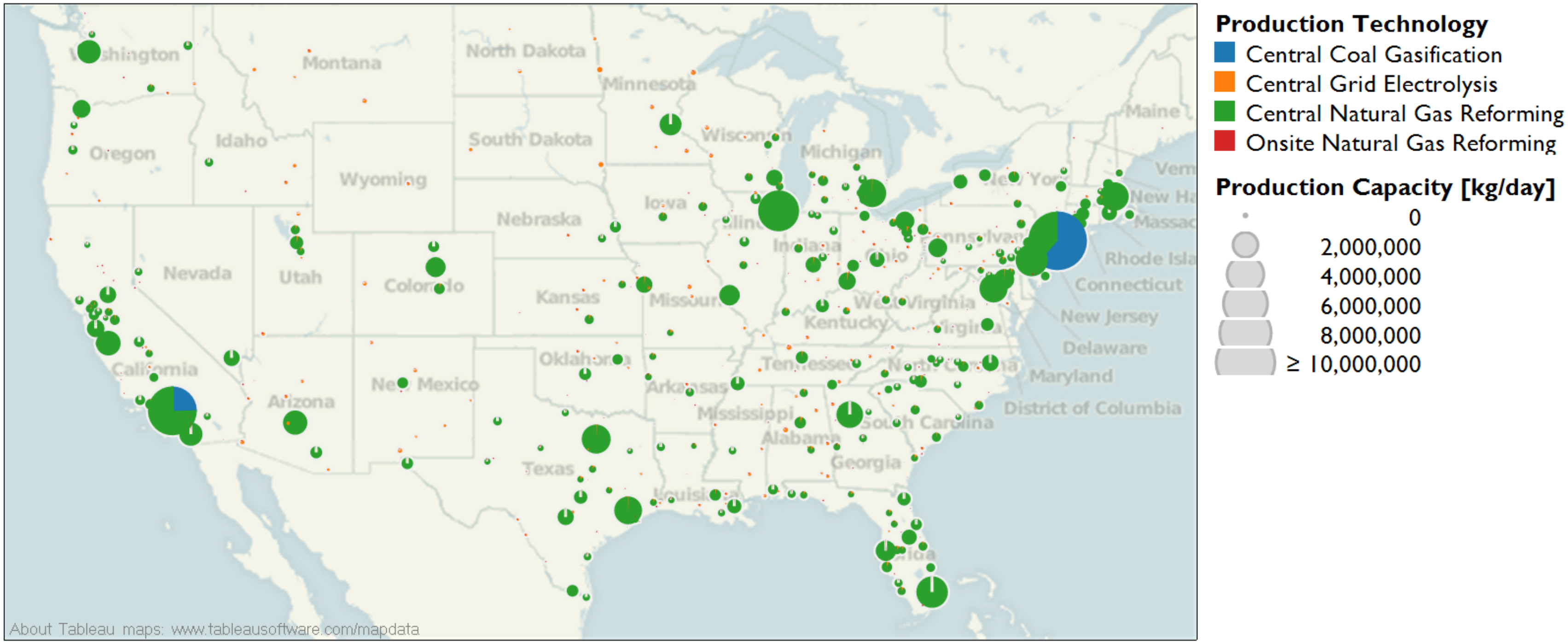

Figure 13. Geographic and capacity distribution of new hydrogen production capacity in the early market "hydrogen success" scenario, by production technology.

Note that none of the production technologies includes carbon capture and storage.

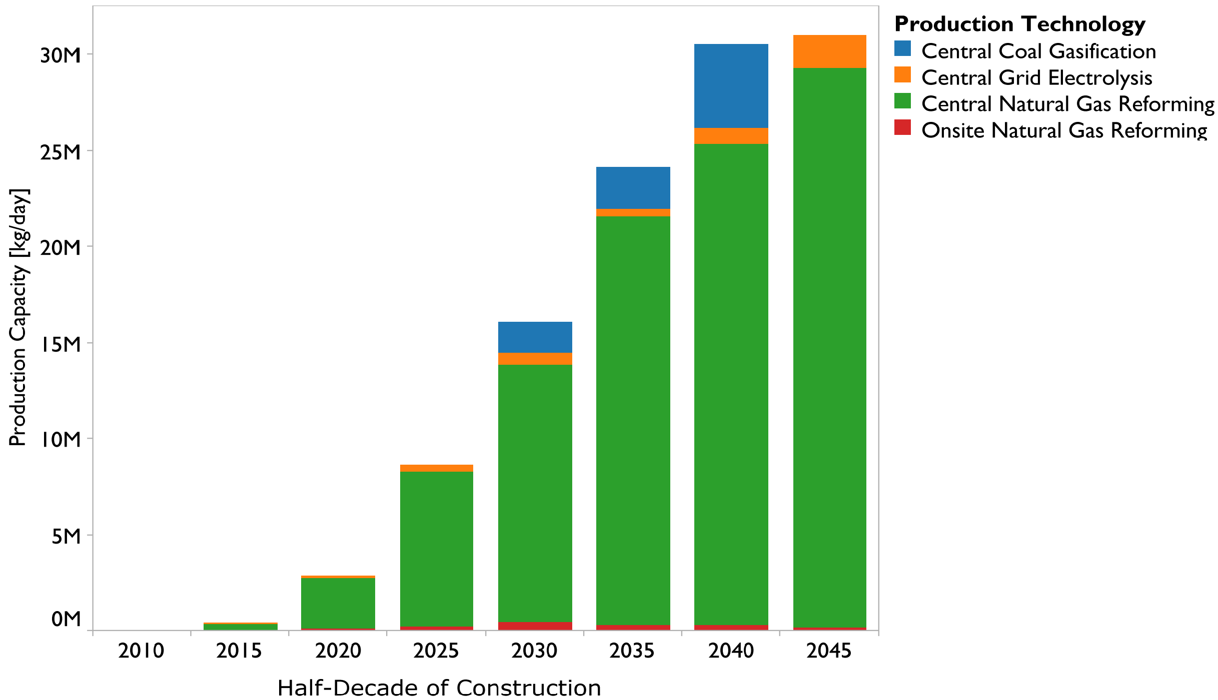

Figure 14. Distribution of new hydrogen production capacity, by technology and half-decade of construction, in the early market "hydrogen success" scenario.

Note that none of the production technologies includes carbon capture and storage.

Figure 15 catalogs the infrastructure build-out near 20 major cities. Note that in Los Angeles and New York, central natural gas reforming outcompetes coal production, which is then outcompeted by central natural gas reforming by the year 2045. Onsite natural gas reforming and central grid electrolysis only compete in major cities in the early years of infrastructure development, when station sizes are small and high-volume delivery infrastructure components are not fully built out.

The optimization algorithm selects among three modes of transporting hydrogen from production facility to fueling station: gaseous pipeline delivery, liquid truck delivery, and gaseous truck delivery. Gaseous truck delivery is the dominant mode of delivery up to 2035, and remains as a major mode out to 2050 even as new pipeline delivery systems become more prevalent. This trend is shown in Figure 16 and Figure 17. In the early years, production facilities can be located near enough to city gates that long-distance pipeline transmission of hydrogen is not competitive, Once there are sufficient numbers of nearby demand centers to build larger, regional production facilities with better economies of scale, however, the long-distance transmission of hydrogen makes economic sense, especially with synergies among multiple cities. The actual least cost delivery mode depends on the size of the expected flows and on the distances; Figure 18 quantifies which technological pathway is least expensive for a given distance and delivery capacity. (Note that gaseous hydrogen trucks dominate much of this parameter space and that other pathways have relatively small niches.) Three key conclusions are:

1. Gaseous hydrogen pipelines are favorable for high flow conditions and moderate distances.

2. Truck delivery predominates at lower flow conditions (i.e., for gaseous transport) or longer distance (i.e., for liquid transport).
3. Rail technologies are not optimal because the scenario geospatial configuration lacks synergies for transmitting hydrogen at very long distances and moderate to high flows.

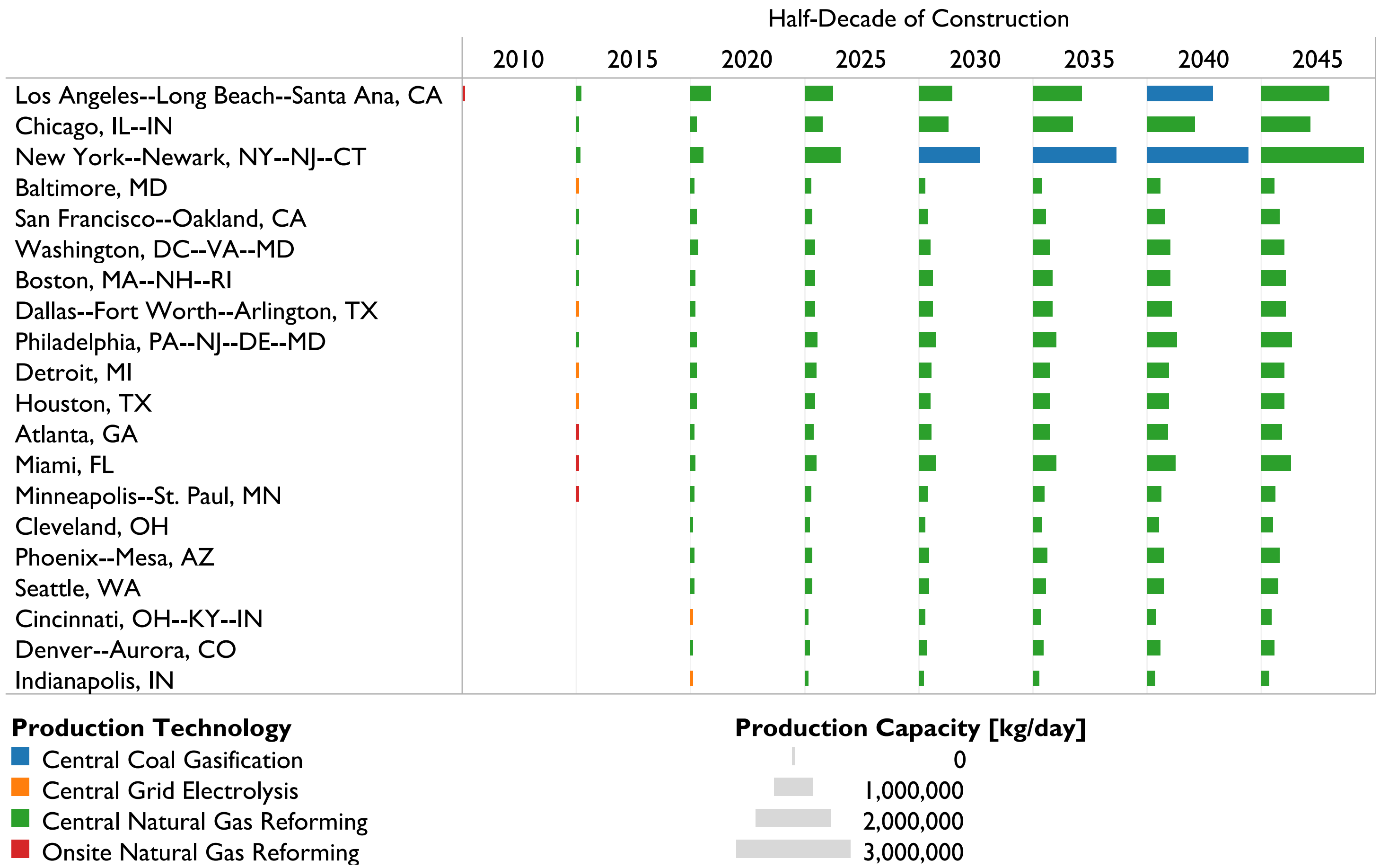

Figure 15. Sequencing of the addition of nearby hydrogen production, by capacity, technology type, and half-decade of construction, for the early market "hydrogen success" scenario.

Note that none of the production technologies includes carbon capture and storage.

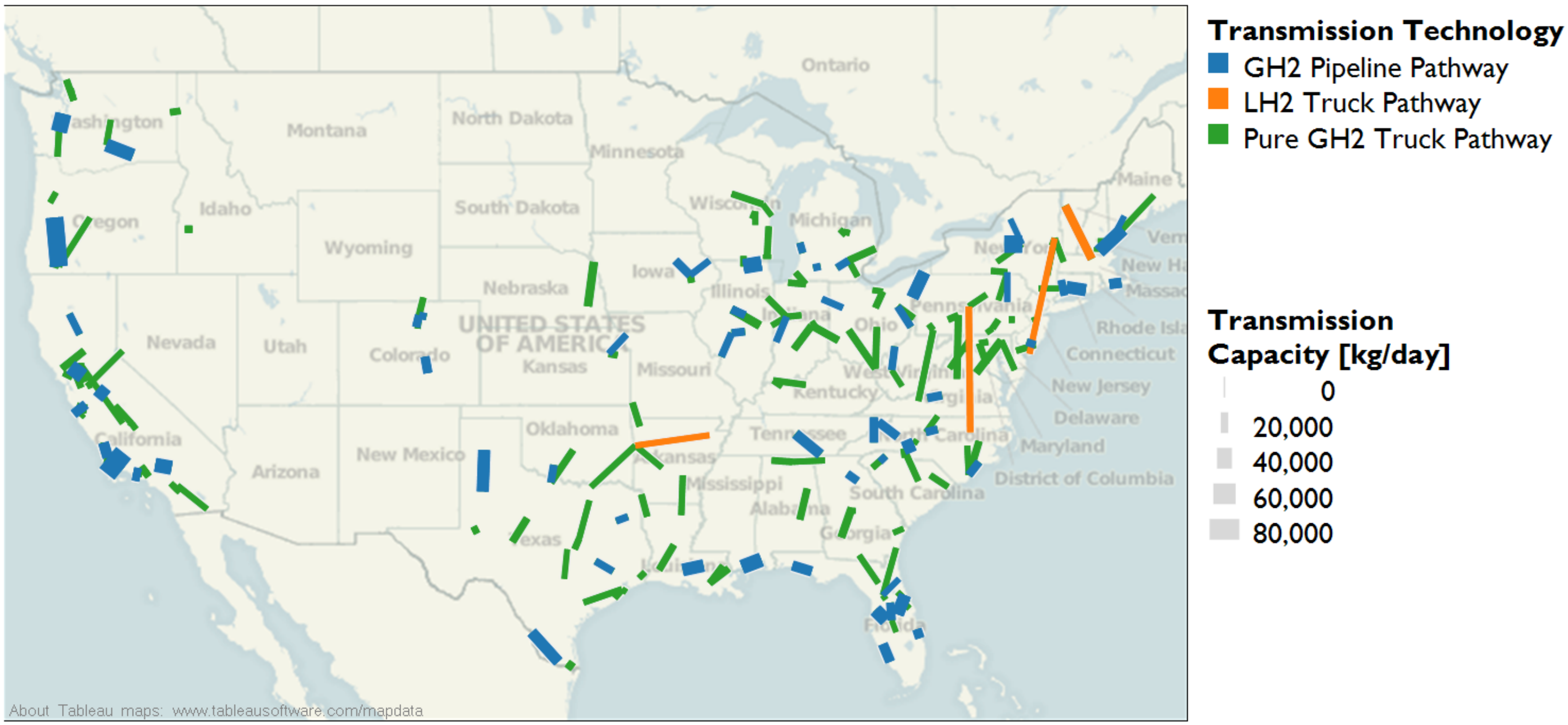

Figure 16. Geographic and capacity distribution of new hydrogen delivery capacity in the early market "hydrogen success" scenario, by transmission technology and capacity in 2050.

Note: GH2 = gaseous hydrogen; LH2 = liquid hydrogen.

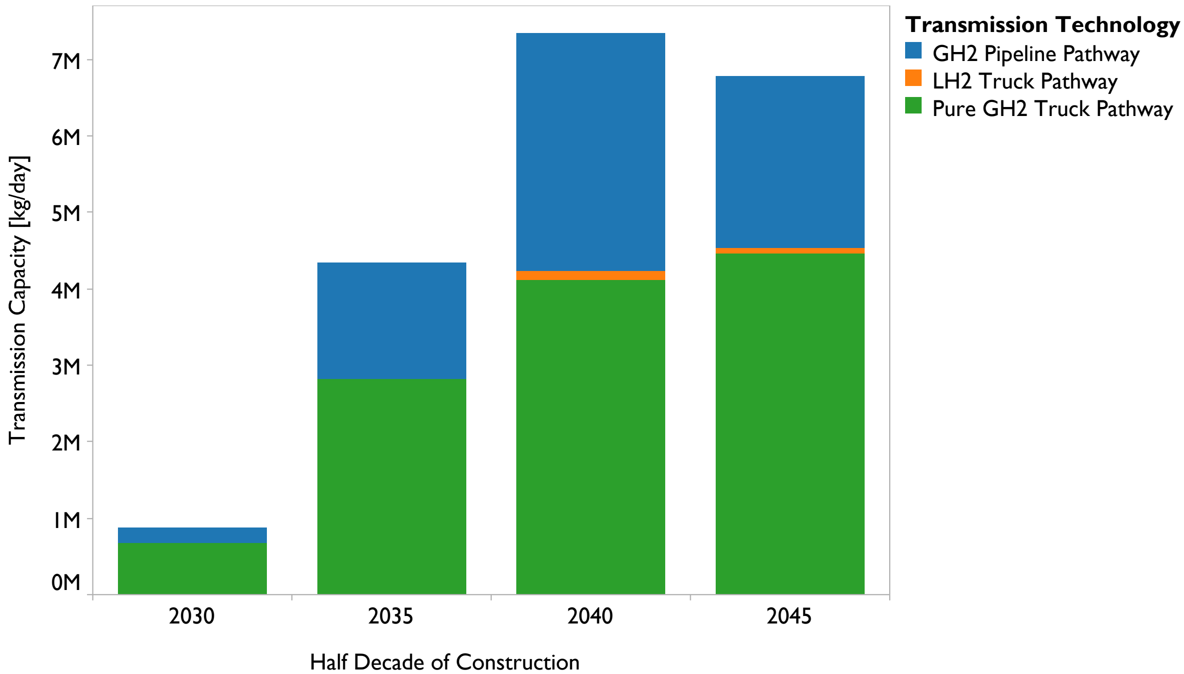

Figure 17. Distribution of new hydrogen delivery capacity, by technology and half-decade of construction, in the early market "hydrogen success" scenario.

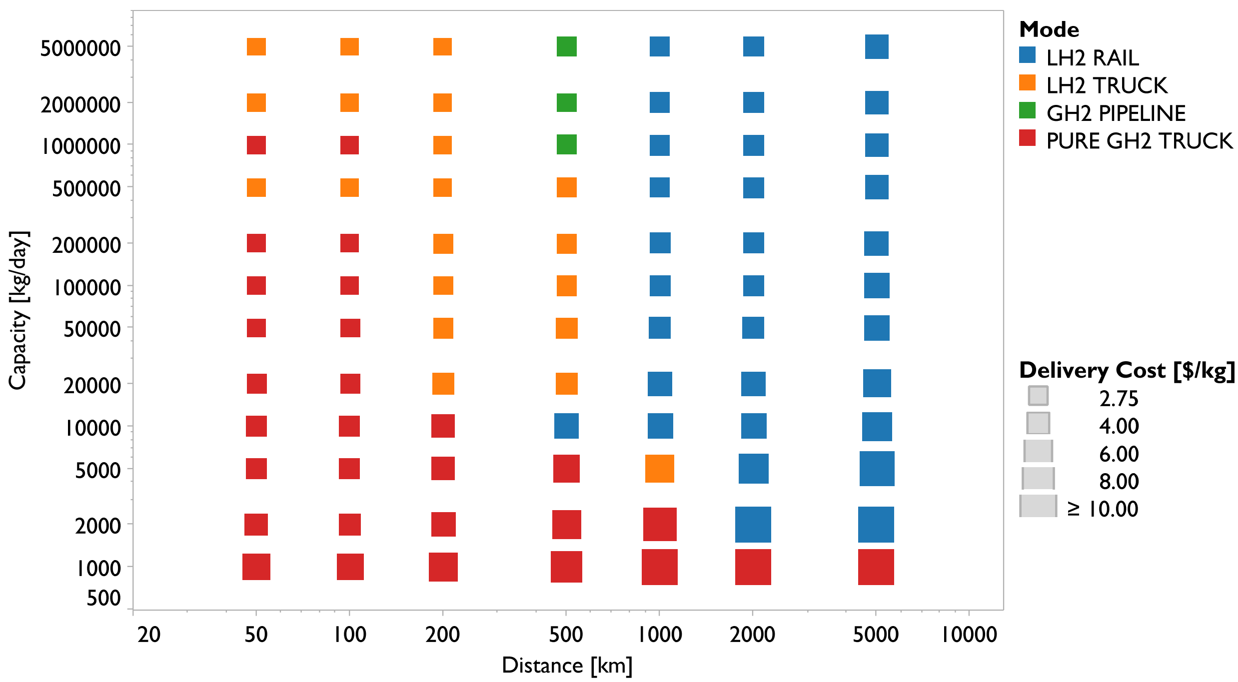

Figure 18. Minimum delivery costs in SERA as a function of distance.

3.4 Delivered Cost and Cash Flows

Each component in the network (production, storage, delivery, and dispensing) is associated with an annual cash flow, categorized by type of expenditure (capital, operation and maintenance, etc.), and overall cash flows and delivered hydrogen costs are reported for each consumption location (typically urban areas). Using these individual cash flows, we can compute a variety of metrics summarizing the cost or price of hydrogen delivered to FCEVs. Figure 19 plots a nationally averaged delivered cost of hydrogen that is computed by taking the total levelized cost for hydrogen feedstock, production, and delivery expenditures in the given year and dividing that total by the corresponding amount delivered. This long-term levelized delivered cost for hydrogen tends toward \$6.00/kg nationally and approaches this level as early as 2025. Underutilization of infrastructure in the first several years after its construction raises the overall proportion of capital costs.

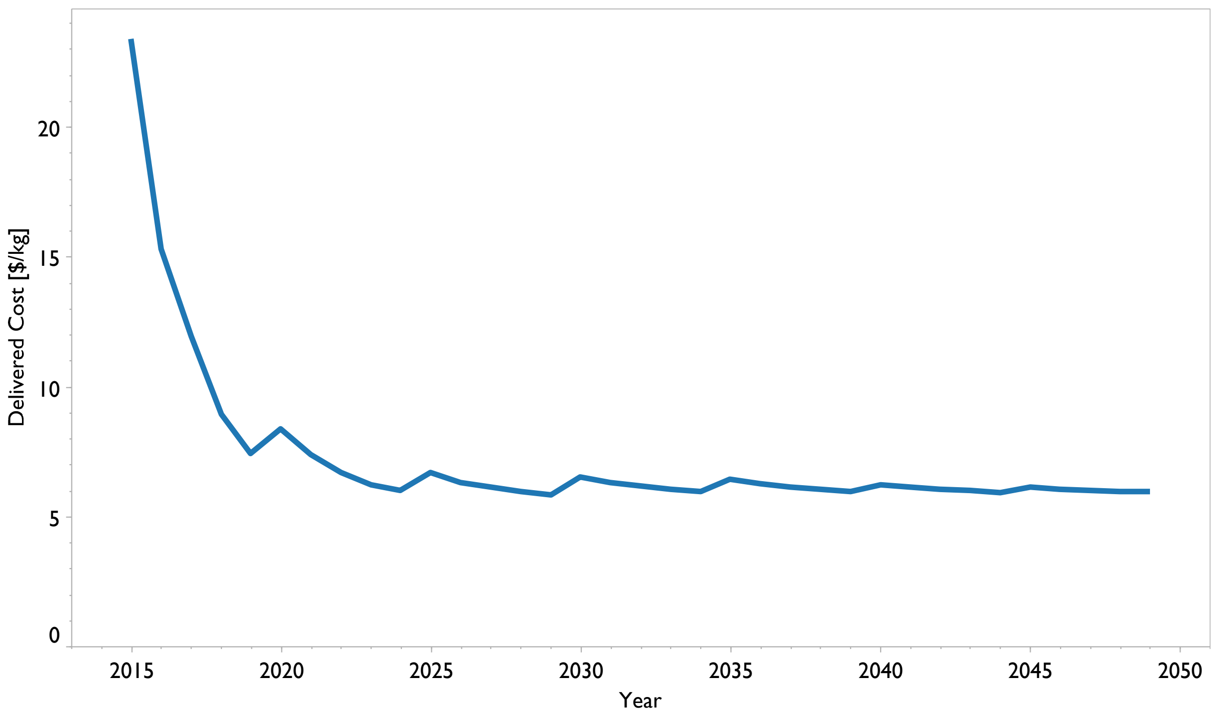

Figure 19. National average delivered cost of hydrogen for the early market "hydrogen success" scenario.

This "delivered cost" is computed as the total levelized cost for hydrogen feedstock, production, and delivery expenditures in the given year divided by the corresponding amount delivered.

If we specify a price for delivered hydrogen, we can compare revenues to expenditures. Figure 20 shows the breakdown of capital, operation/maintenance, and feedstock costs against sales when hydrogen is priced nationally at \$8/kg for all years. Figure 21 provides the total cumulative and annual cash flows at that price, and we see that a zero cumulative cash flow is reached shortly after 2021. Note that because we are optimizing infrastructure in five-year increments and that newly built infrastructure is often underutilized in the first four years of its existence, there is a pattern of increasingly favorable cash flows for four years and then a setback (as new construction occurs) in the fifth year: the shift from positive revenue in 2019 to negative revenue in 2020 on the right side of Figure 21 is such an example.

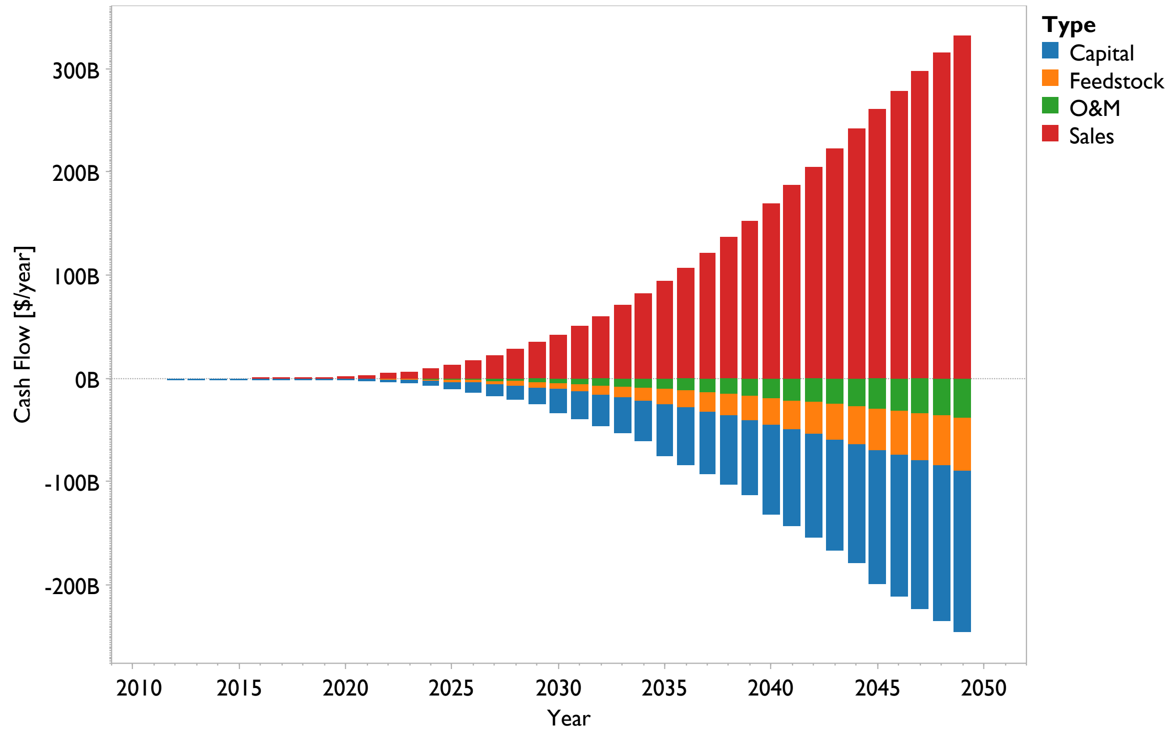

Figure 20. Breakdown by type of the cash flow (see Figure 21 below) when hydrogen is priced at $8/kg for the early market "hydrogen success" scenario.

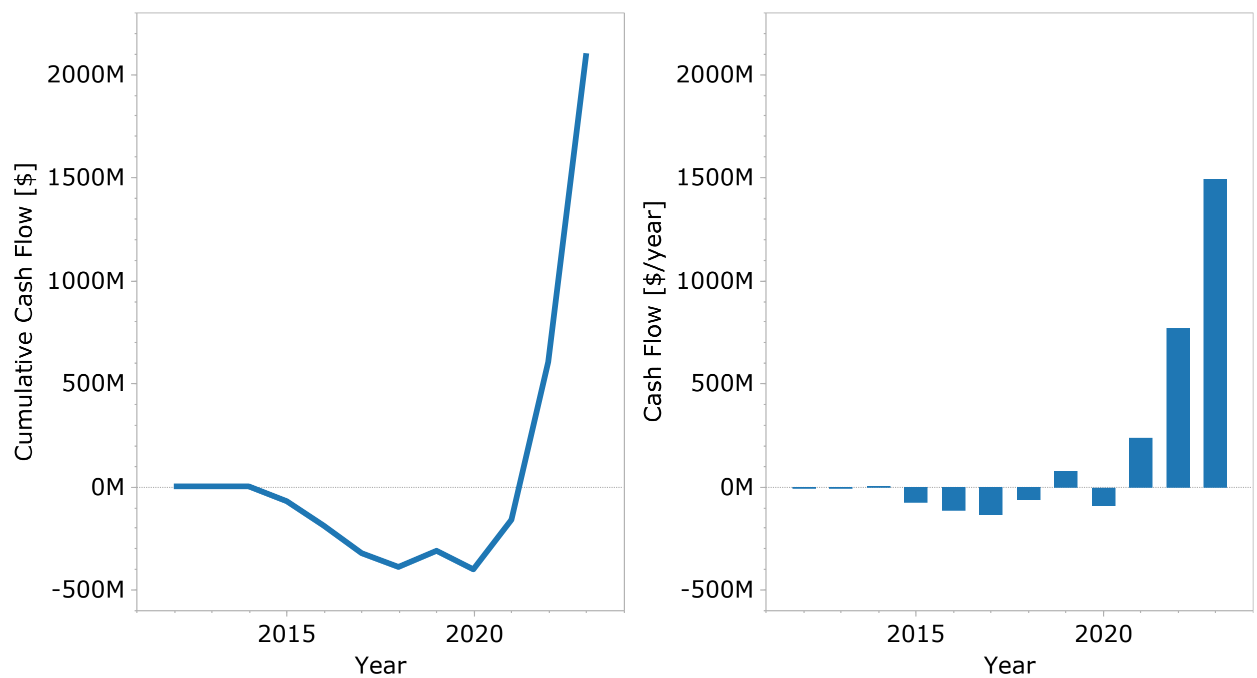

Figure 21. Cumulative cash flow (left) and annual cash flow (right) if hydrogen were priced at the example price of $8/kg in the early market "hydrogen success" scenario.

Another way of summarizing these cash flows is to look at the price at which delivered hydrogen would need to be sold in order to achieve a net-zero industry cash flow by a given year. Figure 22 shows that a zero cumulative cash flow is achieved in about 2018 or 2025 if hydrogen is priced at $11.00/kg or $6.75/kg, respectively. In general, cost computations are sensitive to the geographic regions and time windows over which costs are averaged and whether future sales are subsidizing current sales or sales in large urban areas are subsidizing sales in smaller urban areas; costs can be quite low if only large cities are considered. The next section will provide examples of how costs are specific to regional geography.

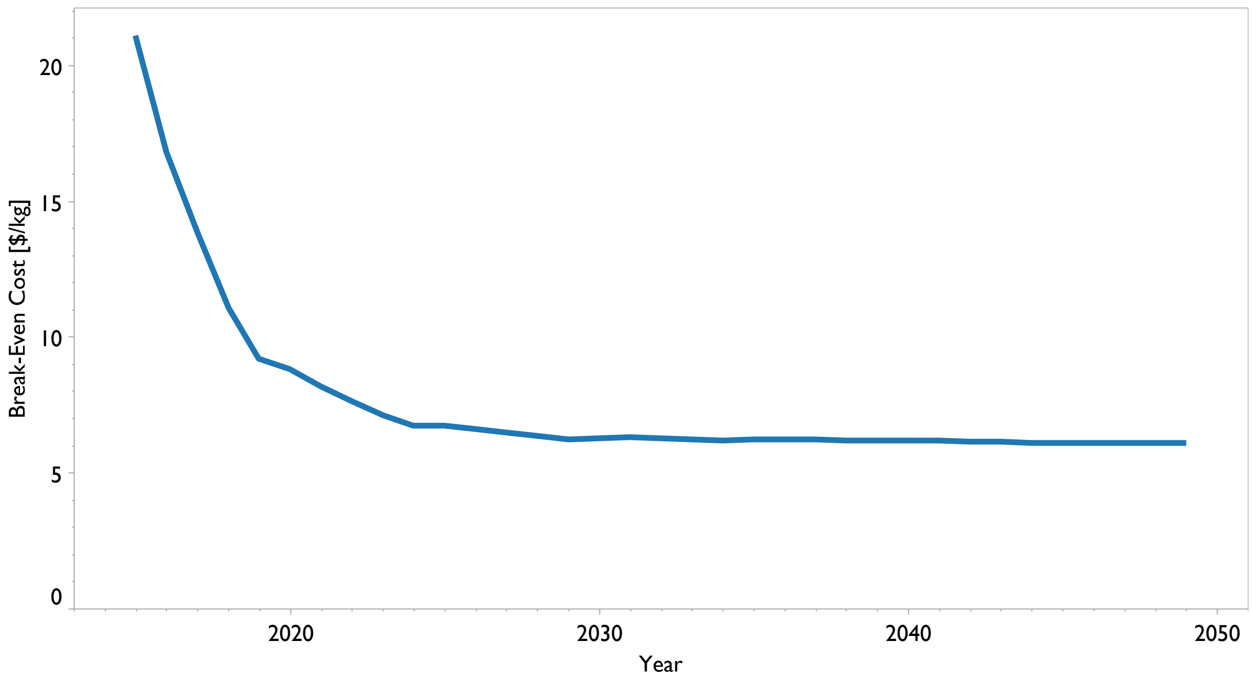

Figure 22. Hydrogen price needed to achieve zero net cash flow in particular years for the early market "hydrogen success" scenario.

This "break-even cost" is computed as the total levelized cost for hydrogen feedstock, production, and delivery expenditures up to and including the given year divided by the corresponding amount delivered. If hydrogen were priced at this break-even cost, then zero cumulative cash flow would be achieved in the year in question.

4 Details for Regional Markets

As an example of applying the SERA model to a particular region, rather than a national scenario, we now consider the details of the early market "hydrogen success" scenario among eight states in the northeast (Connecticut, Massachusetts, Maine, New Hampshire, New Jersey, New York, Rhode Island, and Vermont). Regional data and visualizations can be readily extracted and generated from the results of Section 3.2. Figure 23 plots the urban areas considered in this region. (Note that urban areas that straddle state boundaries are somewhat arbitrarily assigned to single states.) As can be seen in Figure 24 and Figure 25, New York dominates the region in terms of FCEVs and demand, but Massachusetts and Connecticut have substantial amounts of FCEVs too. (Note that much of the demand in New Jersey is assigned to the Census Bureau's New York City–Newark urban area, which is labeled as belonging to New York in the plots.) We can also see in these plots that states with smaller cities come into play much later in this scenario because of the sequencing of FCEV introductions in NAS-like scenarios.

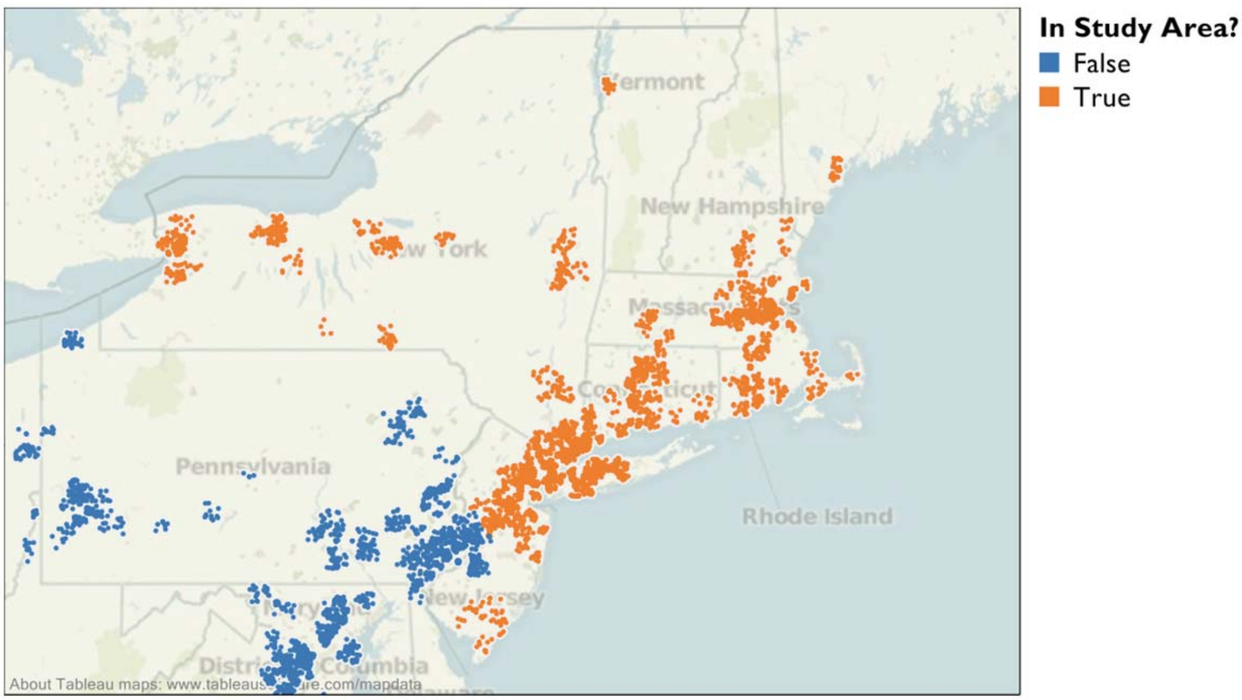

Figure 23. ZIP codes within the northeastern states study area (orange).

The station counts, capacities, and placements exhibit quite a bit of geographic variation. For instance, Figure 26 shows that the average station capacity for New York and for the region as a whole is quite a bit higher (more advanced) than the national average, to which the station capacity in Massachusetts is comparable. The other states have much smaller station capacities in these years because of the later introduction of FCEVs and the smaller concentration of demand. Figure 27 maps the station size distribution for the region. The delivered cost of hydrogen and the cumulative cash flow at $8/kg pricing (Figure 28) show corresponding geographic diversity: the regional and New York delivered costs track the national ones in the early years and drop about $1/kg below them after the first 10 years. The other states have delivered costs that drop more slowly and to a higher asymptote. These effects are even more pronounced when the year at which zero cumulative cash flow is achieved: New York and the region precede the nation by several years and the other states follow it.

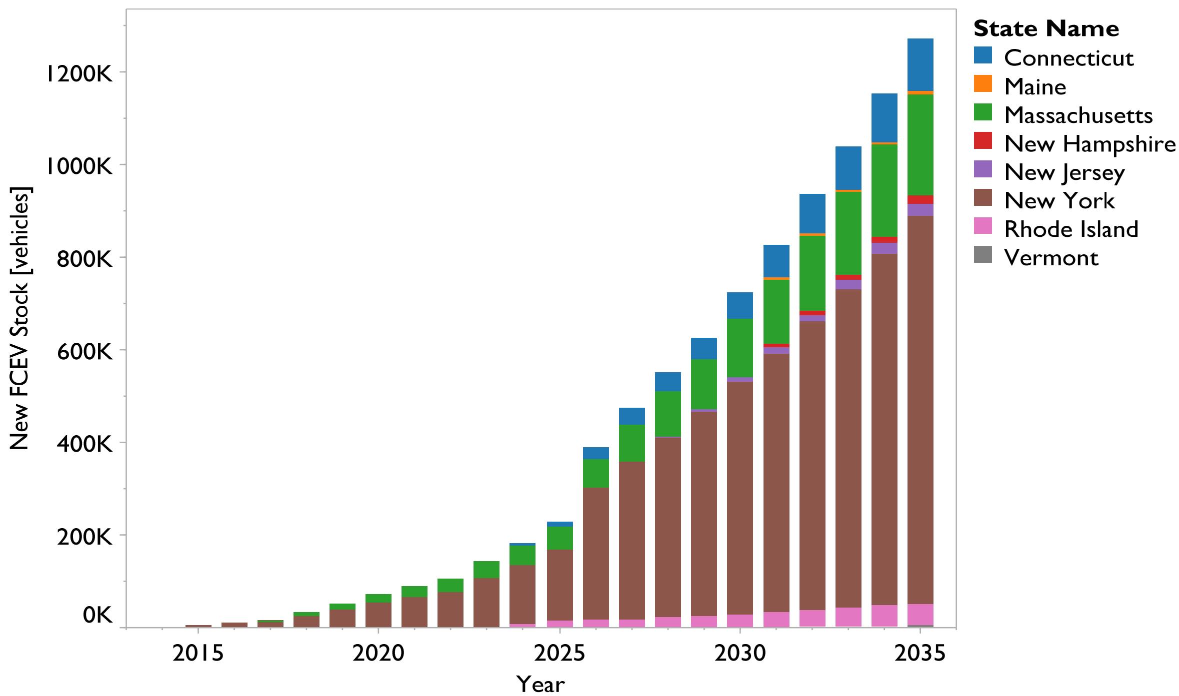

Figure 24. New FCEV introductions for eight northeastern states under the early market "hydrogen success" scenario.

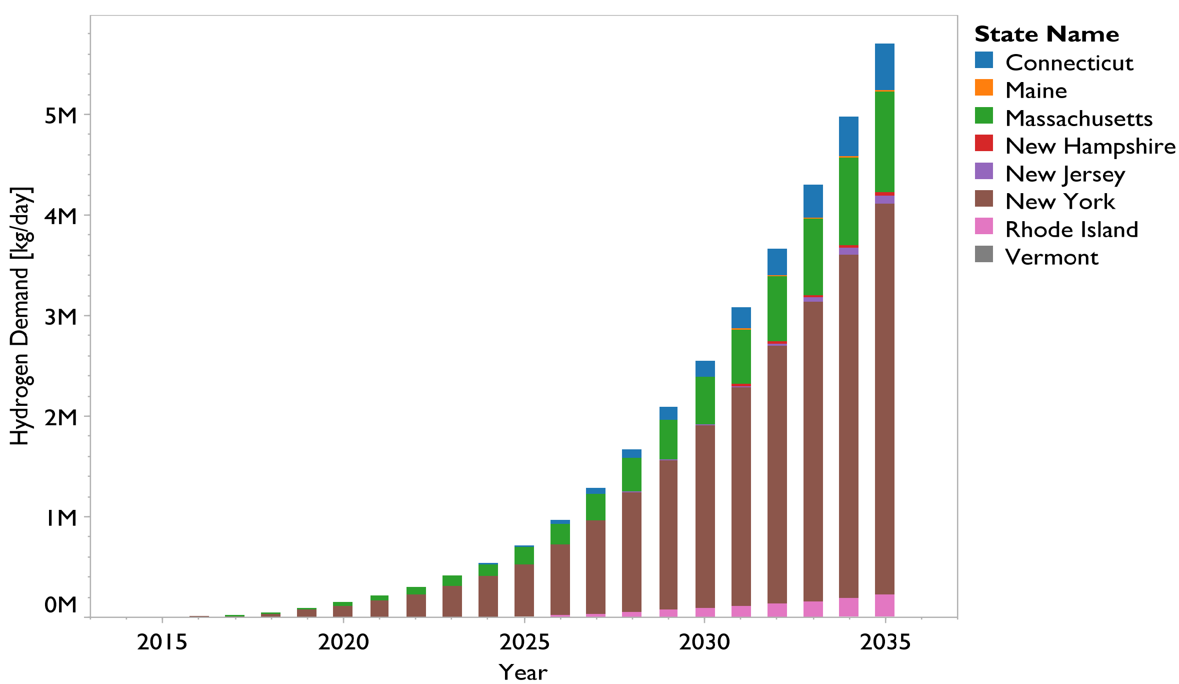

Figure 25. Hydrogen demand in the northeastern states portion of the early market "hydrogen success" scenario.

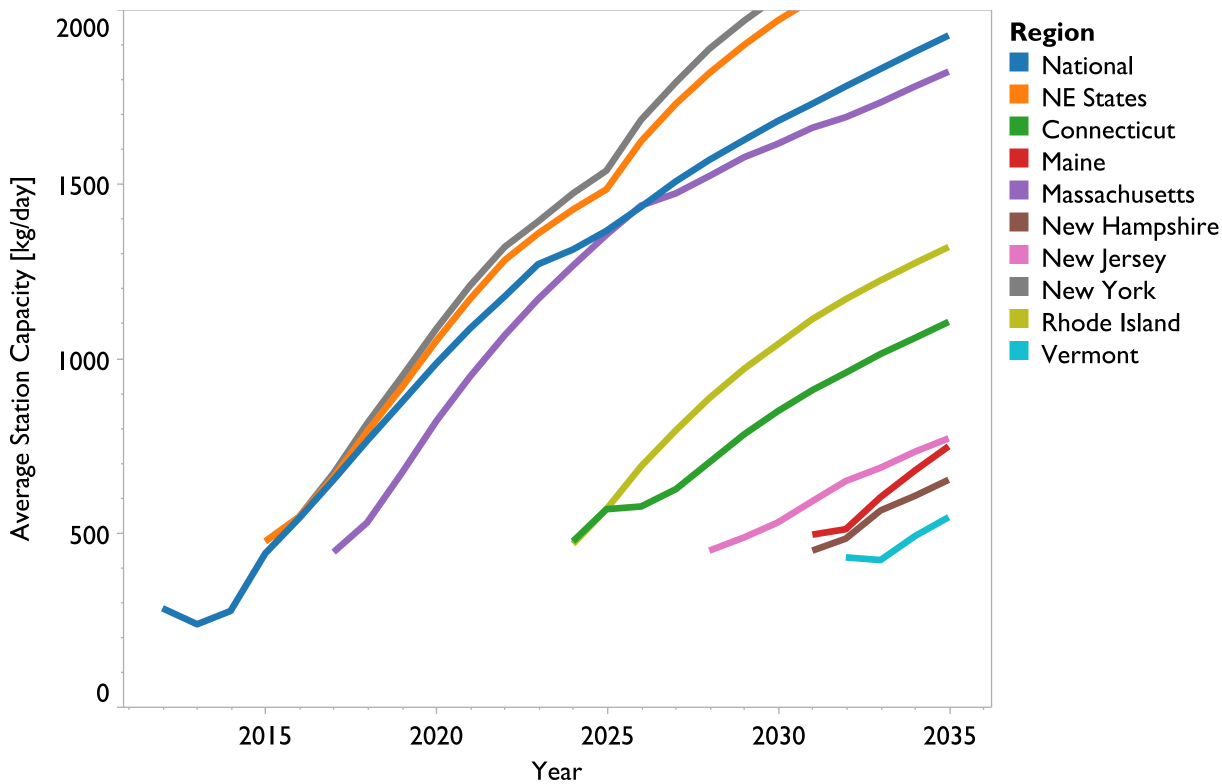

Figure 26. Average station capacity, by state, for the northeastern states portion of the early market "hydrogen success" scenario.

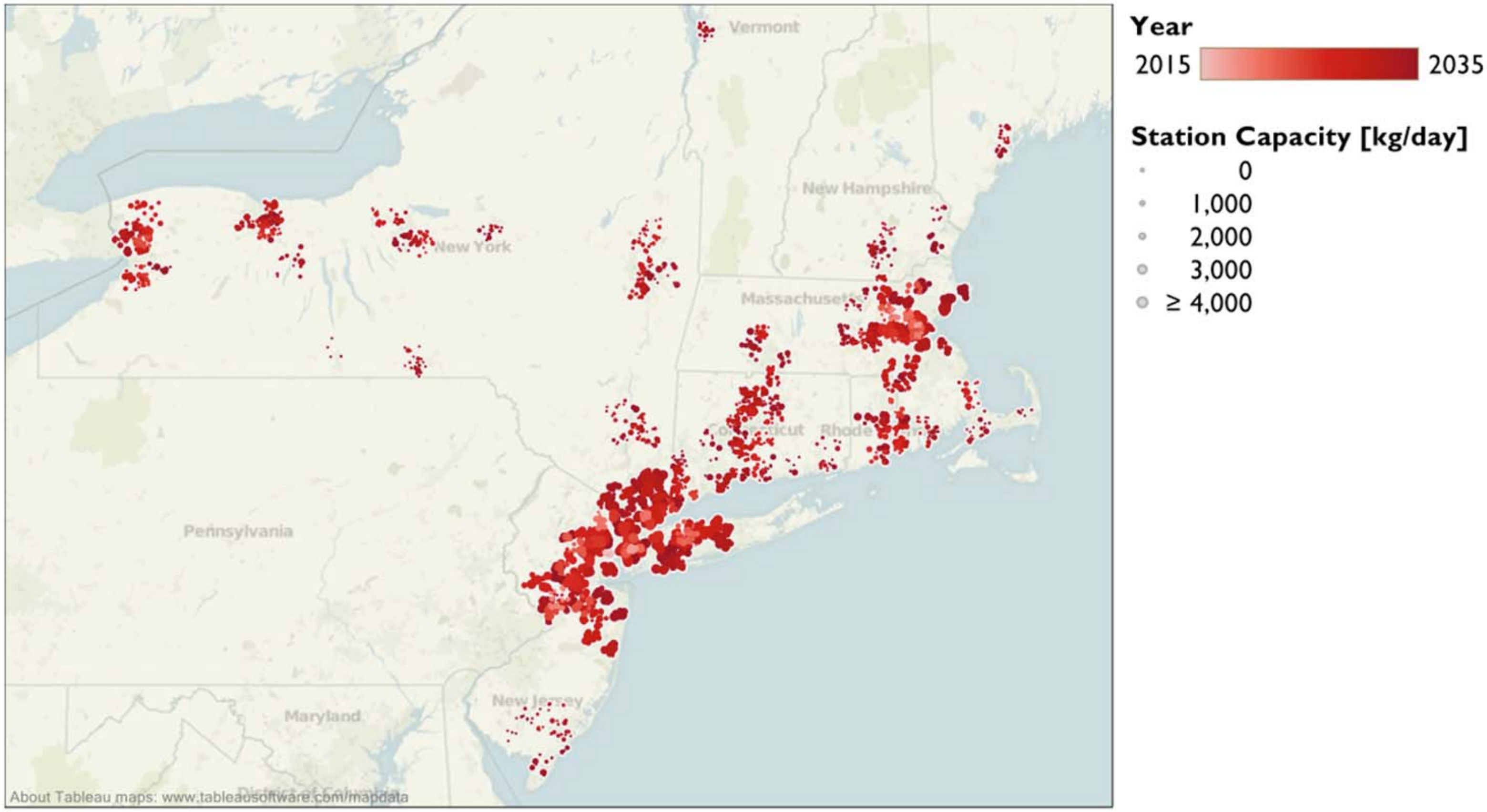

Figure 27. Geographic distribution of new FCEV fueling station construction, by year, in the early market "hydrogen success" scenario.

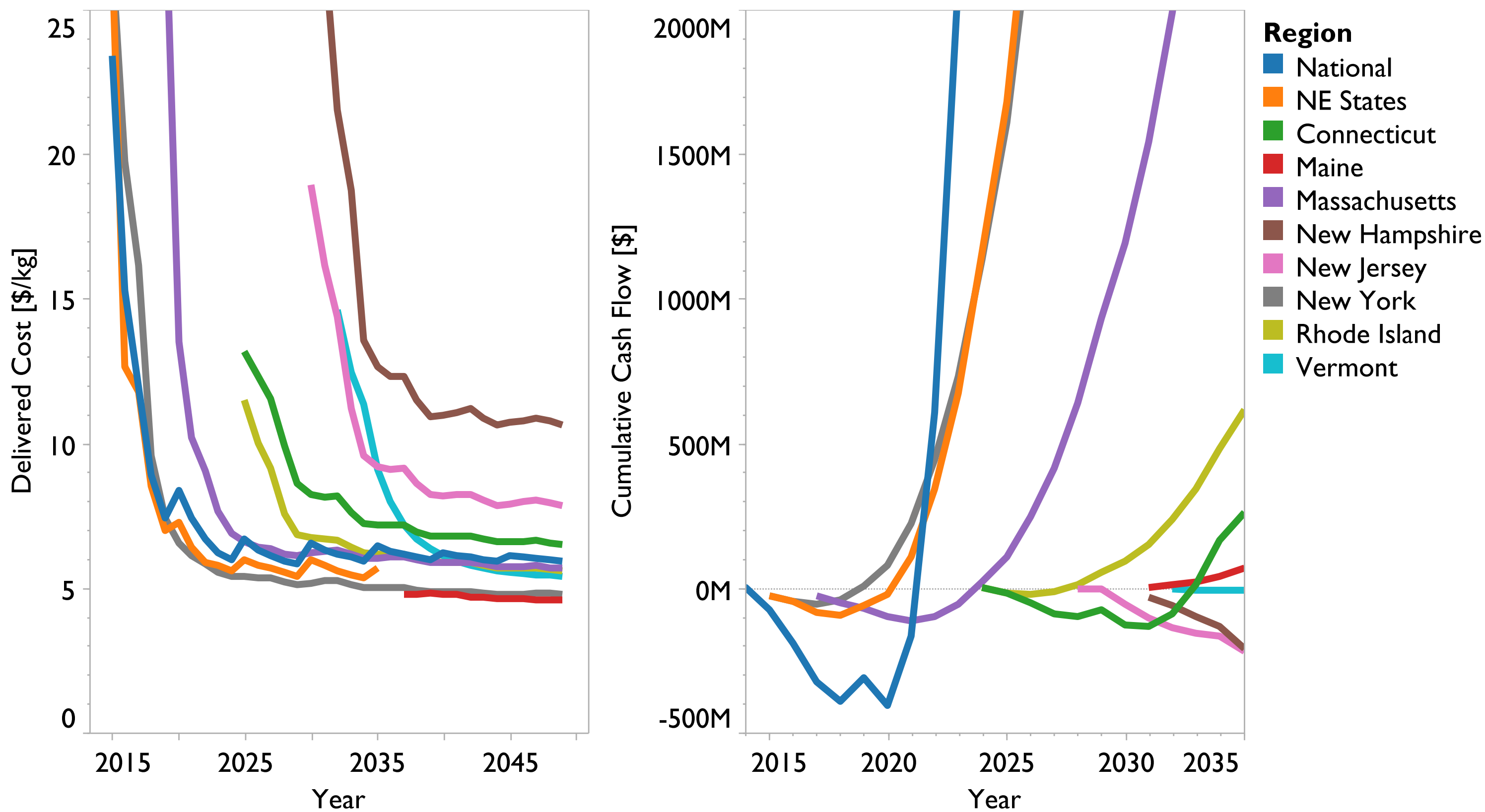

Figure 28. Delivered costs (left) and cumulative cash flows (right) if hydrogen were priced at the example price of $8/kg in the early market "hydrogen success" scenario.

5 Enhancements to the Hydrogen Station Siting Algorithms

Estimates of the demand for hydrogen over time are typically made only at coarse spatial resolutions. An accurate assessment of potential generation and distribution costs, however, depends on the geographic arrangement of both production facilities and fueling stations. The objective of SERA's intra-region module is to disaggregate the demand for fueling stations within regions so as to be able to better estimate likely infrastructure and distribution requirements and costs over time.

5.1 General Framework

SERA's intra-region module provides a tool set for disaggregating demand and estimating spatiotemporal system growth at much finer scales. The distribution of fueling stations (in both capacity and space) will evolve over time as the demand for hydrogen increases. The evolution will likely depend on factors such as:

- Population density (which may vary as a function of time)
- Affinity of different neighborhoods for fuel cell vehicles
- Location of interstates, major roadways, and commercial centers as well as traffic flow volumes along these routes
- Location and size of existing stations.

Pertinent data can be obtained from many sources. The objective heretofore has been to develop a model architecture for the hydrogen system that can be adapted to include many types of information and modeling assumptions that improve the realism of solution outcomes. Figure 29 details the information flows in the enhanced approach, and Figure 30 indicates the basic components of a scenario developed using the enhanced intra-regional simulation capabilities. The creation of new stations is driven fundamentally by demand. The total number of new stations created in a given year depends primarily on the incremental increase in annual demand for hydrogen.

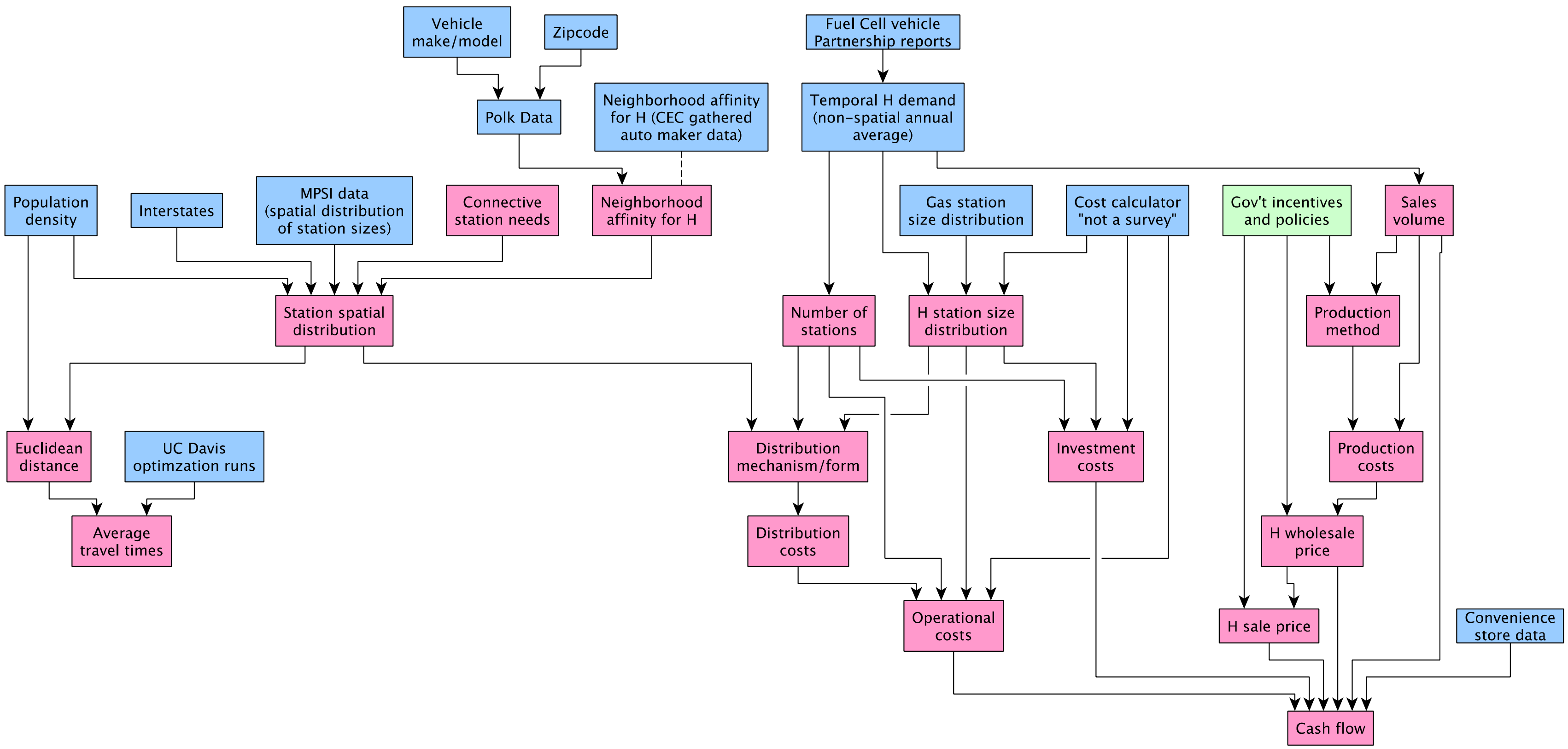

Figure 29. Information flows in SERA's representation of refueling station placement capacity and cash flows.

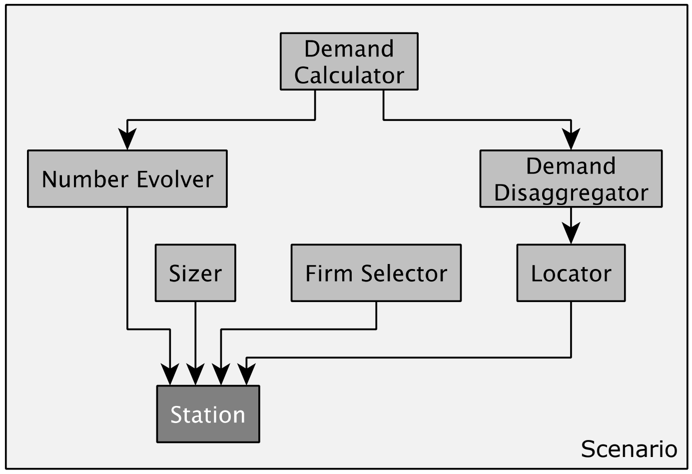

Figure 30. Components of a disaggregation scenario.

Where the new stations are to be located depends on the spatial disaggregation method used to allocate demand to stations. Disaggregation currently is based on a neighborhood's 2012 affinity for alternative fuel vehicles, and primarily HEVs. The likelihood of an individual adopting a hydrogen fuel cell vehicle is held to be proportional to the fraction of alternative fuel vehicles (e.g., hybrid electric, battery electric, natural gas, etc.) in an area. Vehicle demographics were obtained at the ZIP code scale from vehicle registration databases (Polk 2011), and shapefiles describing ZIP code geographic boundaries were obtained from the U.S. Census Bureau.

Additional and more complex influences may also be taken into account. Geographic information system data on the locations of highways and major roads will be incorporated in future enhancements to allow for an increased likelihood of station placement along these thoroughfares. The current geographic distribution of stations is also likely to influence the placement of new stations. For example, the existence of stations in an area may reduce the likelihood of new stations being placed within close proximity. Alternatively, a dearth of stations in an area that would otherwise be unlikely to adopt fuel cell vehicles may increase the likelihood of placing connector stations that allow for refueling along trip routes.

In the California case study, the enhanced biased disaggregation leads to higher relative station densities than the regional average in areas such as Santa Monica, Beverly Hills, Pasadena, Torrance, and Chino and lower densities in Los Angeles, Compton, Long Beach, and Santa Ana. The differing spatial distributions are manifest in an analysis of the distribution of cluster length scales. We maintain hierarchical spatial clustering of the stations following Melaina and Bremson (2006). Clustering was based on the Euclidean distance between stations. As clusters were identified, the smaller-capacity station/cluster was removed and its capacity was summed with and allocated to a new cluster at the location of the larger station/cluster. The separation was retained as the new cluster's characteristic length scale. Biasing the disaggregation by neighborhood affinity leads to an increase in the relative number of stations separated by larger distances (as, essentially, stations are removed from many intervening neighborhoods).

5.2 Tuning to the California Early Market Forecasts

This initial attempt at representing the recently published CaFCP Road Map (CaFCP 2012), "A California Road Map: The Commercialization of Hydrogen Fuel Cell Vehicles," is based only on alternative fuel vehicle penetration and income distribution. A brief analysis suggested that these two parameters fell well short of providing a predictive capability. Based on a logistic regression of the ZIP codes chosen to host hydrogen stations, these two parameters accounted for something approximately 4% of the decision basis. Greater statistical fidelity to the Road Map station placements may be achieved with additional parameters, but ultimately no set of regressions can replicate the deliberations of an informed and engaged stakeholder group.

In reality, the station placement prioritization reflected in the CaFCP Road Map appears to begin with the identification of a select number of metro areas as introduction sites for FCEVs. Once those areas were chosen, the primary driver for selecting station locations became the formation of refueling networks that were sufficiently dense to drive the adoption of the technology by new customers. There was also a secondary emphasis on placing stations at sites linking these disparate regions or providing refueling at common weekend travel destinations. Alternative fuel vehicle penetration and income appear to have been only tertiary factors in placement decisions. The algorithm described below attempts to follow this process for prioritizing station placements.

The overall likelihood, $p(z_n \mid \dots)$, of a new station being placed at z_n is then likely to depend on a number of factors:

- $p_a(z_n)$ = the likelihood of people adopting fuel cell vehicles near z_n
- $p_r(z_n)$ = the likelihood that the road network in the area is conducive to station placement
- $p_A(z_n \mid \mathbf{z})$ = the likelihood that new stations will be placed in such a way as to avoid (or in more complex cases be attracted to) existing stations
- $p_C(z_n \mid \mathbf{z})$ = the likelihood that a station placed at z_n would serve to connect existing locations at distances greater than a single fueling at half of vehicle range
- $p_D(z_n)$ = the likelihood that the region represents a likely travel destination and is within range of an existing cluster of stations.

5.2.1 Adoption Likelihood

We denote the total number of vehicles in cell i by $v^{(T)}_i$ and the number of alternative fuel vehicles in cell i by $v^{(AFV)}_i$. Alternative fuel vehicles represent a fraction, $\Phi^{(AFV)}_i = v^{(AFV)}_i / v^{(T)}_i$, of the total. That fraction is suspected of being correlated with and indicative of the likelihood of people in a region adopting hydrogen fuel cell vehicles. In most cases, however, we'll want to weight this likelihood of adoption in a cell by the population of the cell that can drive (i.e., the total number of vehicles) such that:

$$p_a(z_n) \propto v_n^{(\mathrm{T})} \phi_n^{(\mathrm{AFV})} = v_n^{(\mathrm{AFV})}$$

where the total distribution is normalized such that:

$$\sum_n p_a(z_n) = 1$$

5.2.2 Impacts of Interstates

In addition to the number of early adopters in an area influencing demand for new stations, the presence of interstates also suggests greater traffic volumes, which may also be correlated with a demand for stations. The details of how this correlation occurs (where early adopters live versus where they work versus where they drive) are probably beyond the scope of this study. For now, we may just want to We use a probability distribution proportional to the total traffic capacity to capture the increased likelihood of station placement in areas where there are more, larger roads indicative of greater travel volumes.

In the data set, roads are binned by lane category with "1" representing single-lane roads (one in each direction), "2" representing two- and three-lane roads, and "3" representing roads with four or more lanes in each direction. We make the simple assumption that the average number of lanes (**l**) in the categories is $\mathbf{l} = \{1.0, 2.5, 5.0\}$. We denote length of roads of lane category c in the ZIP code that z_n falls in as s_{cn} and the area of that ZIP code as b_n. The likelihood of station placement in an area, based only on the simplest assessment of the road network, is proportional to:

$$p_r(z_n) \propto \sum_c \frac{l_c s_{cn}}{b_n}$$

where again we stipulate that:

$$\sum_n p_r(z_n) = 1$$

5.2.3 Avoidance of Existing Station Locations

While there are times when particular road intersections have sufficient demand and convenience to drive the placement of multiple fueling stations next door to or across the street from each other, this marketing strategy will likely be uncommon during the early market growth phase when network coverage is a high priority. We therefore seek to minimize the likelihood that stations are placed adjacent to each other. In the CaFCP Road Map, it is suggested that station densities should be such that there is a station within 6 minutes driving time for consumers. Higher densities than this, at least initially, would increase costs and/or reduce coverage. As an approximation, we assume this means stations need not be placed closer than 12 minutes of driving time apart from one another. If we assume an average speed of 30 mph in metropolitan areas this corresponds to a separation, d, of roughly 6 miles.

The decrease in the likelihood of new stations being placed close to existing stations can be modeled using a logistic function with the separation, d, and fuzziness of the boundary, δ, as parameters. The probability of a new station being placed at z_n given the location of a single existing station z_i is:

$$p_A(z_n|z_i, d, \delta) = \frac{1}{\exp\left(-\frac{|z_n - z_i| - d}{\delta}\right) + 1}$$

The probability that a candidate location, z_n, is not within d of *any* existing stations is then:

$$p_A(z_n|\mathbf{z}, d, \delta) = \prod_i p_A(z_n|z_i, d, \delta).$$

Alternatively, we may want to build up a network in such a way that we do not just specify that new stations not be placed too close to existing stations, but that they preferentially be added at a distance of roughly d from existing stations (that is, a new station will be more likely to grow a pre-existing cluster of stations outward rather than uniformly increasing station density anywhere but within the cluster). In this case we might, for a single existing station, define the following:

$$p'_A(z_n|z_i, d, \delta) = \exp\left[-\frac{(|z_n - z_i| - d)^2}{2\delta^2}\right].$$

The probability that the candidate location, z_n, is within a δ-mile-wide band a distance d from at least one of the existing stations is then:

$$p'_A(z_n|\mathbf{z}, d, \delta) = 1 - \prod_i (1 - p'_A(z_n|z_i, d, \delta)).$$

Something could, however, be within a δ-mile-wide band a distance d from at least one station and still lie essentially on top of another station. Really we want it to be within a band around existing stations without lying too close to any of them. The probability that a location does not lie within a distance $d_<$ of any existing location is $p_A(z_n \mid \mathbf{z}, d_<, \delta)$, so the probability that a station lies roughly a distance d from at least one station without lying within a distance $d_<$ of any station is:

$$p_G(z_n|\mathbf{z}, d, d_<, \delta) = p'_A(z_n|\mathbf{z}, d, \delta)\, p_A(z_n|\mathbf{z}, d_<, \delta)$$

where the G indicates this is the distribution relevant to growing a network.

5.2.4 Utility of Connecting Disparate Station Clusters

There is potential utility in connecting disparate clusters of stations, or clusters that are separated by a greater distance than may be traveled on a single fueling. We can denote mean vehicle range by D and the variation about this range by δ. For a single station we might again have the following functional form:

$$p_C(z_n|z_i, D, \Delta) = \exp\left[-\frac{(|z_n - z_i| - D)^2}{2\Delta^2}\right].$$

In this case, however, a new station is only useful in connecting disparate clusters if it is within a δ-mile-wide band a distance D from at least two different stations. It also is useful only if those two stations are in different, isolated clusters. We denote each isolated set of stations as a cluster,

c_k (where k ranges from 1 to the number of clusters, N_c). The likelihood of placing a station for the purpose of connecting disparate station clusters is therefore given by:

$$p_C(z_n|\mathbf{z}, D, \Delta) = 1 - \prod_{m=1}^{N_c} \prod_{n=1}^{m-1} \prod_{i \in c_m} \prod_{j \in c_n} [1 - p_C(z_n|z_i, D, \Delta)\, p_C(z_n|z_j, D, \Delta)]$$

5.2.5 Travel Destinations

Now there is utility in providing a new refueling station at a likely travel destination that is within the range of existing stations. To make things a little easier at first, we neglect where people are traveling from (basically assuming that at least some of them are coming from the closest station cluster). We let u_n represent the average number of out of town (e.g., weekend tourist) visits to a destination in cell n. If the distance between the nearest existing station and cell n is less than half the mean vehicle range, D, then placing a station at the destination is unnecessary. Likewise, if the destination is greater than a distance D from all existing stations then it also does not make sense to put a station there. The likelihood of placing a station at a destination in cell n is then:

$$p_D(z_n) \propto u_n\, p_A(z_n|\mathbf{z}, D/2, \Delta)\, [1 - p_A(z_n|\mathbf{z}, D, \Delta)]$$

5.2.6 Putting Them All Together

The overall spatial probability distribution of placing a new station depends on each of the above factors. However, we can argue that there is a philosophical difference between placing a station to grow an existing cluster, placing a station to start a new cluster, placing a station to link disparate clusters, and placing a station at a travel destination. In fact, most of these acts are mutually exclusive. If we let q_g denote the relative likelihood that a new station is placed with one of these goals in mind—with the stipulation that

$$\sum_g q_g = 1$$

—the geospatial probability distribution for siting a new station with the purpose of growing an existing cluster is given by:

$$p_a(z_n)\, p_r(z_n)\, p_G(z_n|\mathbf{z}, d, d_<, \delta).$$

The distribution for siting a new station with the purpose of starting a new cluster is given by:

$$p_a(z_n)\, p_r(z_n)\, p_A(z_n|\mathbf{z}, 2d, \delta),$$

where we note that the unprimed p_A distribution is used with an exclusory distance around existing stations of twice the consumer-desired separation. The distribution for siting a new station with the purpose of linking disparate clusters is:

$$p_a(z_n)\, p_r(z_n)\, p_C(z_n|\mathbf{z}, D, \Delta).$$

And, finally, the distribution for siting a new station at a travel destination is:

$p_r(z_n)\, p_D(z_n|\mathbf{z}, D, \Delta)$

Thus, the overall spatial probability distribution of a new station placement will be:

$$
\begin{aligned}
p(z_n|\mathbf{z}, d, \delta, D, \Delta, \mathbf{q}) = {} & p_a(z_n)\, p_r(z_n) \times \Big[\\
& \qquad q_1\, p_G(z_n|\mathbf{z}, d, d_<, \delta) + \\
& \qquad q_2\, p_A(z_n|\mathbf{z}, 2d, \delta) + \\
& \qquad q_3\, p_C(z_n|\mathbf{z}, D, \Delta) \\
& \Big] + \\
& q_4\, p_r(z_n)\, p_D(z_n|\mathbf{z}, D, \Delta)
\end{aligned}
$$

5.3 Example Applications

Figure 31 shows the results of the aforementioned station placement model in Chicago. This demonstrates that the model mimics the non-uniform distribution of station sites under early market conditions, and that it clusters stations near areas of high HEV registration density but maintains realistic spacing between the stations and places “connector stations” between areas of high HEV registration density.

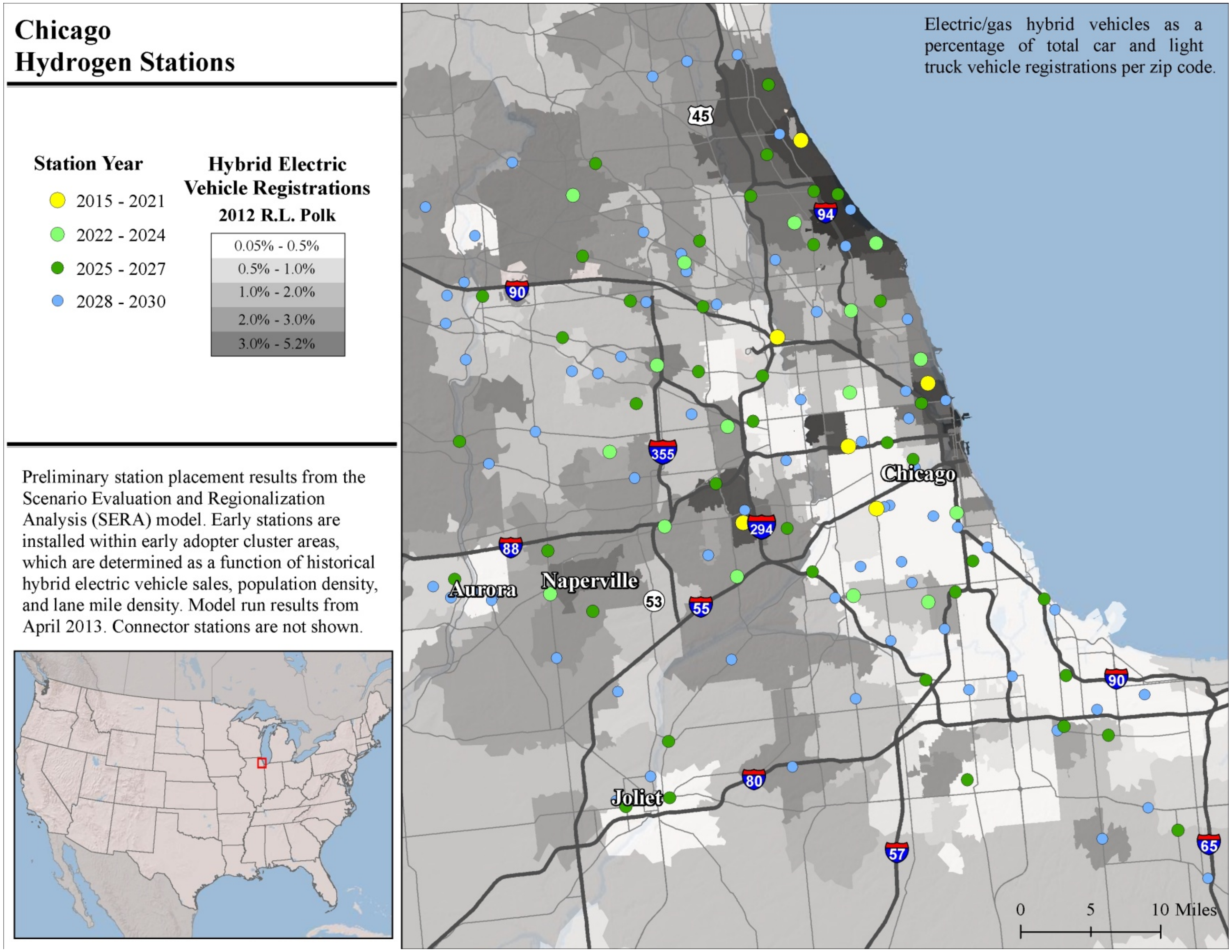

Figure 31. Modeled FCEV fueling stations in the Chicago area.

The density of HEV registrations is plotted in grayscale.

6 Summary

We developed detailed temporal and spatial scenarios for early market infrastructure clustering and vehicle rollout for use in SERA by tuning nationwide scenarios to observations and lessons learned in California early market evolution and planning. The resulting scenarios, which partially account for early-market intra-urban clustering effects, are characterized by more aggressive FCEV rollouts than in the standard NAS scenarios (NAS 2008). This is due to market adoption trends occurring later in time in the CaFCP Road Map (CaFCP 2012) scenarios and adherence to the market saturation trends over the long term from the NAS scenarios.

Our analyses of these scenarios focus on understanding the infrastructure build-out and the cash flow implications in temporal and spatial detail by optimizing the choice of hydrogen production and delivery infrastructure. These early-market clustering analyses highlighted the following insights:

1. Low natural gas costs in most regions and the favorable economies of scale for large coal plants lead to the predominance of central natural gas reforming and coal gasification.
2. Central grid electrolysis has niches in areas of low electricity prices.
3. Onsite natural gas reforming is optimal in low-demand conditions.
4. Gaseous hydrogen pipelines are favorable for high flow conditions and moderate distances.
5. Truck delivery predominates at lower flow (i.e., for gaseous transport) or longer distance (i.e., for liquid transport).
6. Long-term levelized delivered costs for hydrogen tend toward $6.00/kg nationally.
7. Zero cumulative cash flow is achieved in about 2018 or 2025 if hydrogen is priced at $11.00/kg or $6.75/kg, respectively. (See Figure 4 for an example.) However, using alternative accounting methods for cash flow or different financing assumptions would alter this conclusion.
8. Underutilization of infrastructure in the first couple of years after its construction raises the overall contribution of capital costs to the total cost per kilogram results.

We also generated FCEV fueling station placements for the whole nation in a manner that is consistent with (1) the historical experience with the evolution of the gasoline retail station capacity distribution over time, (2) the propensity of FCEV fueling station locations to be clustered near likely FCEV early adopters, and (3) constraints on the proximity of FCEV fueling stations to other FCEV stations, to transportation corridors, and to travel destinations. The realistic sizing, placement, and timing of FCEV stations further improve the realism of cash flow estimates and our understanding of their geographic variability.

In general, these SERA-based analyses and scenarios provide unprecedented spatial, temporal, and cost detail in a manner that can readily be leveraged to enhance future planning and analysis of early market FCEV adoption dynamics, to characterize niche market geographies, and to leverage infrastructure supporting emerging markets such as forklifts or backup power to infrastructure supporting light-duty vehicles.

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