

Sustainable Transportation Energy Pathways (STEPS)

Session 2: The Role of Hydrogen in Transportation: What Have We Learned in STEPS3?

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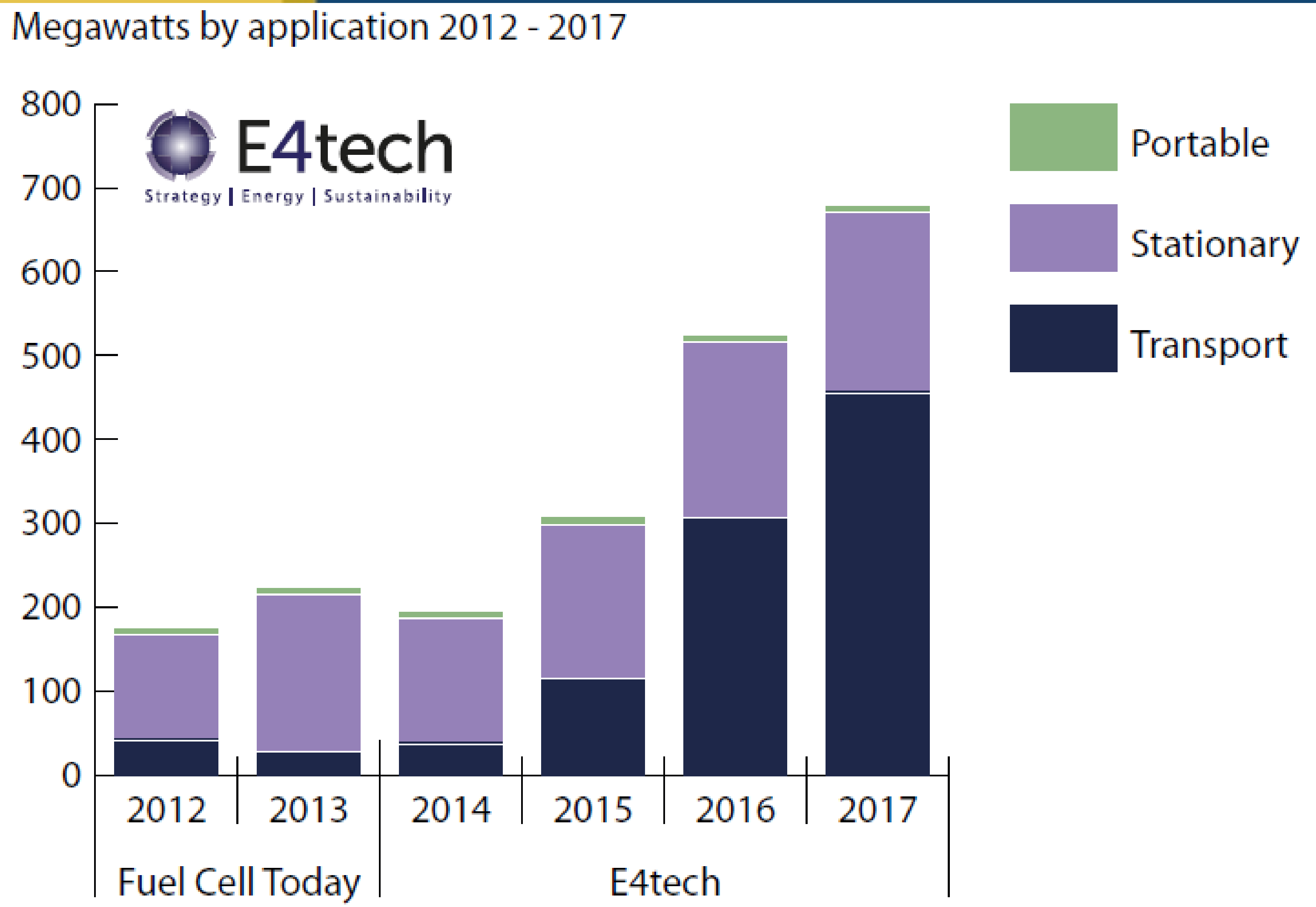
CONTEXT: H2 & Fuel Cells in Transportation

- H2 FCV Rollout
  - Expanding markets for FCV
  - H2 Infrastructure buildout
  - Emerging medium and heavy duty/freight applications
- H2 integration within energy system/infrastructure
  - H2 and NG system
  - Complementarity of H2 and electricity
    - H2 as energy storage
    - Integration of renewables
    - Power to X
- Long term Strategies toward zero emission energy: Roles for H2?
  - H2 FC is one of the only zero emission options for hard-to-decarbonize transport applications like freight

Growth of FC markets, notably transport



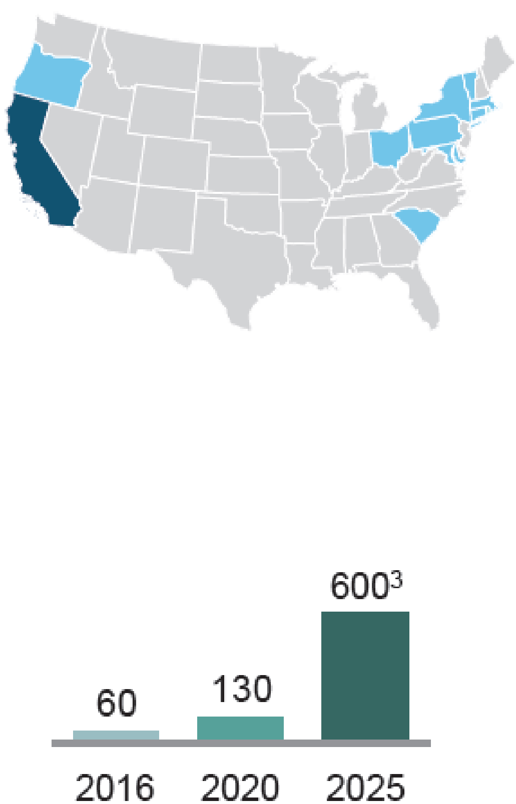
Footnote to charts: Data from 2012-2013 are as published by Fuel Cell Today, including their forecasts for 2013; 2017 is our forecast for the full year, based on firm data from January to October. We have slightly revised the figures for 2016 in this report.

Infrastructure Rollout initiated in key regions

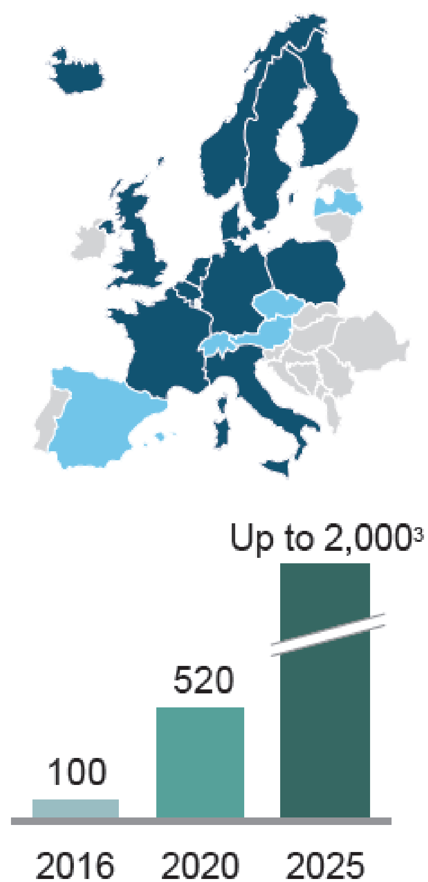
Leading Western and Asian countries plan to roll out a significant hydrogen infrastructure over the coming decade. Number of hydrogen refueling stations (HRS)[1]

Significant HRS network development | Minor HRS network development[2]

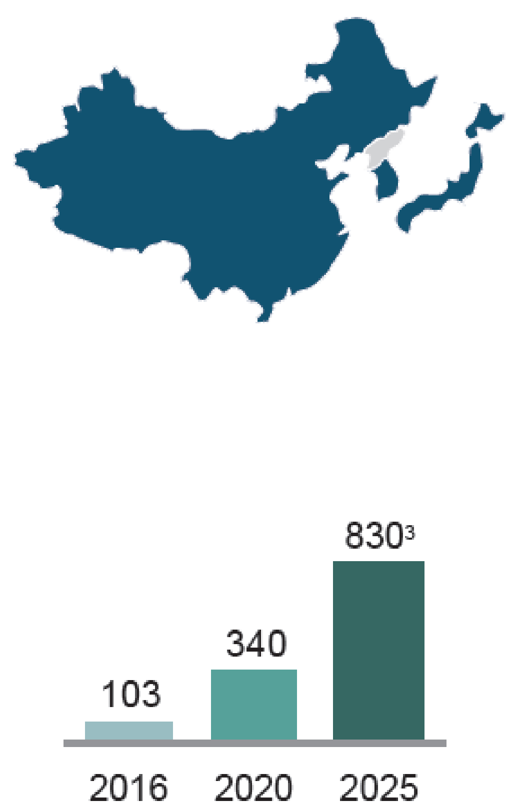
US



Europe



Asia

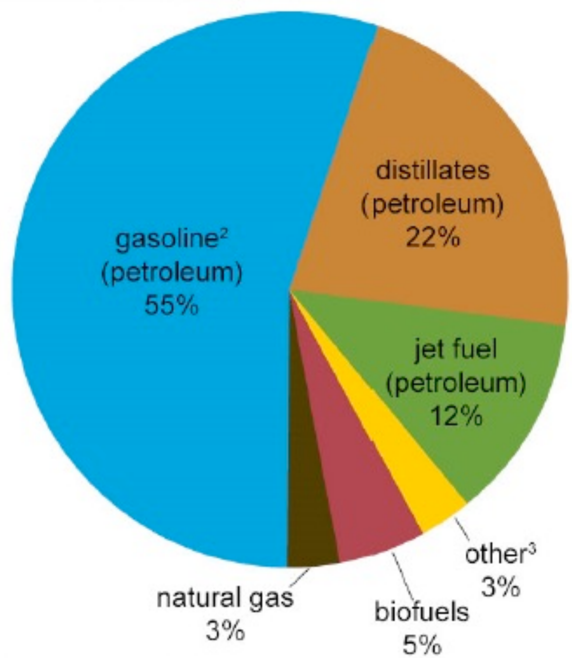


1 Publicly available HRS from countries with a significant HRS network development
2 Countries or states with no major HRS outlook as of today
3 Depending on the number of FCEVs on the road

Source: H_2 Mobility, US DOE, Hydrogen Europe, Air Liquide

Zero emission freight technologies: H2/FC emerge as alternative

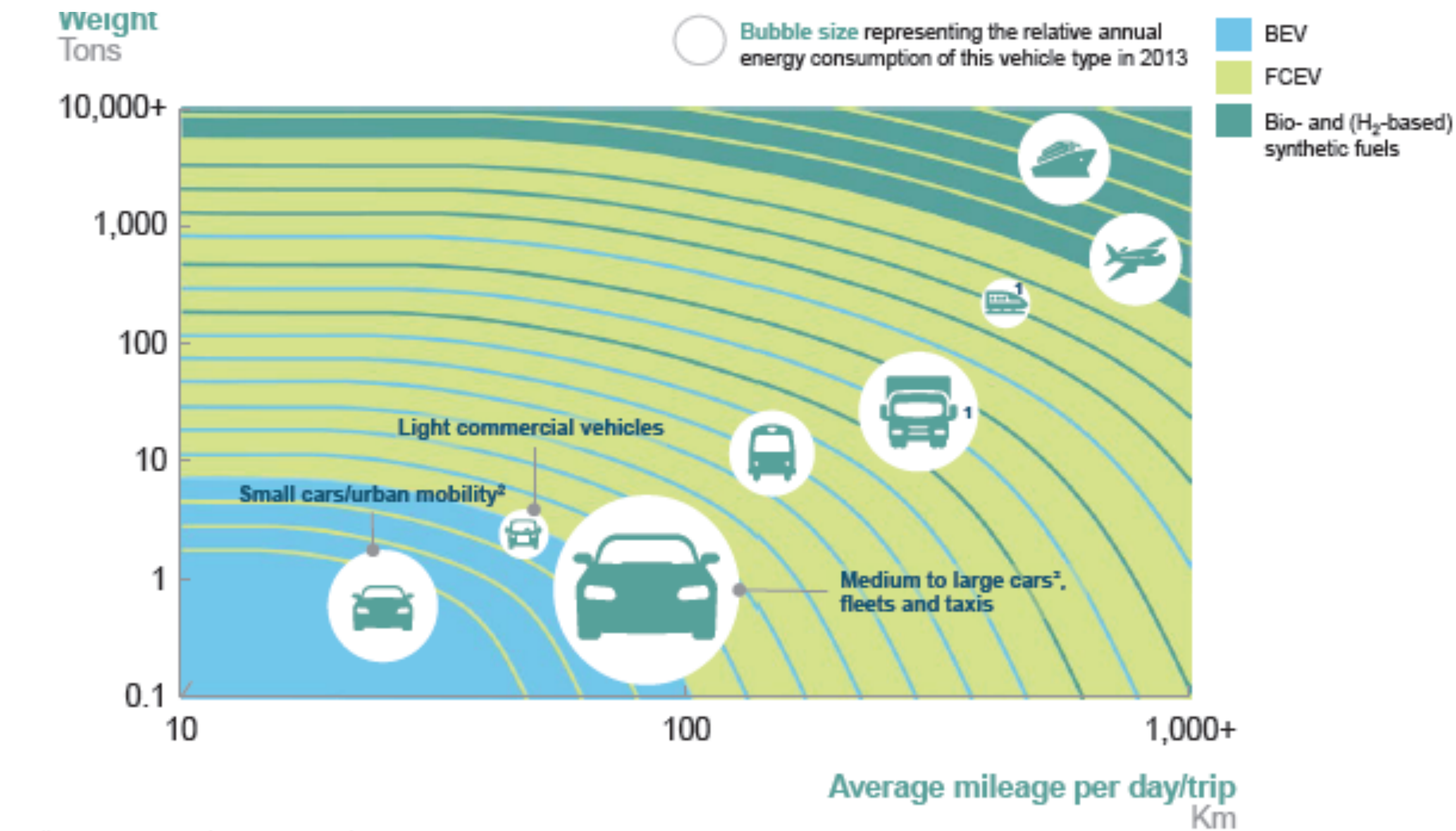
U.S. transportation energy sources/fuels, 2017[1]



[1] Based on energy content

COMPLEMENTARY Roles seen for H_2 FCVs, PLUG-IN EVs

Transport Sector Roles: H_2 FCVs, BEVs, Synfuels

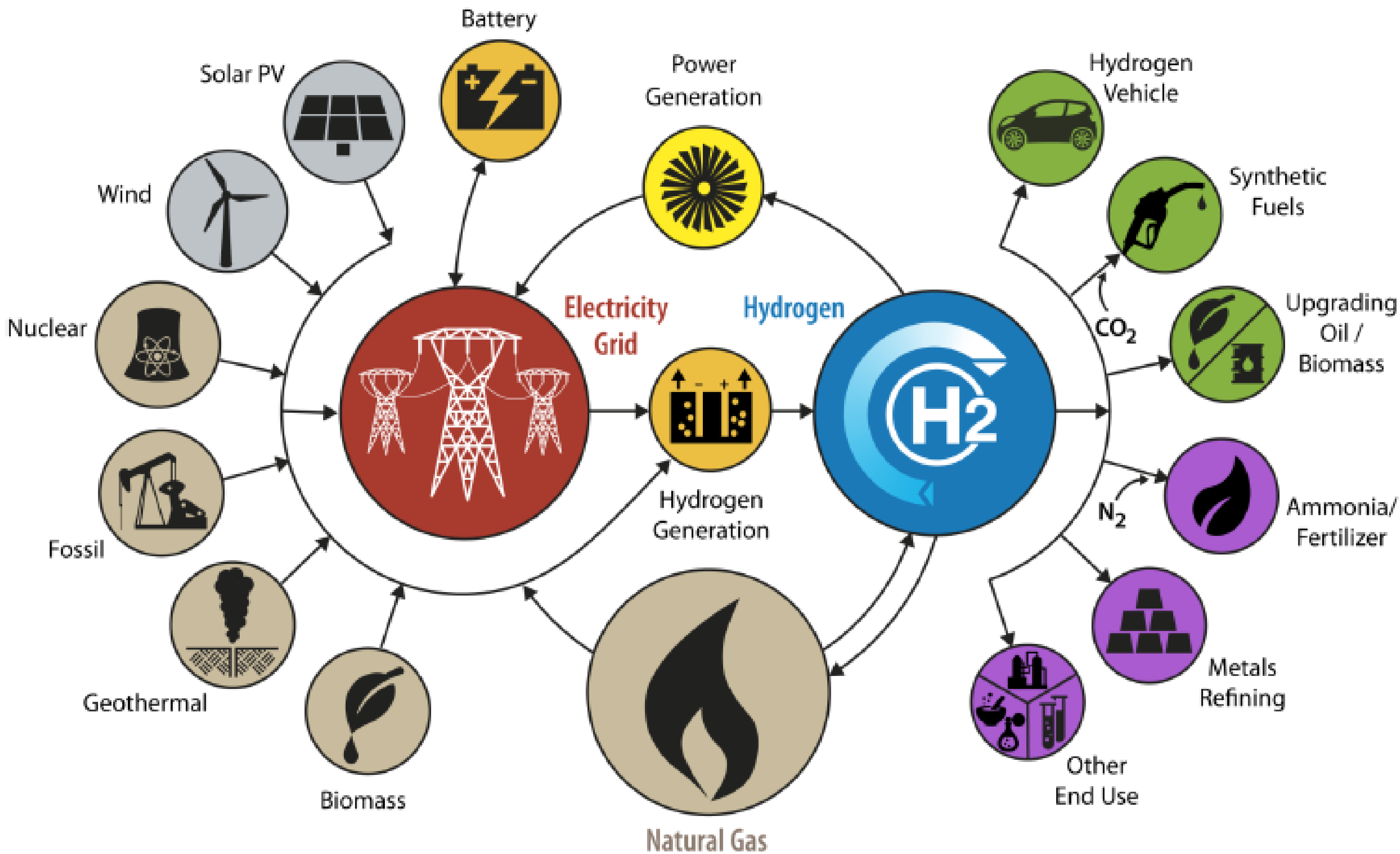


1 Battery-hydrogen hybrid to ensure sufficient power
2 Split in A- and B-segment LDVs (small cars) and C+-segment LDVs (medium to large cars) based on a 30% market share of A/B-segment cars and a 50% less energy demand

Source: Toyota, Hyundai, Daimler

LONG TERM VISIONS FOR ZERO CARBON ENERGY: How does H2 fit, and how can we make a transition?

H_2@Scale: Linking Natural Gas, Electric and H_2 Grids



STEPS3 H2 RESEARCH
Technology Assessment, Regional H2 Transition Studies, Integration of H2 within the energy system, Alternative Scenarios for Low-C Futures & Role of H2

- Technology Assessments of H2 and FCV
  - Techno-economic Assessments of H2 trucks and buses
  - H2 in Aviation, Rail
- Understanding H2 Transitions
  - Transitions in Light Duty Sector
  - Transitions in Medium and Heavy Duty Truck Sector
  - H2 Infrastructure buildout
    - Regional case studies: H2 infrastructure for LDV and MD/HD
- Integration of H2 within energy system/ infrastructure
  - H2 and NG system (NG as a bridge to H2)
  - Complementary roles of H2 and electricity
    - Integration of renewables, H2 as energy storage,
    - Power to X
- Strategies & scenarios -> zero emission transportation (role of H2)

STEPS3 H2 RESEARCH: Techno-economic Assessments of H2 FC trucks & buses

Researchers: Andrew Burke, Hengbing Zhao, Marshall Miller, Lew Fulton

Method: Vehicle simulation for range of H2 FC and other vehicle types. Technoeconomic assessment, comparison of alternative fueled medium and heavy vehicles.

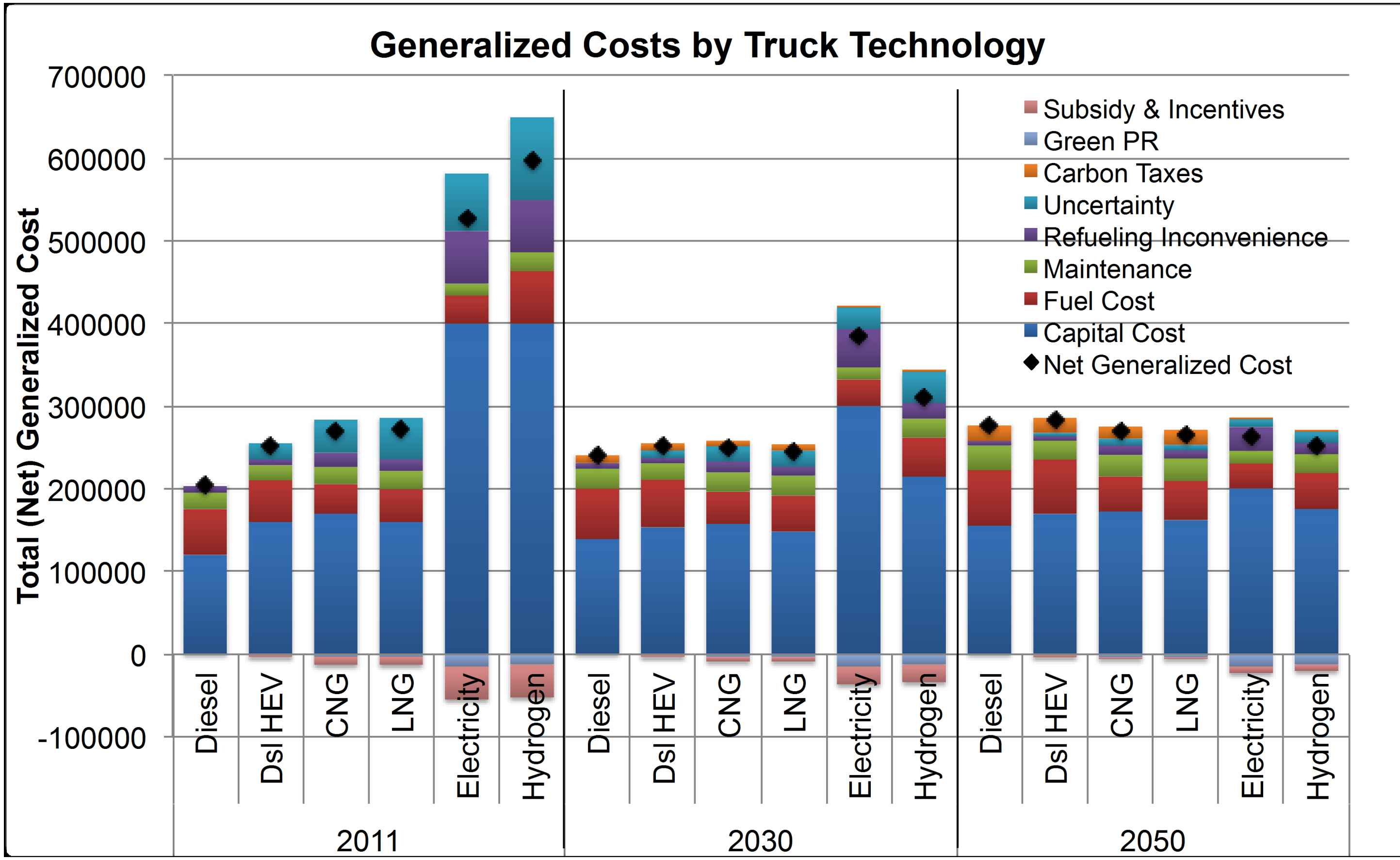
Results: H2 FCV trucks compete with other low emission options in a variety of applications

Publications: Burke, Andrew and Hengbing Zhao (2017) Fuel Economy Analysis of Medium/Heavy-duty Trucks: 2015-2050. Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-17-49

Zhao, Hengbing and Andrew Burke (2015) Modelling and Analysis of Plug-in Series-Parallel Hybrid Medium-Duty Vehicles. *European Electric Vehicle Congress*

Fries, Michael, Sebastian Wolff, Lorenz Horlbeck, Mathias Kerler, Markus Lienkamp, Andrew Burke, Lewis Fulton (2017) Optimization of Hybrid Electric Drive System Components in Long-Haul Vehicles for the Evaluation of Customer Requirements. Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-17-44.

Truck Technology Cost Comparison



STEPS H2 RESEARCH: H2 in Rail

Researchers: Raphael Isaac, Paul Erickson, Lew Fulton

Method: Assessment of Options for Low Carbon Rail. Evaluate practicality, costs and greenhouse gas-related benefits of different propulsion technologies and fuels for U.S. freight and passenger (i.e. intercity/commuter) rail. Two example routes, one existing (for passenger rail) and one devised (for freight), are used to construct the analysis and better understand the implications of fuel strategies in a “real world” context.

Results: Although diesel-electric locomotives currently dominate freight and non-urban passenger rail, a number of other fuels could be considered in the near future. These include biodiesel and the new “renewable diesel” drop-in diesel replacement fuels. With the low prices of natural gas in recent years, it is another important fuel alternative. Though few longer-distance rail systems in the US run on electricity, this energy carrier is widely used in Europe. Finally, hydrogen and fuel cells are now being explored for non-urban rail systems and some rail yard applications. These options and the requisite locomotive technologies are all considered for our example routes.

Publications: Isaac, Raphael and Lewis Fulton (2017) Propulsion Systems for 21st Century Rail. *Transportation Research Procedia* 00 (2017)

STEPS H2 RESEARCH: H2 in Aviation

Researchers: Guozhen Li, Joan Ogden, Lew Fulton

Method: Assessment of Options for Low Carbon Aviation

Results: While H2 aircraft are technically feasible, the required refueling infrastructure at airports appears to pose a significant barrier to a hydrogen pathway for aviation. Thus, careful planning of refueling infrastructure must be addressed when considering H2 for air transportation. Due to the large throughput of H2 at a commercial airport, which is estimated to be in the order of thousands of metric tons of H2 per day, liquid H2 can be produced at much lower cost than it is today's typical volumes. The large volume and low cost of liquid H2 suggest that airports could be central hubs in a H2 economy, supplying low-cost H2 not only for airplanes but also ground vehicles and residential uses. H2 airport takes enormous amount of land and power for fuel production. These impacts must be considered when planning a H2 airport. H2 can reduce aviation GHG emission only when produced from electrolysis with renewable electricity. The costs of such GHG abatement put H2 as a longer-term emission reduction solution for aviation, behind efficiency improvements and bio jet fuels.

Publications :Li, Guozhen, *The Hydrogen Fuel Pathway for Air Transportation,* Thesis, Masters of Science Degree, University of California, Davis, ProQuest Dissertations Publishing, 2015. 10036120.

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LAND AREA REQUIREMENTS FOR LH2 FUEL FACILITY AT SFO AIRPORT

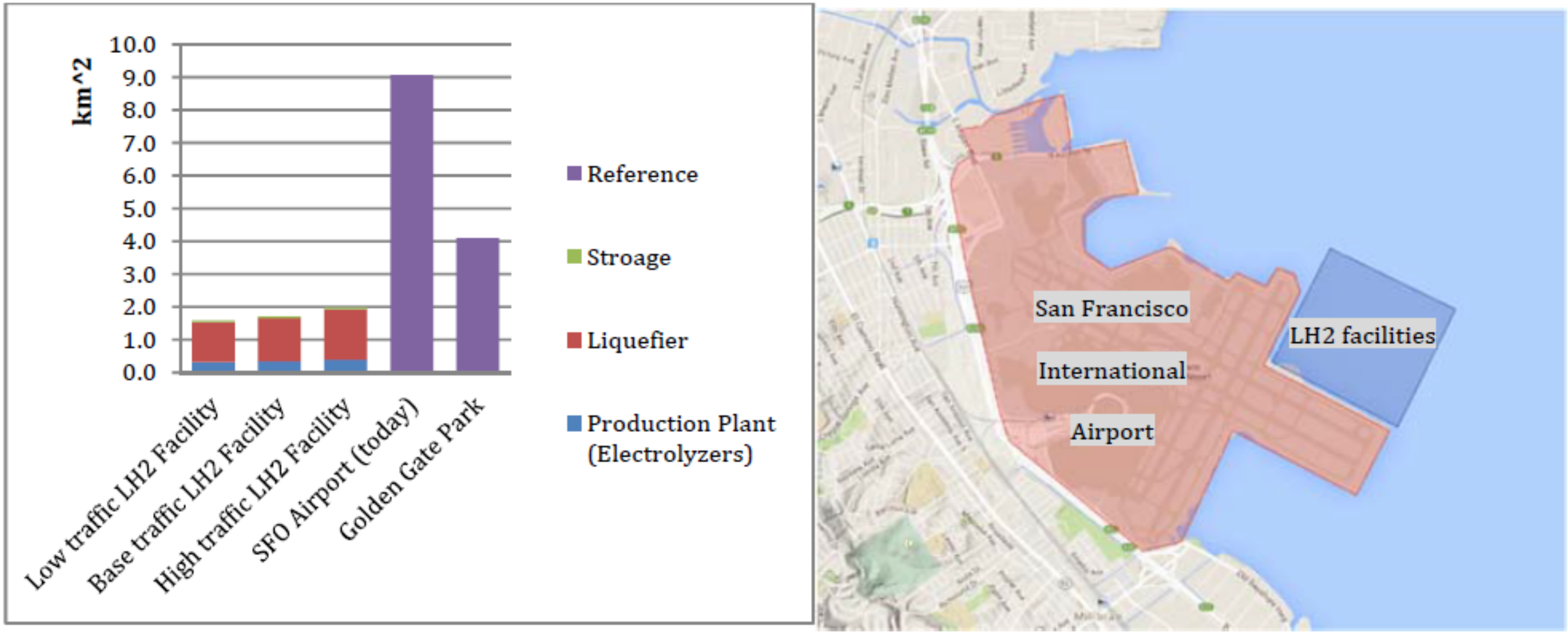


Figure 3 LH2 fuel facility land area requirements.

STEPS H2 RESEARCH: Regional Analysis of ZEV Transitions in Light Duty Sector

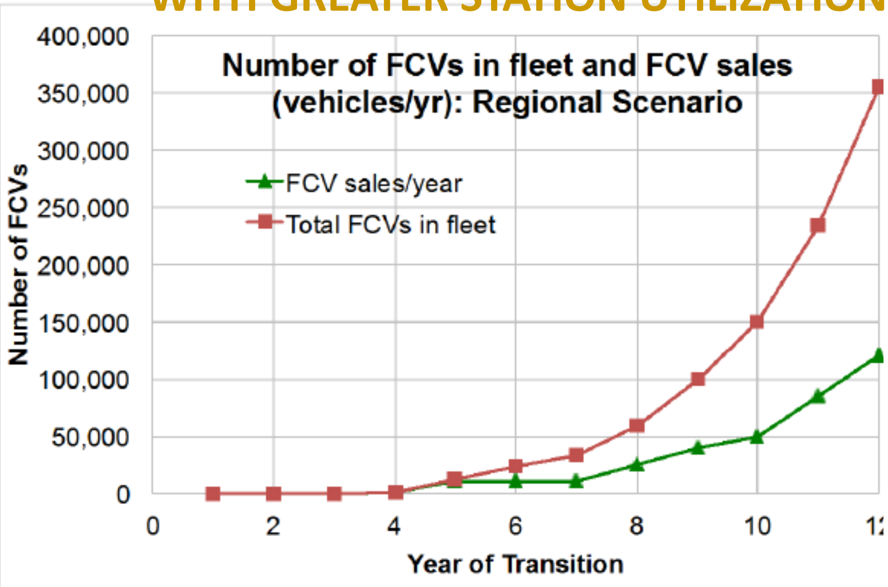
Researchers: Joan Ogden, Lew Fulton, Dan Sperling

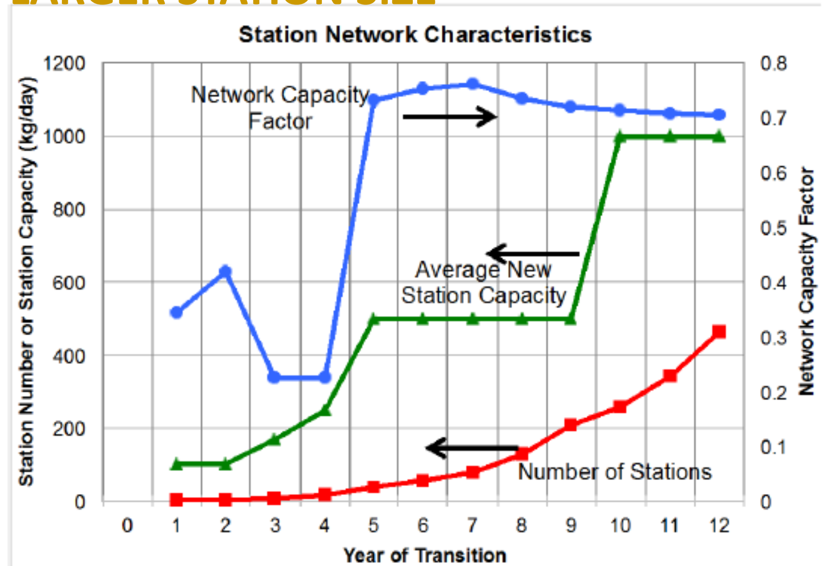
Results: Transition costs for adoption of FC vehicles to 2035.

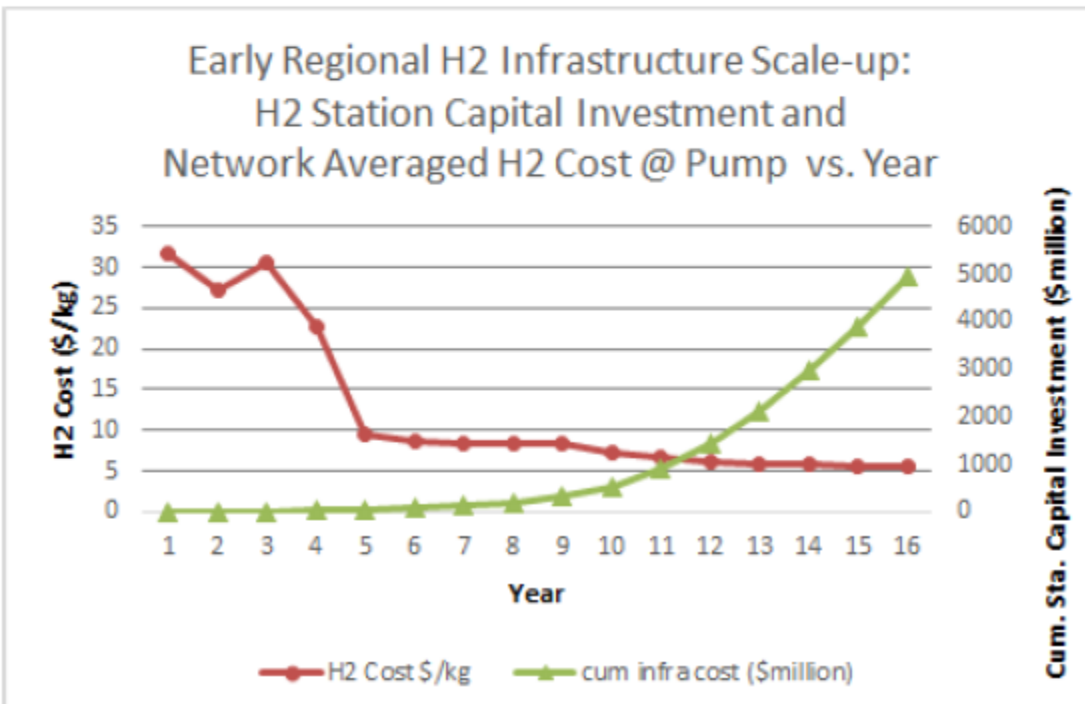
- Regional infrastructure analysis: Beyond 100 H2 stations in CA
- USA analysis: Transition Cost

Publication: Ogden, Joan M., Lewis Fulton, Daniel Sperling (2016) Making the Transition to Light-duty Electric-drive Vehicles in the U.S.: Costs in Perspective to 2035. Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-16-21

REGIONAL H2 INFRASTRUCTURE ROLLOUT: H2 COSTS BECOME COMPETITIVE WITH GREATER STATION UTILIZATION, LARGER STATION SIZE







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STEPS H2 RESEARCH: Regional case study of H2 infrastructure for Medium and Heavy Duty trucks in California

Researchers: Guozhen Li, Joan Ogden

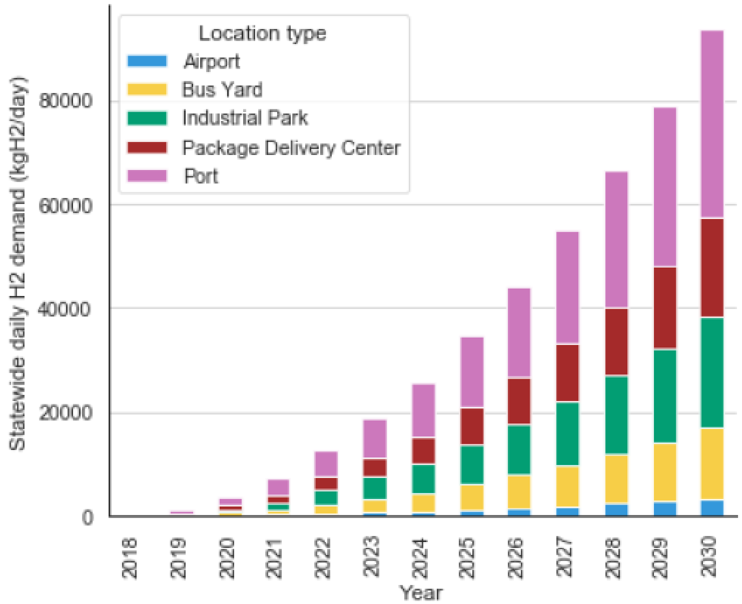
Method: Regional scenario study of H2 infrastructure for MD/HD trucks in California. Develop a predictive model that simulates the population growth of medium-duty (MD) and heavy-duty (HD) hydrogen fuel cell vehicles (FCVs) and estimate their hydrogen fuel demand with temporal and spatial granularity. Find optimal refueling facility layouts to meet the fuel demand. Additionally, several scenarios of MD/HD FCV growth pathways for California are simulated and compared.

Results: These scenarios suggest that California may need about 130 refueling facilities to meet the hydrogen fuel demand from the local MD/HD FCV market by 2030, and each facility needs to handle demands ranging from hundreds of kilograms of hydrogen per day to tens of thousands of kilograms of hydrogen per day.

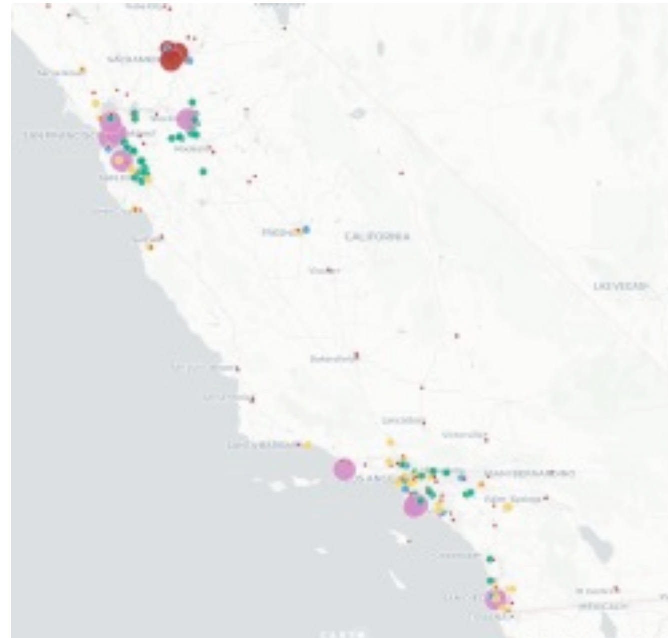
Publication: Guozhen Li and Joan Ogden, "Simulation-Based Scenario Analysis on Growth of Medium-Duty and Heavy-Duty Hydrogen Fuel Cell Vehicles and Their Refueling Infrastructure Needs in California," to be presented at the 2019 TRB meeting, Washington, DC, January 11, 2019. Paper number 19-02958.

Guozhen Li and Joan Ogden, "Hydrogen Fuel Demand and Infrastructure Placement for Medium- and Heavy-Duty Vehicles in California," working paper, Institute of Transportation Studies, May 2018.

FCV Truck Fleet Scenario

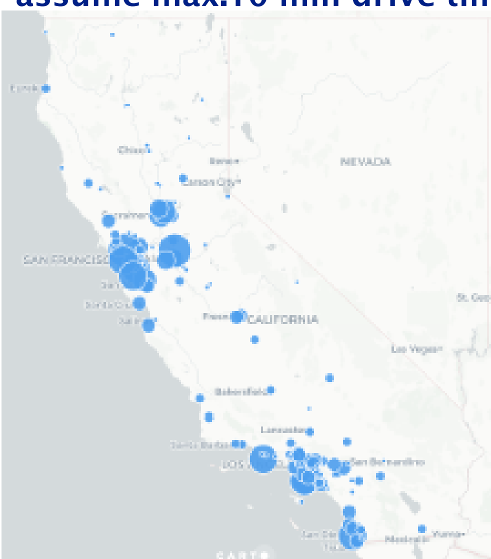


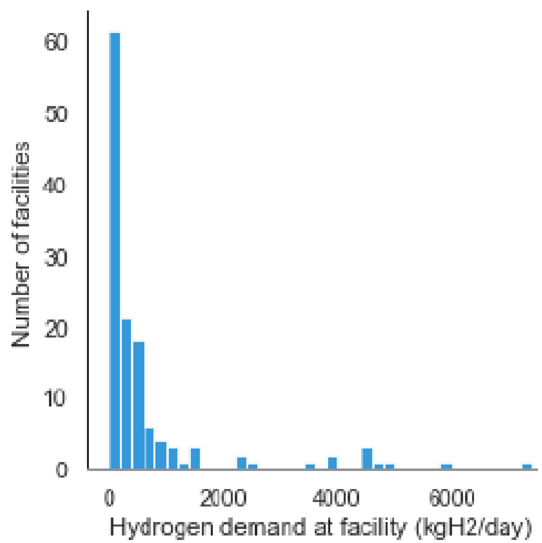
2030 H2 Demand for 10,000 Trucks



130 H2 Station Network

assume max.10 min drive time: fleet hub to stations

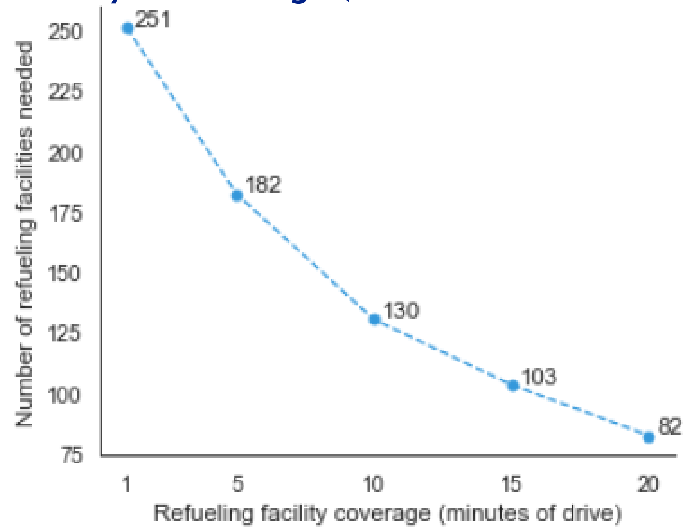




(a) Facilities map (b) Histogram of demand at facility

stations needed

Sensitivity to coverage (drive time to station)



STEPS H2 RESEARCH:
Is Natural Gas a Bridge to Hydrogen Transportation?

Researchers: Joan Ogden, Amy Myers Jaffe, Daniel Scheitrum, Zane McDonald, Marshall Miller

Method: Review diverse literatures: H2 and NG transport applications; use of H2, H2/NG blends in NG system; power to gas. Develop scenarios for introduction of H2 vehicles in California, assess outlook for adapting NG system to H2 and H2 blending; compare CA to European context.

Results: Case by case analysis needed before injection of H2 into NG pipeline infrastructure. Blend limit of 5-15% H2 by vol. may ultimately limit how much H2 could be transported as a blend in NG. This may make it difficult to utilize the existing NG system to deliver H2 transportation fuel at the scale needed to achieve deep cuts in transportation related GHGs. In a 2 degree world, demand for H2 transportation fuel would far outstrip the ability of the NG system to deliver H2 as part of a blend. In the long term, if H2 becomes a major transport fuel, dedicated renewable H2 supply system would be needed.

Publications: Ogden, Joan M., Amy Myers Jaffe, Daniel Scheitrum, Zane McDonald, Marshall Miller (2018) Natural Gas as a Bridge to Hydrogen Transportation Fuel: Insights from the Literature . *Energy Policy* 115, 317 - 329.

Jaffe, Amy Myers, Rosa Dominguez-Faus, Joan M. Ogden, Nathan C. Parker, Daniel Scheitrum, Zane McDonald, Yueyue Fan, Tom Durbin, George Karavalakis, Justin Wilcock, Marshall Miller, Christopher Yang (2017) The Potential to Build Current Natural Gas Infrastructure to Accommodate the Future Conversion to Near-Zero Transportation Technology. Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-17-04

STEPS H2 RESEARCH: Grid Interaction of EVs: California Case Study with the CalEV model (H2, FCVs to be included in future).

RESEARCHERS: Behdad Kiani, Joan Ogden, Alan Jenn, Alex Sheldon, Ryan Barr

METHOD: We create scenarios representing future penetration of EVs in Southern California, by optimally controlling the vehicle-to-grid (V2G) and grid-to-vehicle (G2V) time of day usage in accordance with people's daily use pattern. This analysis is conducted using a grid operation optimization for one year at an hourly step. We created a technoeconomic optimization model, called CalEV, using the MESSAGE (Model for Energy Supply Strategies and their General Environmental Impacts**)** platform. CalEV optimizes the system as a mixed-integer mathematical model. Our system simulates a smart grid, where the interaction between EVs and grid is optimized based on technoeconomic factors, such as pricing, travel demand, and electricity supply. ***System benefits may include producing low-cost zero-carbon fuel for FCEVs, generation of zero-carbon industrial feedstock, providing flexible supply and energy storage for the grid, and providing a source of low-carbon gas.***

RESULTS: We model the Los Angeles power grid and optimize grid interaction of EVs for the year 2020, such that the battery capacities in the electric vehicle could be efficiently utilized. A demand driven optimization model is developed based on hourly vehicle mile travel distribution. We assume any parked, plugged EV can interact with the grid. Optimal V2G and G2V energy flow is calculated based on factors such as battery capacity, charging and discharging rates, required energy for driving demand, hourly electricity price ramp-up constraints, etc. We find that utilizing parked EV batteries through a smart grid network can help flatten the daily load (reducing the "duck curve") by utilizing mid-day solar energy and then providing power for peak load. The net effect in our scenario for 2020 is 800MW relative to a daily peak demand of 3500MW (for a selected day in spring). The effect will naturally increase beyond 2020 as more EVs are added. This can reduce the need for expensive capacity expansion and can contribute to stability of electricity prices and help justify the expenses associated with V2G-related grid investments. In future we will consider electrolytic hydrogen as energy storage for transportation or other uses.

PUBLICATIONS: 1. Joan M. Ogden, "Prospects for Hydrogen in the Future Energy System", Research Report – UCD-ITS-RR-18-07, Institute for Transportation Studies, UC Davis, March 2018.

2. Kiani, B. "Grid Impact Modeling for Large Scale Penetration of Zero Emission Vehicles in California", STEPS Spring 2018 Symposium and Board Meeting, UC Davis, CA, May 15th & 16th 2018. (Presentation and Panelist) https://steps.ucdavis.edu/wp-content/uploads/2018/05/2.-KIANI.Grid-Impact-Modeling-for-Large-Scale-Penetration-of-Zero-Emission-Vehicles-in-California.pdf

3. Ryan Barr, Joan Ogden, Behdad Kiani, Alan Jen, "Electric Vehicles as a Tool to Integrate Renewables" , STEPS Spring 2018 Symposium and Board Meeting, UC Davis, CA, May 15th & 16th 2018. (Poster Session) https://steps.ucdavis.edu/posters-spring-2018-symposium/

4. UC Davis grid modeling impacts of large scale EV penetrations (2030), webinar for BMW technical team, May 2018.

5. See Posters this meeting.

STEPS H2 RESEARCH: Scenarios for Low Carbon Transportation Futures : Role of H2

RESEARCHERS: Lew Fulton, Marshall Miller, Chris Yang, Andrew Burke, Qian Wang

RESULTS: H2 plays a role in diverse transport applications across different scenarios

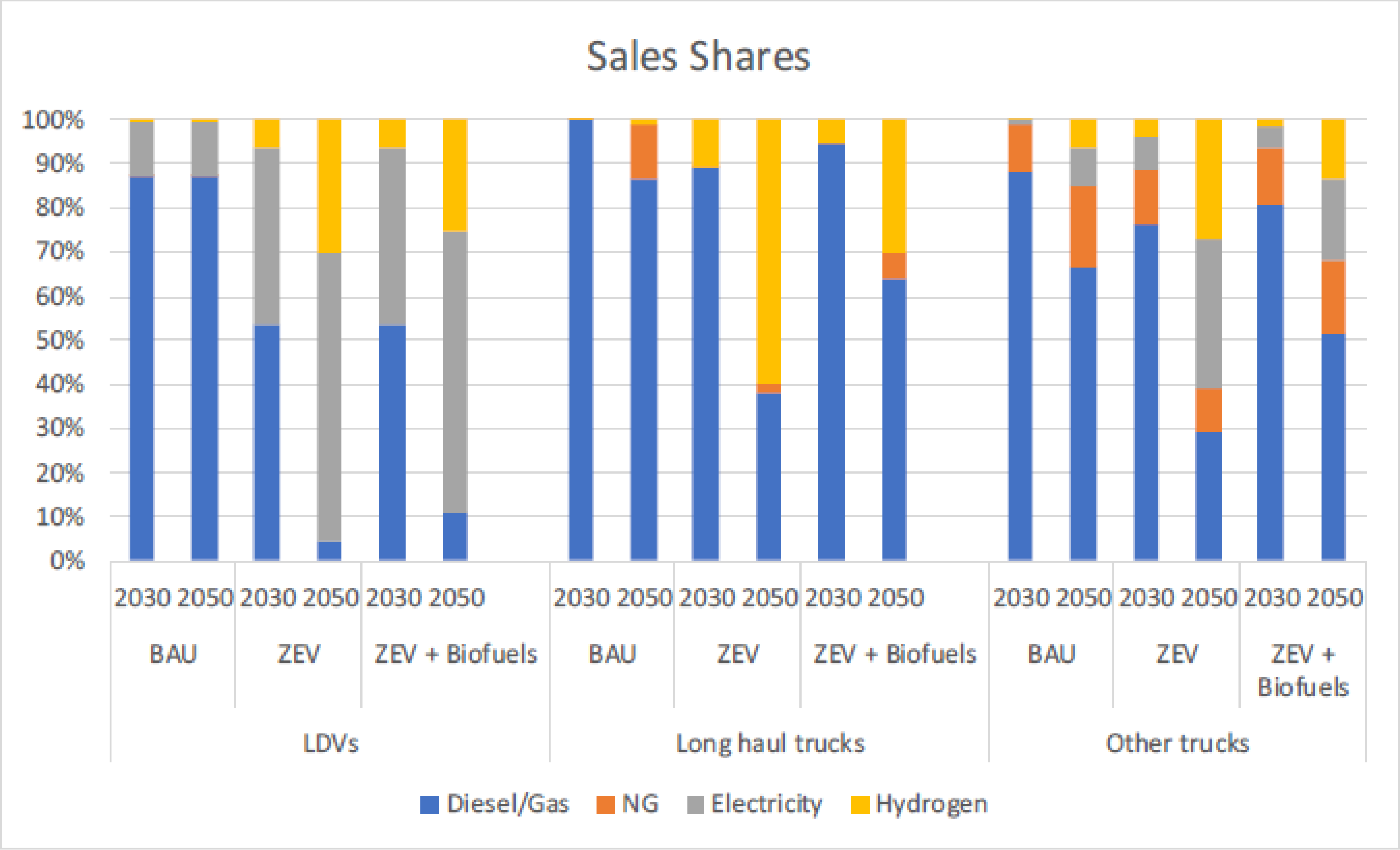


Figure 1. Vehicle sales shares across vehicle types, scenarios, technologies and years.

SUMMARY: STEPS LEARNINGS ABOUT H2 AND FC

- H2/FC potentially competitive in diverse transport applications.
- H2/FC complementary to plug-in vehicles. “and” not “or”. Our energy system modeling indicates roles for both ZEV technologies.
- Non-LDV H2 FCV applications potentially attractive, and may be critical as H2 is one of the only zero emission options for freight.
- Regional infrastructure rollouts. Network breaks even with higher utilization, larger stations. Scale up may take time, but in long term cost of transitions << than benefits.
- Role of H2 in NG system. Technical considerations may limit the amount of H2 that could be transported as a blend in NG . For massive scale H2 FC development, need dedicated H2 supply system.
- H2 proposed as enabler for increased penetration of variable renewables. We’ve begin to investigate synergy with electric grid, storage, demand. H2 enables “Power to X”, producing diverse renewable fuels.
- Low Carbon energy future scenarios typically include mid to long term roles for H2 in LDV and MD/HD transportation.