California Hydrogen Infrastructure and ZEV Adoption Towards a Carbon Free Grid in 2045

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Abstract

The transportation sector is a major source of California's greenhouse gas emissions, contributing 41% of the state total[1]. California policy is moving rapidly toward Zero Emission battery electric vehicles (BEV) and hydrogen fuel cell vehicles (FCV). Governor Newsom has issued an executive order that all new in-state sales of passenger vehicles should be Zero Emission Vehicles (ZEV) by 2035. Further, the California Air Resources Board has approved rulemaking requiring that more than half of trucks sold in the state must be zero-emissions by 2035, and all of them by 2045 [1a].

California has the ambitious goal of achieving a 60% renewable electricity grid by 2030 and 100% carbon free grid by 2045. High penetration of variable renewable energy (VRE) requires seasonal storage to match supply and demand and hydrogen could be a possible candidate for this purpose [1b]. The author has developed the CALZEEV energy-economic model to study possible roles for hydrogen in a VRE intensive future grid with a large Zero Emission Vehicle fleet, comprised of both BEVs and FCVs. In particular, we study whether we can provide sufficient seasonal storage for a 100% zero carbon electricity grid and the potential role of H2 infrastructure in a BEV/FCEV combination for a sustainable path towards a zero-emission energy system. The role of hydrogen infrastructure in seasonal storage for balancing VRE generation while meeting demand for hydrogen vehicles year around has been studied, including economic impacts.

1. Introduction

With the US rejoining the Paris agreement, we are expecting a higher and faster adoption of renewable energy into the national grid[2] . California has been a leader in implementing environmentally-friendly policies and it is predicted that we will need a nationwide strategy to move towards a carbon-free economy. Electrification of the transportation sector and higher

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penetration of renewable energy grids are important issues that need thorough analysis nation-wide based on regional potentials. Electrification of the transportation sector will amplify challenges associated with time of day charging demand and a renewable-dominated grid will require high temporal and regional resolution models to analyze the dynamic load both during peak hours and seasonal variations. As more electric vehicles enter the fleet, particularly in the medium and heavy-duty sectors, electrical infrastructure and load management will become more critical, and seasonal storage technologies for reducing curtailment of variable renewable electricity will be a key factor in achieving these goals.

Various models have been developed by private entities and government organizations to analyze the impacts of EVs on the grid. These models have been used to better understand how renewable energy might be integrated into the future electric grid, but in general have not concentrated on the transport sector or the potential effects of hydrogen seasonal storage. Further they have not modeled infrastructure transitions and the cost of infrastructure buildout.

E3's RESOLVE model[3] has been used to model a limited number of time-slices (37 independent days of 24 hours) within a year but cannot model how hourly and seasonal storage can move stored energy continuously from one season to another. SWITCH[4] concentrates on renewable energy potential in several regions but relies on hourly load estimation for those specific regions which takes tremendous effort to produce and update the hourly load profile as its input. This is because hourly load profiles are available based on utility territories and not on renewable potential regions as defined in SWITCH. NREL's EVI-Pro and RECHARGE analyze the charging behavior based on transportation demand and require integration with another grid model to represent grid interaction[5][6]. This and other similar models that do not optimize all levels of the electric sector simultaneously, cannot make decisions regarding Vehicle to Grid (V2G) and Grid to Vehicle (G2V) timing, or the timing of smart charging (V1G), so the charging can take place in a more favorable and economic way for the electricity sector. Many electricity sector modelers have tried to find a way to analyze detailed design of the electricity grid up to the local substations to be able to evaluate the real cost of upgrading the grid and evaluate the installation of high-power chargers capable of fast charging of medium and heavy-duty BEVs[6]. Because of the complexity at the local level, these studies have not represented the effects of vehicle-grid integration on the entire electricity supply system.

2. Model Development

CALZEEV (California Zero Emission Energy and Vehicle Model) is an energy/economic model built on the MESSAGE (Model for Energy Supply Strategies and their General Environmental Impacts) platform[7][8][9][10]. The model not only incorporates an hourly dispatch model, but also endogenously optimizes long term capacity expansion of technologies. This allows us to look at how hourly load and future electricity demand for charging EVs will affect the operation of the overall energy system. Assuming a growing population of electric vehicles to meet state goals, we developed a range of scenarios for year 2045 for future projections. We estimated state-wide growth of electricity demand for other sectors of the economy, based on CEC projections of electricity demand and peak load. Transportation energy demand was endogenously calculated by the model, based on assumed VMT. Beside the grid impact, GHG mitigation effects by increasing ZEVs penetration and reaching near 100% carbon free grid by year 2050 has been analyzed.

In addition, extensive data on the Reference Energy System of California was gathered and analyzed. Reference Energy System is the energy supply chain defined for our case study in CALZEEV. CALZEEV is a demand driven model that minimizes the total cost of energy supply system in a multi-period capacity expansion planning. In this study, we considered a time frame between 2017 and 2045 where NPV (Net Present Value) of all costs are calculated by the model in 2017 dollars and an interest rate of 4%. 2017 is the base year of our study which means that all existing capacities of the technologies defined in the model (such as power plants, transmission lines, charging stations, etc) are given for year 2017 with their historical information for the year they came into service. Based on their plant life, model makes decision on new investments.

Figure 1 shows the energy supply chain for the California electricity grid and possible hydrogen infrastructure to provide electricity for end-use sectors including transportation sector. In this study, transportation technologies which were considered are BEV and FCEV light duty vehicle and long-haul heavy-duty vehicles. These two vehicle subsectors were chosen, as they are the largest GHG emitters within the transport sector. To develop the model to incorporate other sectors of economy, the steel industry is chosen as an industry sector that can replace hydrogen for natural gas in direct reduction process. Other subsectors, such as residential, commercial and agriculture electricity demand forecast were incorporated as exogenous inputs to the model. Figure 2 shows a more detailed diagram for the hydrogen supply chain and its infrastructure for storage, transmission and distribution of hydrogen to FCV refueling stations.

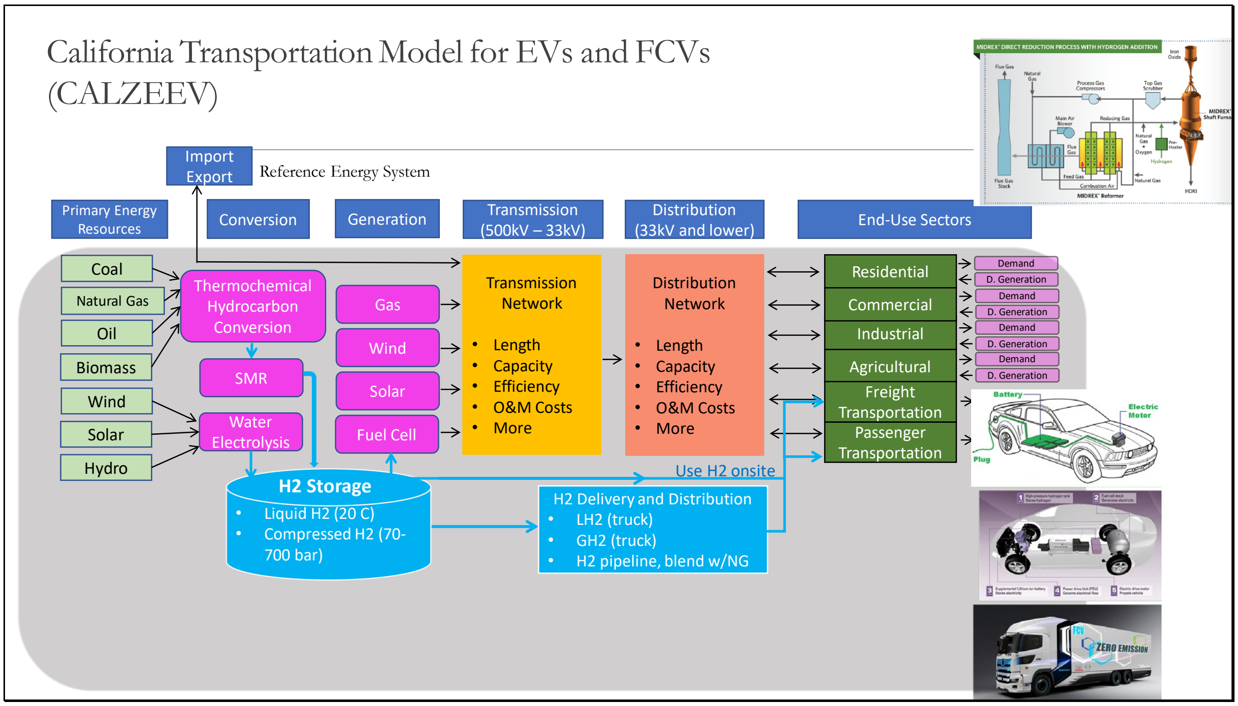

Fig. 1: Energy supply chain for electricity and hydrogen infrastructure in California for California Zero Emission Energy system and Vehicle Model

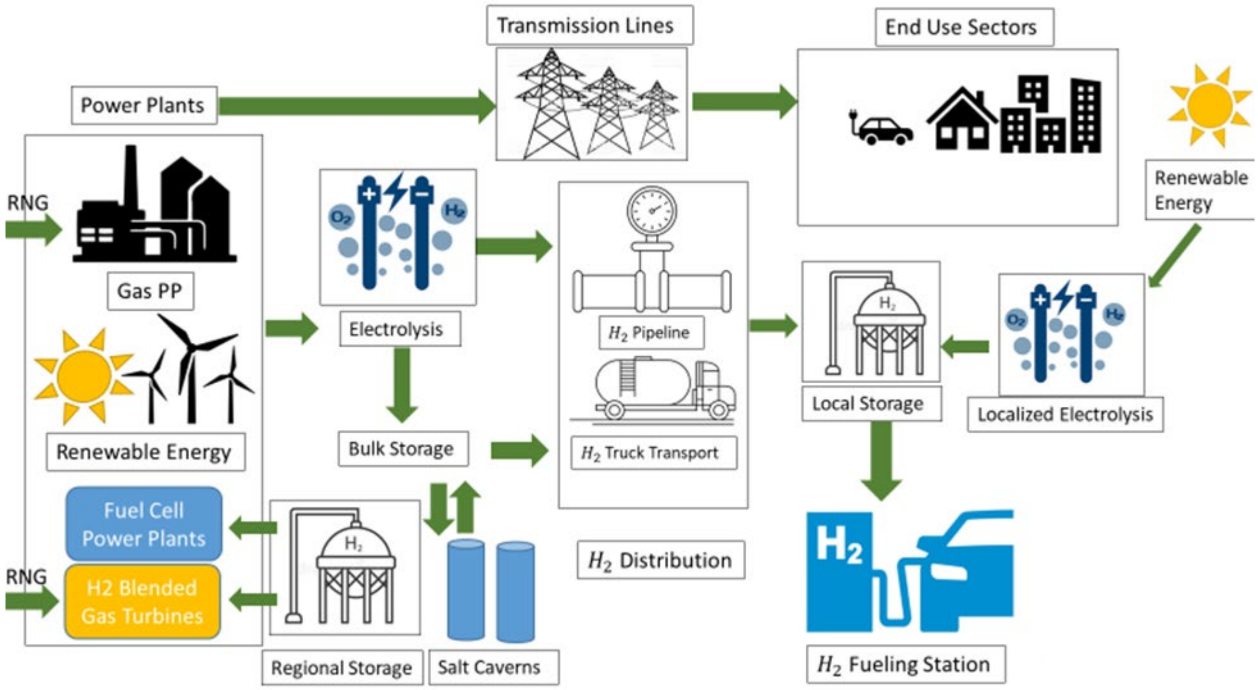

Fig. 2: A more detailed schematic diagram of CALZEEV structure on modeling the hydrogen infrastructure from production, storage, transmission and H2 fuel dispensers. Gas PP means natural gas power plants.

2.1 Hydrogen Supply Chain in CALZEEV

The hydrogen supply chain is incorporated into CALZEEV by defining PEM electrolyzers that can be connected directly to renewable generation sites or feed from the grid. CALZEEV makes the decision on how much capacity of each type of electrolyzer needs to be installed and their optimal hourly operation within each period. Produced hydrogen is then stored in three different storage technologies that are defined in the model as follows:

- Salt Caverns in Utah that are connected to electrolyzers that are being installed in Utah only. The investment cost for salt caverns is assumed to be $20/kg. We have assumed a 100kton capacity constraint for salt caverns that can be built in Utah due to geographical resource limitations.
- NG pipeline infrastructure in California for H2 blending and storage purposes. The cost of extraction of the blended H2 is assumed to be

$0.30/kg[11]. We assumed current NG infrastructure would have a capacity limit equivalent to 30% energy capacity for H2 storage purposes.

- Above the ground built H2 storage tanks with unlimited possibility of building them but a higher cost of $650/kg investment cost.

Hydrogen can be transmitted and distributed to end-use sectors through pipelines assuming a total of 20 miles distance between storage and end-use demand. In this model, hydrogen demand is for transportation fueling stations and the steel industry only.

Hydrogen fuel cell power plants are assumed to use hydrogen from storage tanks and the generated electricity is supplied to the grid.

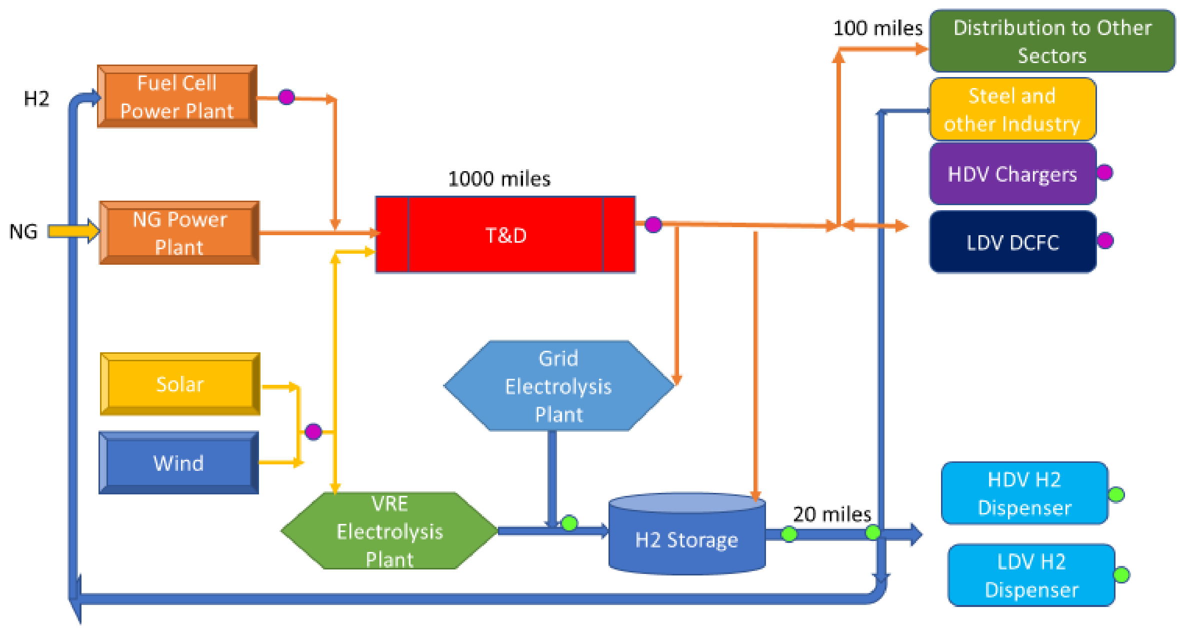

Fig. 3: Schematic diagram of electrolytic hydrogen production options and H2 to power defined into optimization model. Blue lines are H2, orange and yellow are electricity. The electric line from transmission to storage and pipelines shows compressors electricity consumption. (DCFC = DC Fast Charger, HDV = Heavy Duty Vehicle, LDV = Light Duty Vehicle)

Electricity generated either from renewable energy or thermal power plants (natural gas turbines) feed the grid. Electrolysis plants have the option to either get electricity from the grid or directly from renewable energy plants on site. The produced hydrogen, either green (hydrogen from 100% from solar or wind electrolysis) or mixed with grey hydrogen (electrolytic hydrogen produced from grid electricity) enters the hydrogen storage, transmission and distribution systems. Figure 3 shows the schematic diagram of electrolytic hydrogen production options defined in the CALZEEV optimization model.

Although our goal is to study the optimal BEV-FCEV combination for the 2045 California energy system and effects on emission mitigation, in this study, we decided to fix the BEV and FCEV number of vehicles based on Transition model scenarios for year 2045. Also, the steel industry in California was added to industry end-use sectors assuming 100% change from NG to H2 for DRI (Direct Reduced Iron) processes in 2045.

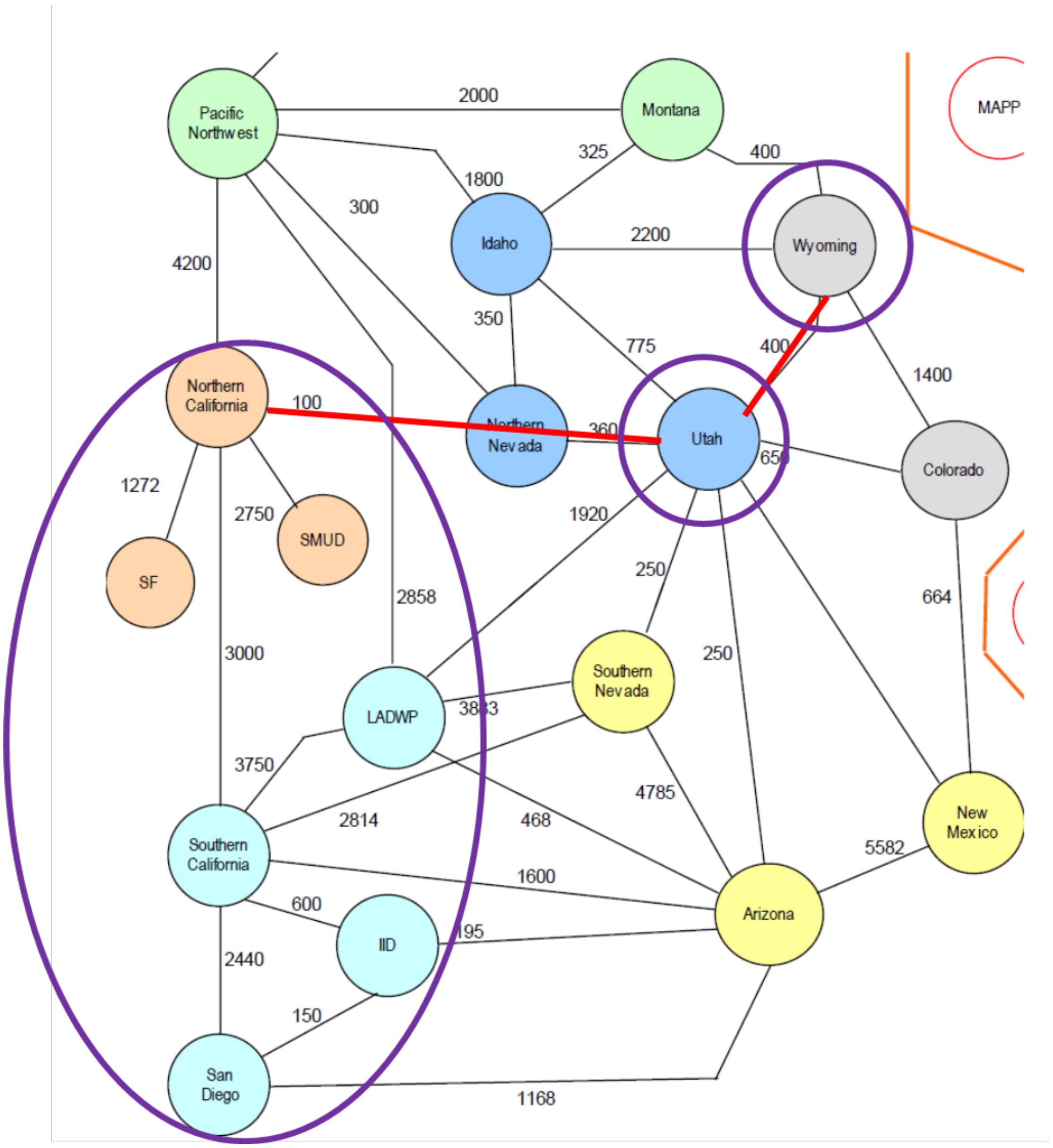

Fig. 4: Western interconnect electricity grid network. Regions in CALZEEV incorporated in this study are represented by purple lines.

3. Scenario Description

3.1 Transportation Technologies

High FCV case scenario from Transition model in year 2045 was used as an input to CALZEEV model. This scenario assumes 119000 BEV long haul trucks in 2045, 100,000 VMT yearly operation for each truck. All other long haul trucks and other HDV/MDV trucks have been considered to be FCEVs and hydrogen demand required to fuel these trucks have been calculated from Transition model. For long haul FCEVs, it is assumed they have 60kg H2 tanks with 11.3 miles/kg H2 fuel efficiency forecasted for 2045. For the BEVs, the battery pack is assumed to have 1000 kWh capacity with a total weight of 13,000lbs.

For LDVs, we assume there will be about 17 million BEVs each with 100kWh battery packs and about 13 million FCEVs each having 5kg H2 tanks. Table 1 shows characteristics of different vehicle types assumed for 2045 transportation demand in CALZEEV.

Transportation Sub-Sector	**LDV**		**HDV (BEV Long haul only)**	**All other HDV/MDVs (including FCV long hauls)**
Vehicle Type	**BEV**	**FCEV**	**BEV**	**FCEV**
Stocks	17.4M	12.7M	118741	846000 (60,000 long hauls)
VMT	208.8B	152.4B	11.8B	12.6B
Energy (TWh)	58.12	93.74	24.99	43.58
Fuel Efficiency	3.57 Mile/kWh	64 Mile/kg	0.47 Mile/kWh	Depending on vehicle type
Battery/tank Capacity	100kWh	5kg H2 Tank	1000 kWh	60 kg H2 tank for long hauls

Table 1: Total energy consumption of each vehicle category based on their VMT and fuel efficiency assumed for 2045. Data were extracted from the Transition Model (an EXCEL spreadsheet scenario model created at UC Davis by Marshall Miller, et at.) and were used as input to CALZEEV model.

Grid interconnection for BEVs depends on daily driving need, battery storage and availability to have grid interaction (V2G and G2V). We assumed that grid interaction will mostly take effect while vehicles are mostly not driving. For this reason, we used an inverse function of hourly VMT as a constraint when BEVs would be available for grid interaction. (BEVs are charging when they are not driving). Figure 5 shows the normalized curves for VMT and charging constraint incorporated in CALZEEV for LDV BEVs.

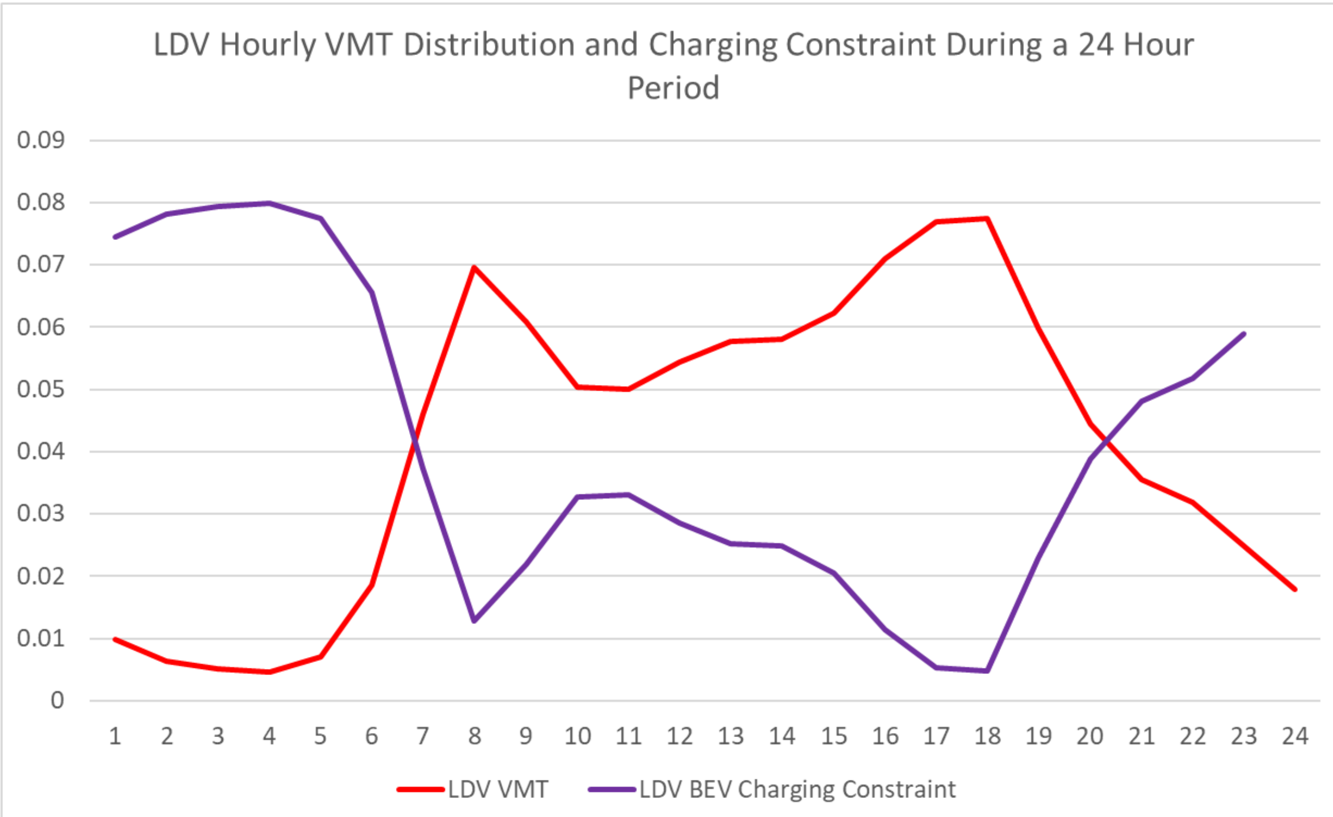

Fig. 5: Normalized hourly VMT distribution for LDV used for driving demand for 2045. Yellow line is the normalized charging constraint for LDV fleet (indicates the probability that BEVs are charging).

3.2 H2 for Steel Industry and other Sectors Electricity Demand

We also have steel industry with H2 demand in 2045, 3 Million ton/yr production capacity in California with Hydrogen consumption of 650Nm3/t DRI (Direct Reduced Iron) (54kgH2/t). Hourly electricity load for all other sectors of economy for base year is from CAISO-OASIS real data. Electricity forecast and peak load forecast were estimated based on CEC electricity forecast reports.

3.3 CALZEEV Inputs and outputs

Inputs and outputs to CALZEEV model are listed as follows:

3.3.1 CALZEEV Inputs

- **Electricity Generator technologies:**
    - Historical capacity for each generator (from eGrid)
    - Installation cost ($/kW) of each electricity generator type
    - Fixed O&M cost ($/kW/yr) for each generator type
    - Variable O&M ($/kWyr) of each generation type
    - Efficiency and plant lifetime for each generator type
    - Fuel cost for each generator ($/MWh)
    - Capacity factor for wind and solar in each region for every hour of the year
    - Hourly load (MWh) for other sectors in each region
- **Transmission lines (higher than 33kV lines)**
    - Historical capacity of existing transmission lines
    - Transmission efficiency (based on length)
    - Transmission installation cost ($/kW-mile) between all pairwise regions
    - Transmission fixed and variable O&M costs ($/kW/yr and $/kWyr) per mile between all pairwise regions
- **Distribution lines (33kV and lower) within each region**
    - Historical capacity of existing distribution lines
    - Distribution efficiency
    - Distribution installation cost ($/kW-mile) within each region
    - Distribution fixed and variable O&M costs ($/kW/yr and $/kWyr) per mile Hydrogen demand (kg) in each region per day
- **Transportation sector (Electric vehicles)**
    - Historical capacity of existing charging stations within each region
    - Installation cost ($/kW) of each type of chargers
    - Fixed O&M cost ($/kW/yr) for each type of charger
    - Variable O&M ($/kWyr) of each type of charger
    - Efficiency and plant lifetime for each type of charger

    - Hourly VMT of different vehicle types in each region
    - Fuel economy, battery capacity and charging constraints of each vehicle type
- **Transportation sector (FCV vehicles)**
    - Hydrogen fuel demand in each region from spatial model (or adding fuel dispensers based on VMT similar to electric vehicle section)
- **Hydrogen Production, storage, transmission infrastructure**
    - Electrolysis plants, H2 storage, H2 transmission and fuel dispensers techno-economic inputs (Capex, Opex, efficiency, lifetime, etc)

3.3.2 CALZEEV Outputs (for each region):

- Capacity expansion for power plants for each period
- Optimal hourly operation of each power plant
- Capacity expansion of transmission and distribution lines in each period
- Optimal hourly transmission of electricity between each region
- Capacity expansion for EV chargers for each period
- Optimal hourly V2G and G2V grid interaction for BEVs
- Hourly BEV battery SOC based on their capacity and limits
- Capacity expansion for electrolyzers, H2 storage, H2 transmission and fuel dispensers
- Optimal hourly H2 production from VRE or the grid, hourly H2 stored (storage level), hourly H2 transmission and distribution to transportation sector and electricity generation
- Optimal capacity factors for electrolyzers, transmission technologies, charging stations, power plants (except renewable generation which is fixed)
- Capable of adding other sectors to the model

Table 2 summarizes some main techno-economic input used for the model.

Main Input Data

Technology	Capital Cost	(Unit)	other	Fixed O&M ($/kW/yr)	Var O&M+Fuel	(Unit)
Electricity Generation						
Solar PV	1130.00	$/kW		14.00	0.00	$/kWyr
Wind	1495.00	$/kW		51.33	0.00	$/kWyr
Gas Power Plants	882.00	$/kW		20.02	4.62	$/MMBTU
H2P	425.00	$/kW		0.00	0.04	$/kWh
H2 Production	**$/kWout**	**$/kWin**				
Electrolysis	625.00	400.00				
H2 Storage						
Salt Caverns	20.00	$/kg				
H2 Tanks	650.00	$/kg				
NG Pipelines blending	0.00	$/kg	Existing Infrastructure		0.30	$/kg
					H2 extraction cost	
Electricity Grid			**miles**			
Elec Distribution	2.80	$/kW-mile	100.00	12.00		
Elec Transmission	3.84	$/kW-mile	1000.00	11.00		
BEV Charging Stations						
DCFC	1050.00	$/kW				
H2 Fuel Stations						
LDV Fuel Stations	2637.34	$/(kg/day)				
HDV Fuel Stations	2637.34	$/(kg/day)				
H2 Transmission and Compression			**miles**		Elec price for compression	
H2 Distribution	2612.71	$/(ton/day)mile	10.00	3% Electricity input	0.04	$/kWh
H2 Transmission	2612.71	$/(ton/day)mile	10.00	for compression of H2	0.04	$/kWh

Table2: Main techno-economic data for different technologies in CALZEEV model. H2P represents hydrogen fuel cell power plants.

3.4 Renewable Energy Generation

Solar and wind are subject to a fixed pattern that is based on availability and capacity factors in five different regions of California. These patterns are based on historical wind and solar data and are exogenously input to CALZEEV. However, to enable the model to endogenously build the required capacity for wind and solar, two model runs were performed, one with incorporating only higher constraints on the hourly renewable energy availability to endogenously find the optimal capacity installments of renewables and the second run with a fixed pattern to simulate the intermittent behavior of renewables as they are in the real world. When performing sensitivity analysis such as a solar heavy or wind heavy case, model runs were based on fixed capacity.

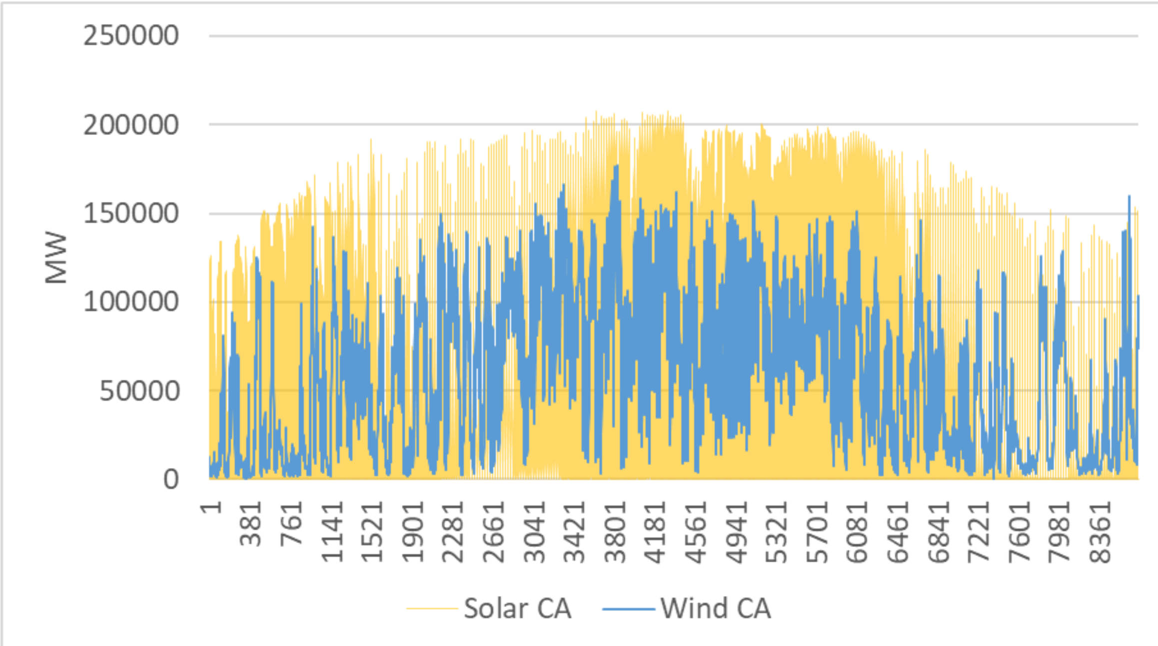

Fig. 6: Hourly fixed wind and solar for year 2045. The pattern originated from CAISO-OASIS historical data and generation required for 2045 is simulated with an assumption of equal wind-solar yearly energy production.

Figure 6 shows a simulation of a 50/50 fixed generation for wind and solar assuming a fixed capacity for each. This figure’s pattern is based on a solar and wind energy pattern that was generated in 2017. As can be seen from the figure, both wind and solar generation show an excess renewable energy availability during summer. There are some out-of-state regions such as Wyoming where there is high potential of wind energy with good capacity factors and a yearly pattern that is complementary to renewable energy pattern in California. Figure 7 shows a sample wind pattern from one of the simulated wind farms in Wyoming. As it can be seen, there is more wind available in winter than in summer.

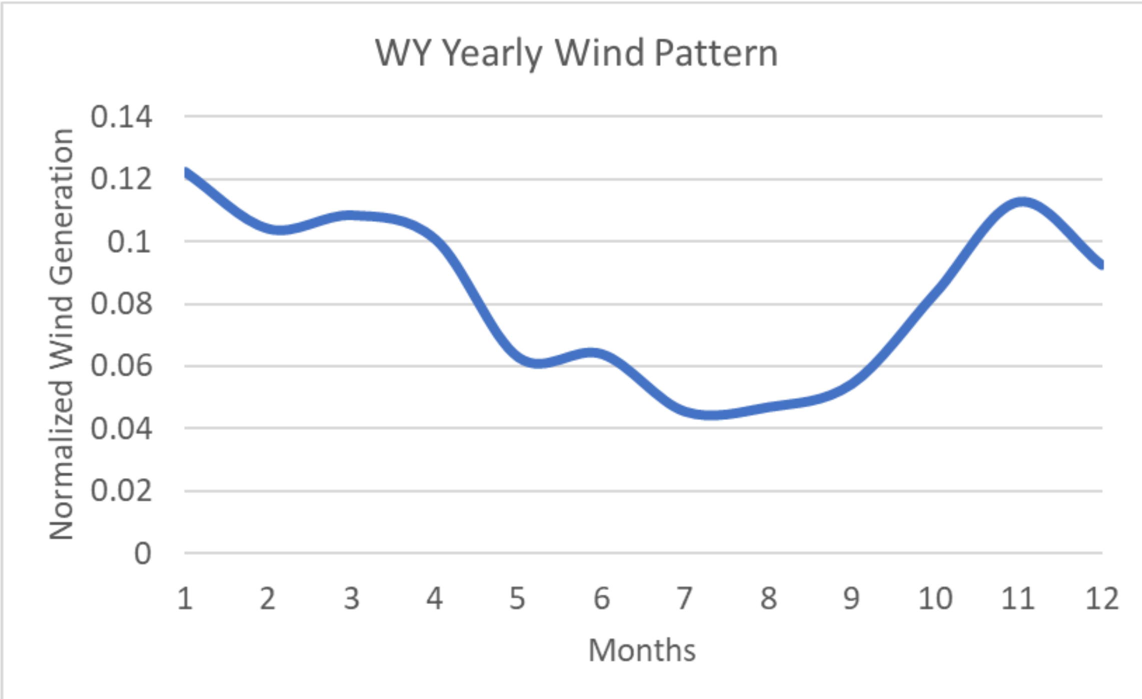

Fig. 7: Normalized Wyoming wind pattern based on CPUC wind simulation studies[12]. This pattern is used to simulate yearly wind energy production equivalent to wind or solar generated in California. Based on transmission costs, CALZEEV optimizes the required transmission capacity expansion and electricity import/export to/from California.

4. Technoeconomic Optimization Results

Optimal results are extracted from CALZEEV which include hourly optimal operation of technologies and optimal capacity expansion for PEM electrolyzers, H2P fuel cell power plants, solar and wind power plants, transmission lines, EV chargers, storage facilities, etc.

4.1 Optimal Electricity Supply Chain

The optimal generation mix for a 100% renewable grid is shown in figure 8. H2P is the electricity produced by fuel cell power plants inside California. Electricity produced from fuel cell power plants in Utah together with out-of-state wind produced in Wyoming are considered as imports to California in 2045.

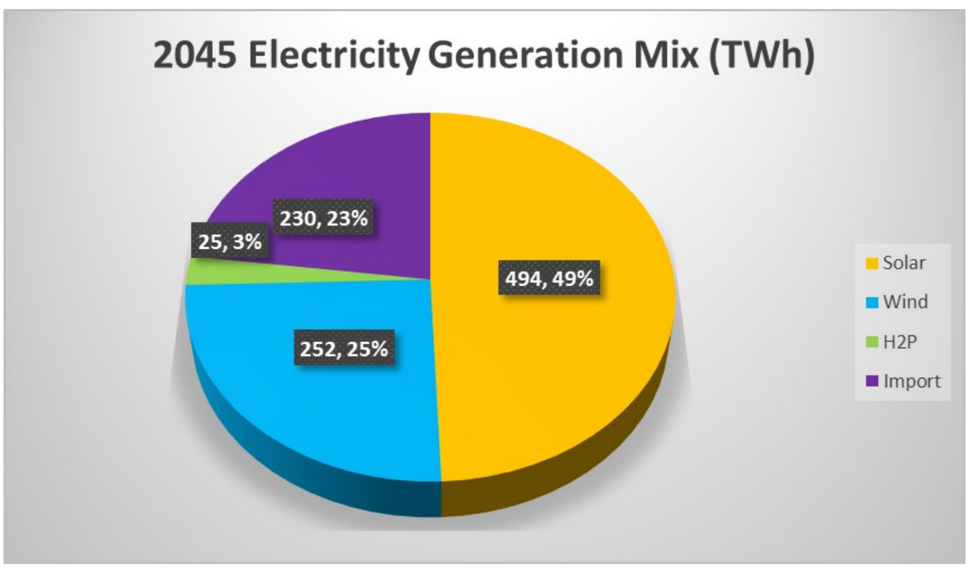

Fig. 8: Optimal generation mix for in-state and out-of-state renewable resources. H2P is the electricity produced by fuel cell power plants inside California. Electricity produced from fuel cell power plants in Utah together with out-of-state wind produced in Wyoming are considered as imports to California in 2045.

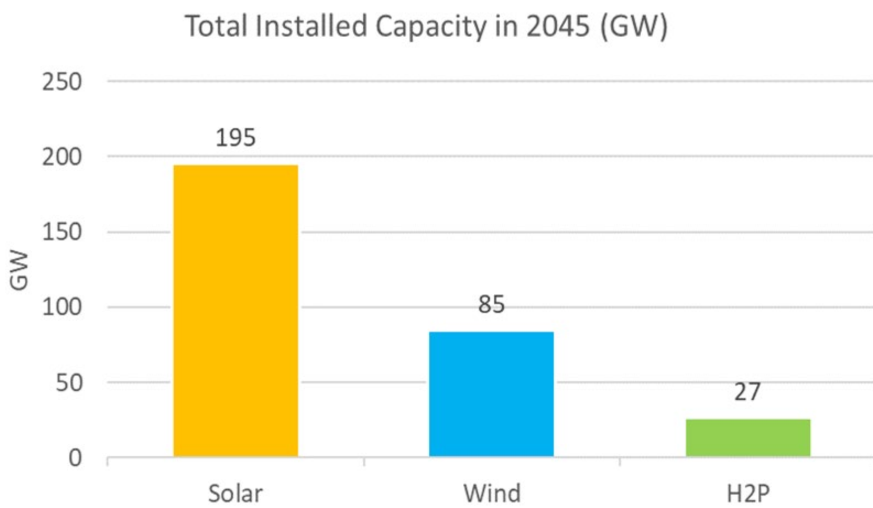

Fig. 9: Optimal capacity expansion of wind, solar and fuel cell power plants (H2P) in California only. Optimal decision is made based on investment costs for upgrading transmission lines and optimal storage needed to be installed for H2 seasonal storage in western states under study.

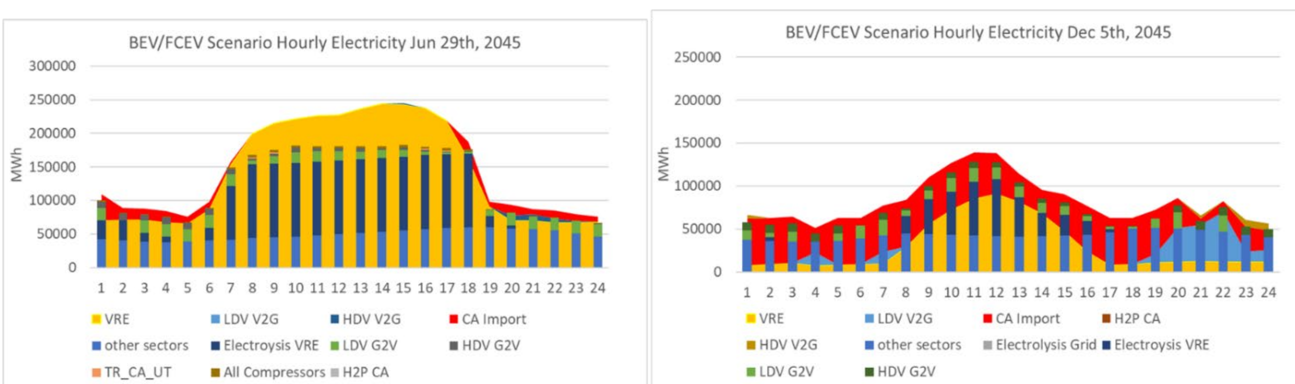

Fig. 10: Optimal hourly operation of supply and demand of electricity is shown for two different days in a year. Left figure is a typical summer day and the right figure shows it for a winter day. Load is shown as stack bars and generation is shown as stacked areas (V2G is considered a generation).

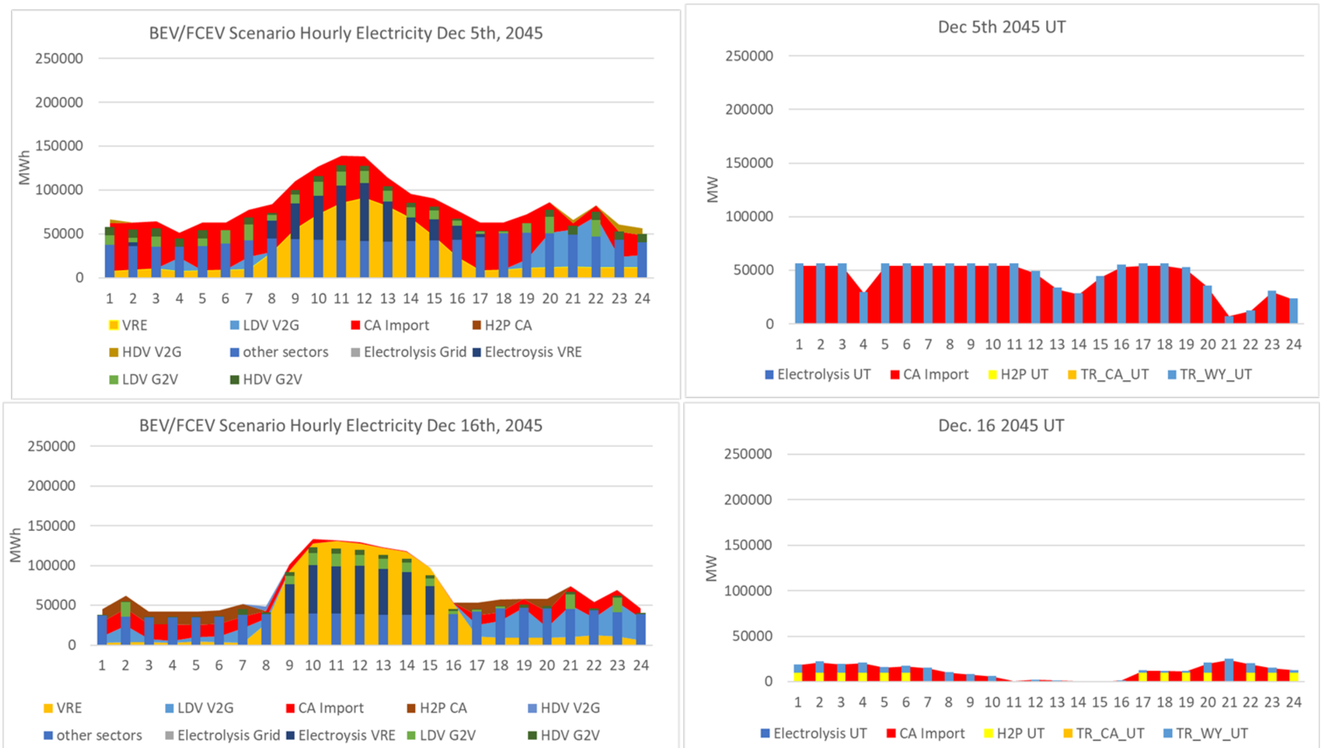

Fig. 11: Left figures represent two typical winter days. Red area reflects import electricity to California. Right figures show how the California imported electricity (the red area in the adjacent left figure) is generated. and transmitted from wind in Wyoming or H2P in Utah, generating electricity from H2 in salt caverns when there is not much wind generation coming from Wyoming.

4.2 Optimal Hydrogen Seasonal Storage Installations to Achieve 100% Renewable Grid in California

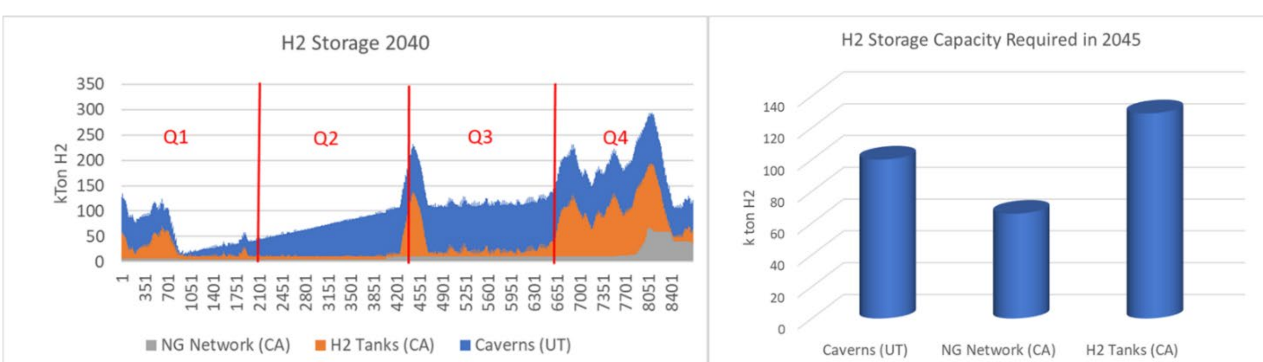

Fig. 12: Optimal hourly storage level for three storage technologies incorporated into CALZEEV. NG pipeline network and H2 tanks are storage technologies in California and salt caverns are storage technologies in Utah.

The left figure shows the optimal hourly storage level for hydrogen in three different storage technologies. H2 Caverns are salt caverns being utilized in Utah, NG pipelines represent H2 blending in California NG pipeline infrastructure being extracted at a later time, and H2 tanks are newly built hydrogen storage tanks in California. Right figure shows total installed storage capacity built for 2045 100% renewable grid hourly and seasonal purposes.

4.3 Optimal Hydrogen Infrastructure and Hourly Operation

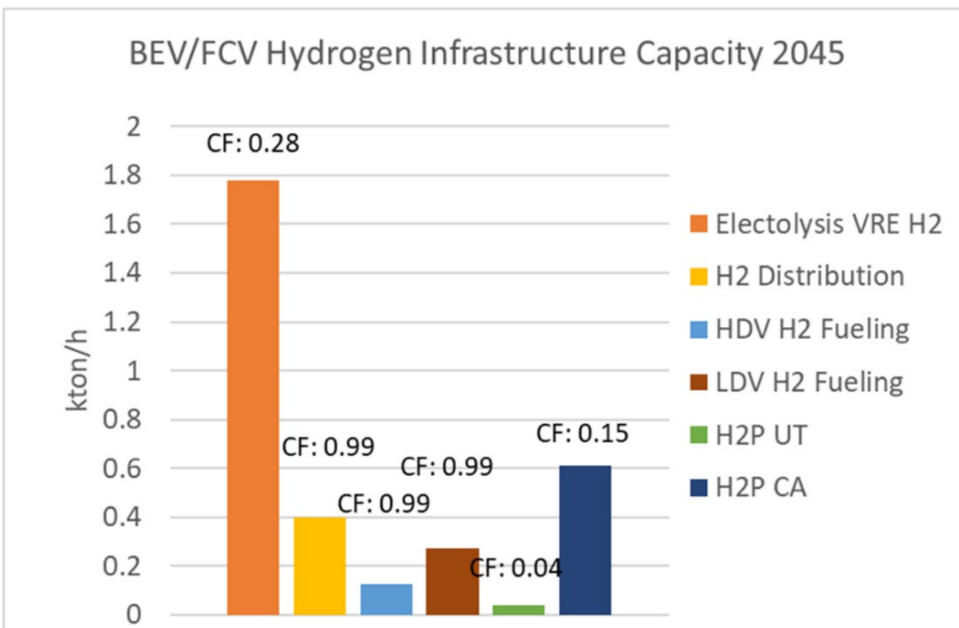

Fig. 13: Optimal H2 infrastructure technologies installed endogenously by CALZEEV for 2045. CF represents capacity factors of each technology endogenously determined by the model based on their optimal hourly operation through the year.

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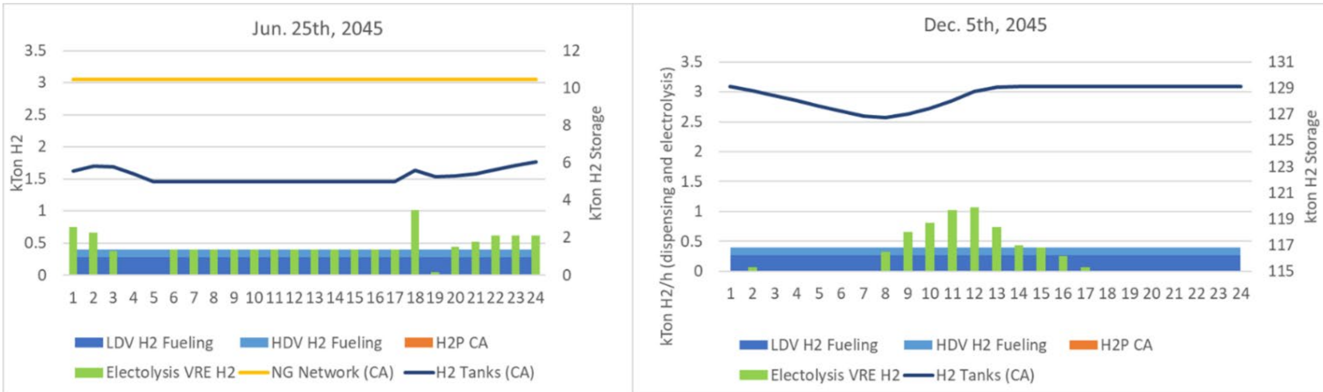

Fig. 14: Hourly H2 production by PEM electrolyzers in California for typical summer and winter days. H2 produced is transported to H2 fuel stations for LDV and HDV fuel demand. Some H2 goes into storage tanks for later consumption by fuel cell power plants.

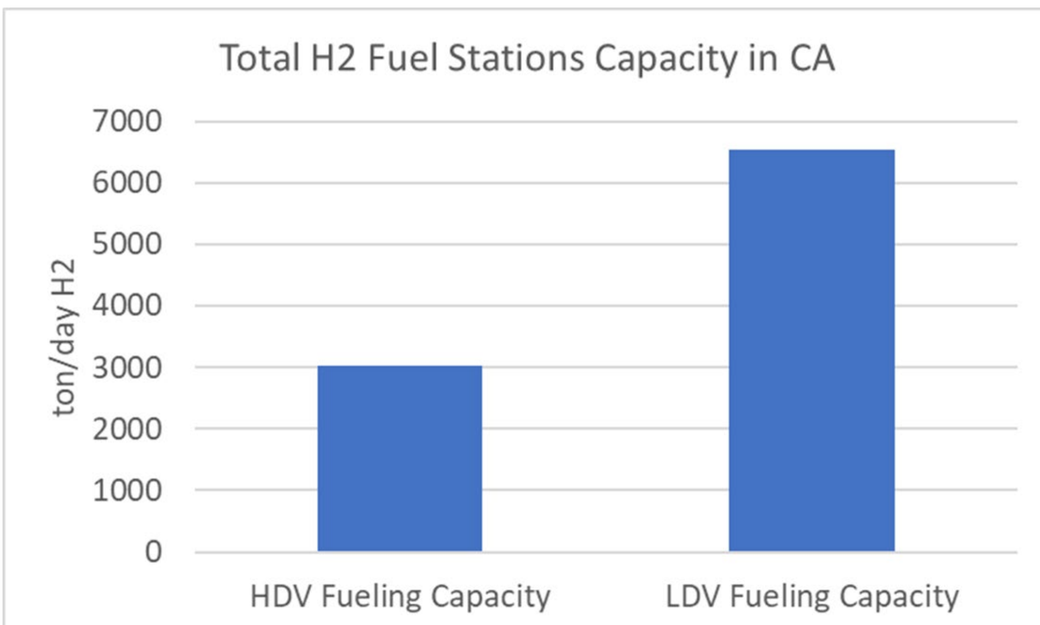

Fig. 15: Total capacity required for LDV and HDV fuel stations to feed the FCEVs transportation demand in California.

5. What does a Solar Heavy, Independent California Mean in 2045?

We ran a scenario with an assumption that California should become an independent state regarding electricity import and having a solar heavy generation same as today. We want to see how much the necessity of seasonal storage would increase by not having out-of-state wind available for California.

The goal of these simulations is to reach a 100% share of renewables in the grid. However, here we included an option for a small fraction of NG power plants (6%) to assure grid stability and to lower storage requirements. Figure 16 shows the share of electricity generation by assuming a fixed solar and wind fraction of about 80%. H2P is Hydrogen to Power producing electricity from stored hydrogen that was produced during excess renewable energy during summer and is endogenously installed based on demand requirements. In this scenario, it is assumed California will be independent and all storage can take place inside the State.

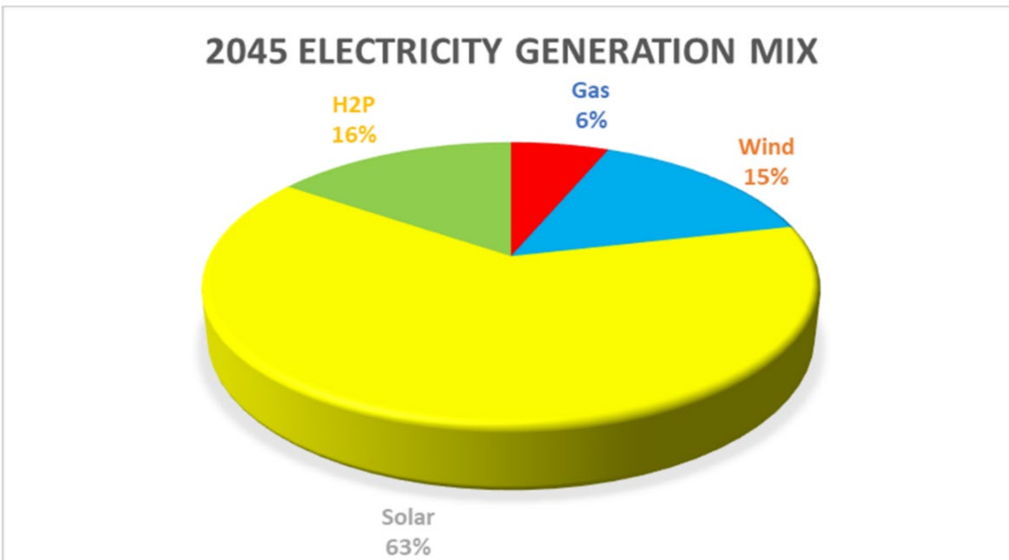

Fig. 16: Share of electricity generation in 2045. H2P is hydrogen to power representing fuel cell power plants. Only 6% of electricity generated is from natural gas power plants and the rest are completely emission free.

We ran some sensitivity analysis to find the trade-off between adding more hydrogen storage to capture more curtailed renewable energy for later use, versus adding more renewable capacity. We noticed that increasing hydrogen storage and transmission cost encouraged building more renewable energy capacity due to its lower cost relative to hydrogen infrastructure cost. In future work we plan to use other options such as carbon capture.

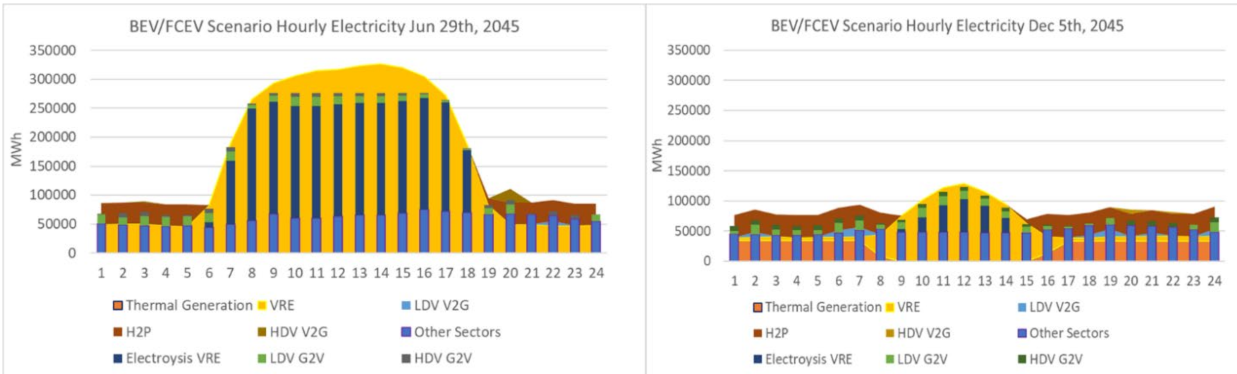

Fig. 17: Hourly electricity generation and load for typical summer and winter days in 2045. Stacked bars show all hourly Loads such as electrolysis, BEV managed charging, load for other sectors. Stacked areas show hourly generation of VRE, G2P, V2G and thermal power plants. “Other Sectors” represents load for all other sectors (Residential, Commercial, Industry) VRE: Variable Renewable Energy (Solar and Wind)

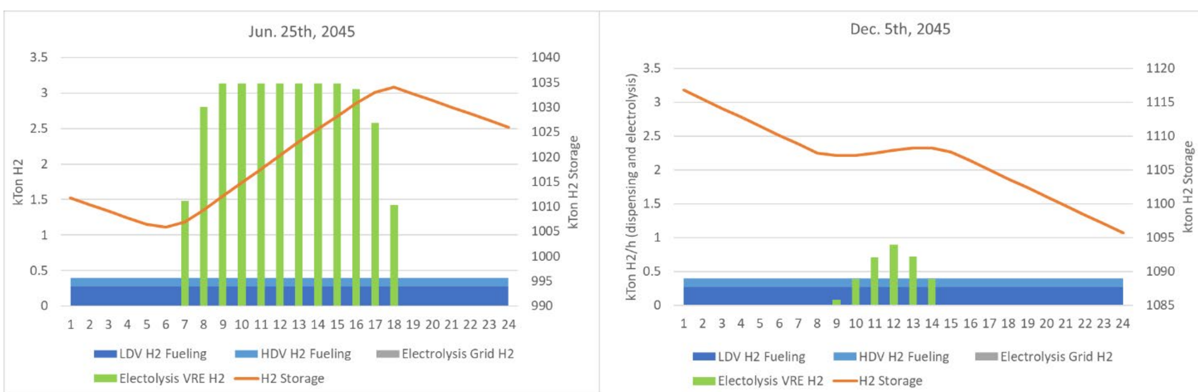

Fig. 18: Hourly hydrogen production, storage and consumption for typical days during summer and winter. Orange Line shows H2 storage level at each hour of the day in ktons represented by secondary vertical axis. Stacked bars show all hourly Production of H2, or H2 used for H2P. Stacked areas show hourly H2 delivered to fuel stations, stored in their tanks for daily operation.

In our system we modeled large scale bulk storage for hydrogen. Figure 18 shows hourly hydrogen production, stored and consumption. Orange Line shows H2 storage level at each hour of the day During summer, most electrolysis is using VRE to produce enough H2 for LDV and HDV fuel stations, industry and some extra production for seasonal storage purposes. During winter, H2 from bulk storage is utilized towards LDV and HDV fuel stations, industry. Small amount is produced by VRE during mid-day

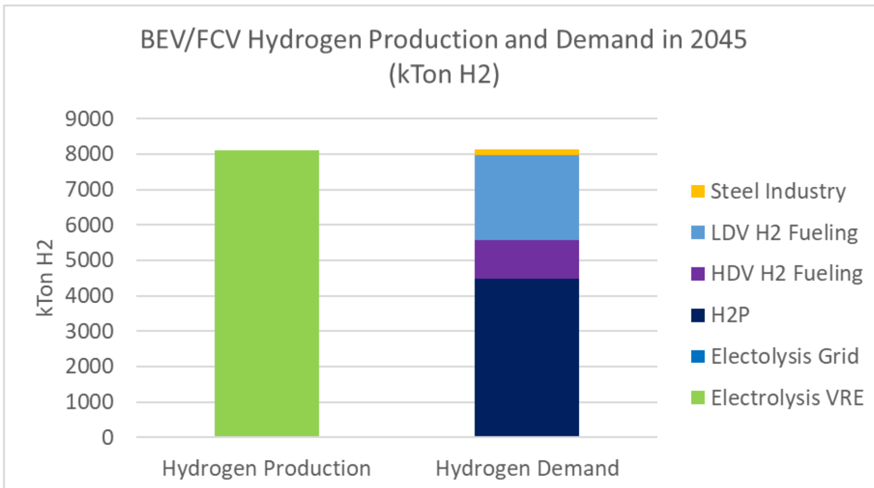

Fig. 19: Yearly hydrogen supply and demand for 2045. The left stacked column shows the optimal electrolytic hydrogen production (from the grid or direct VRE) and the right stacked column shows yearly hydrogen demand for transportation, industry and electricity generation sectors.

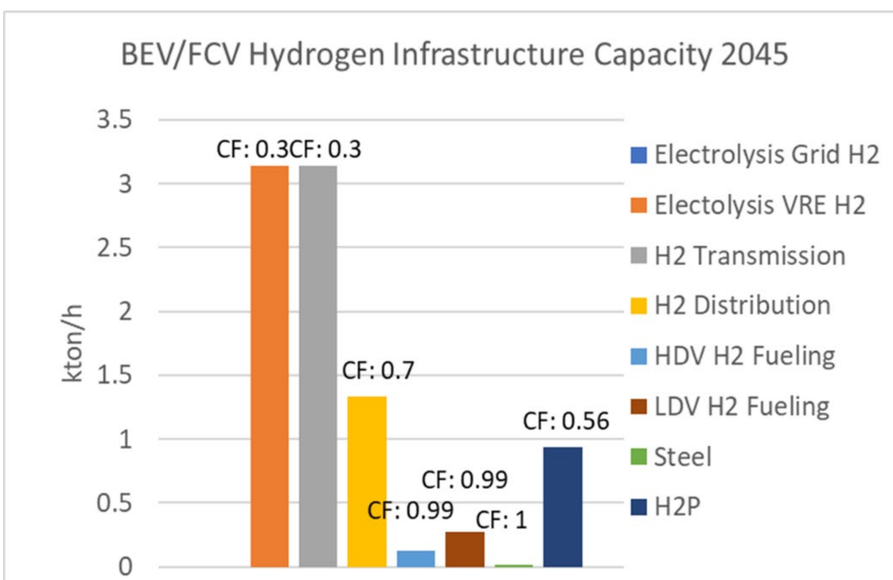

Fig. 20: Hydrogen supply chain infrastructure capacity expansion for year 2045 in kton/h.

Bars represent H2 infrastructure or total installed capacity for each technology in 2045. Capacity factors for each technology is shown on top of each bar.

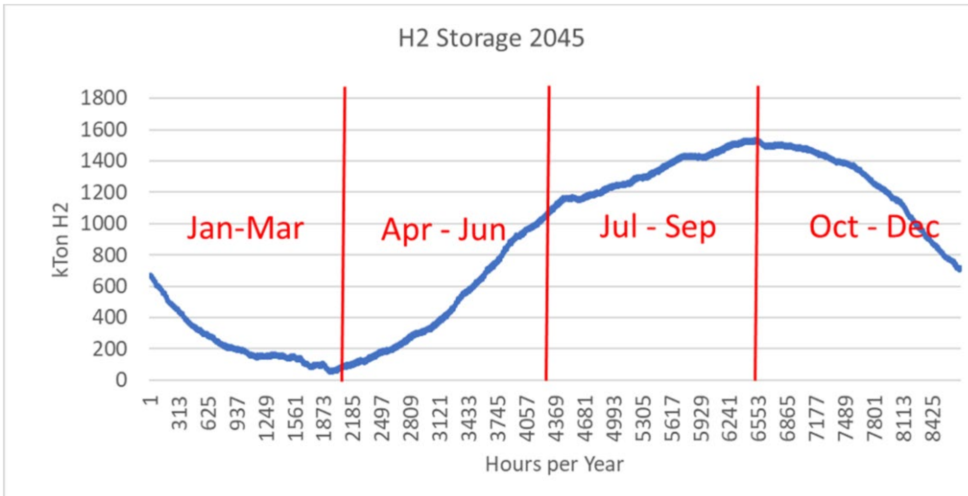

Fig. 21: Hourly optimal Storage of Hydrogen During 2045. About 1550 kTon of H2 Storage Capacity would be required in 2045 to provide seasonal H2 needs for transportation, the Steel industry and the electricity Grid. H2 seasonal storage takes place starting mid spring as VRE potential increases. During winter, stored H2 is utilized for LDV and HDV fuel stations, H2P and the steel industry.

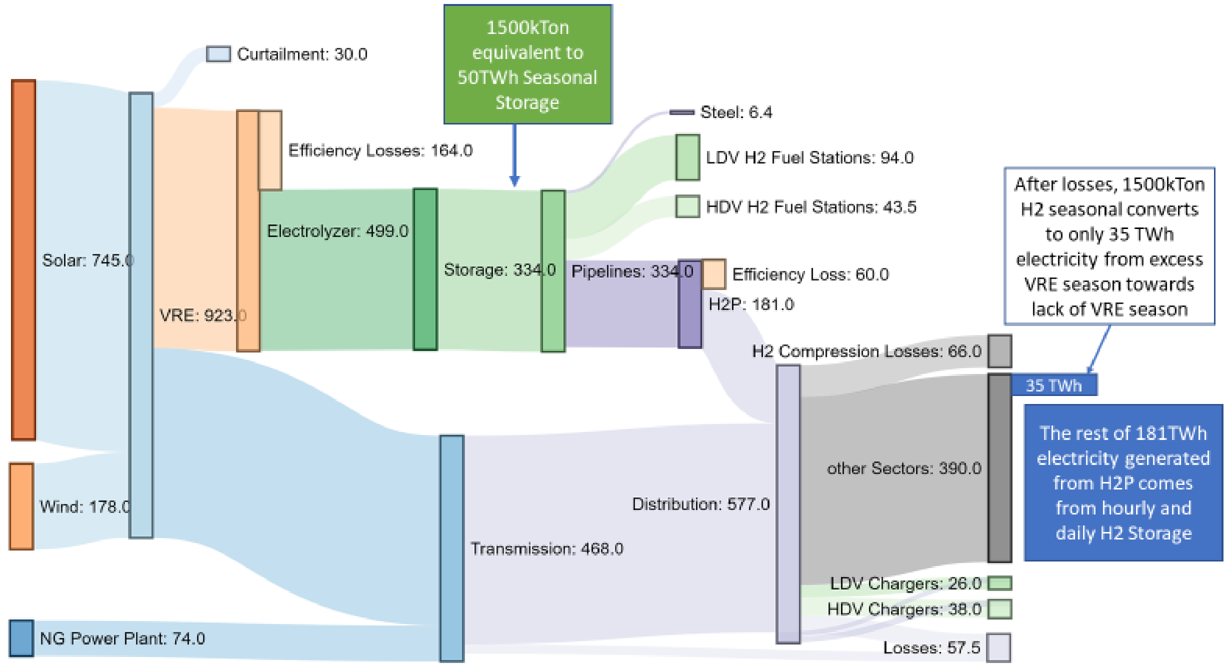

Fig. 22: A Sankey chart showing the energy supply chain. It can be seen that 15,000 kton of H2 storage, after converting to electricity in only a fraction of electricity required at end-use sectors in 2045 and is mostly used to compensate lack of renewable energy hours during winter time. The electricity demand in this chart is comparable to Southern California Edison study for 2045 clean power electrification pathway[13].

6. Sensitivity Analysis: Out-of-State wind heavy scenario for 2045

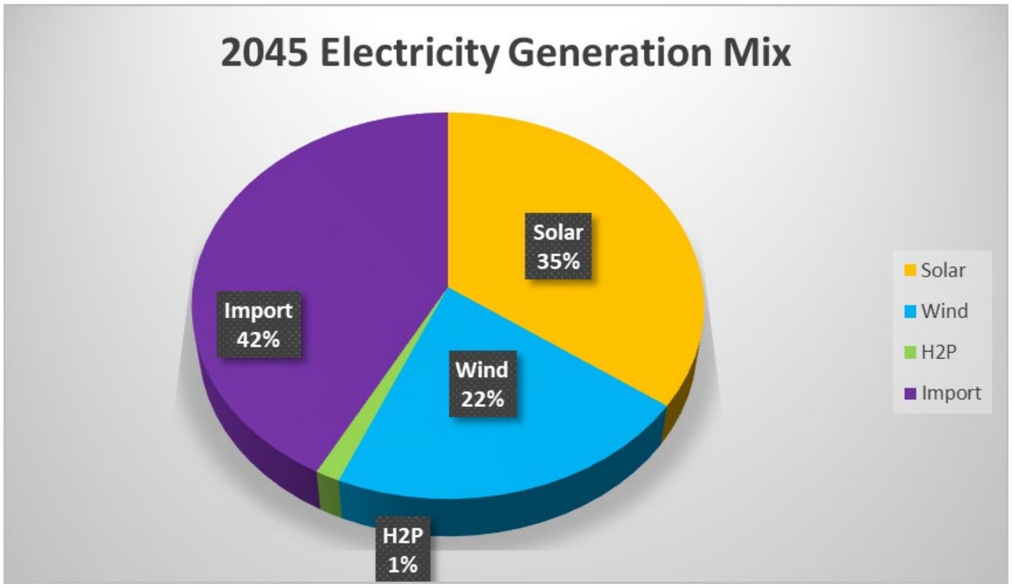

Fig. 23: A out-of-state wind heavy scenario is shown for sensitivity analysis purposes. In this scenario, we assumed only 35% of electricity is generated by in-state solar and 22% by instate wind. 42% of electricity is imported to California mainly from Wyoming.

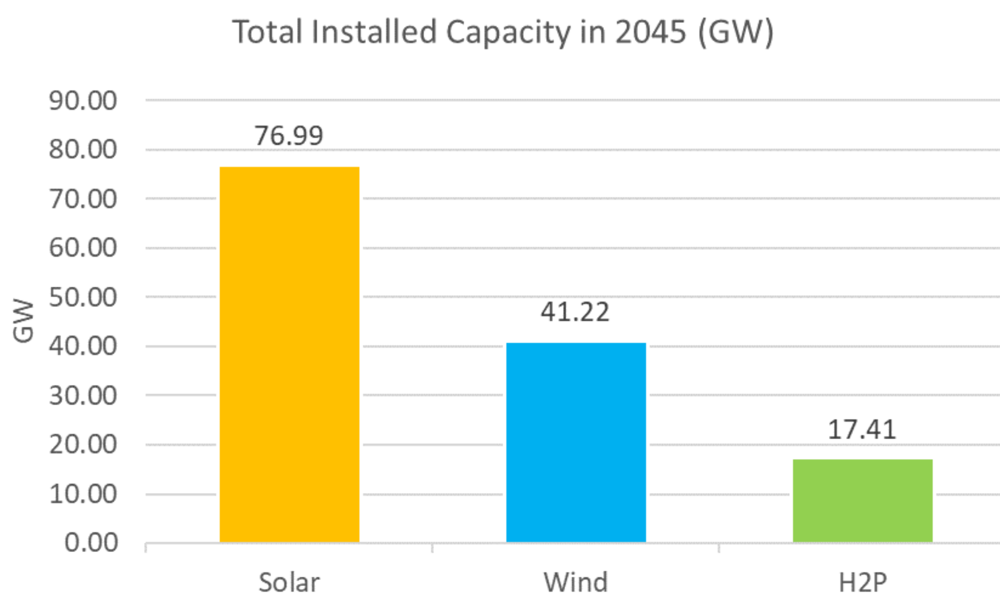

Fig. 24: Total installed capacity required to be installed in California would be much less and more H2P will be required in California relative to the main scenario, but more win farms are installed in WY instead.

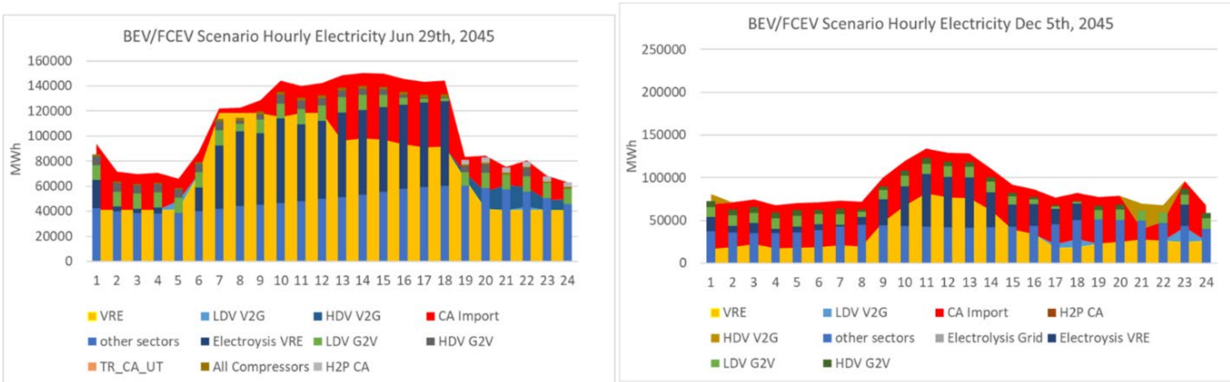

Fig. 25: As the wind dominants here, even in summer we have much more import of electricity into California.

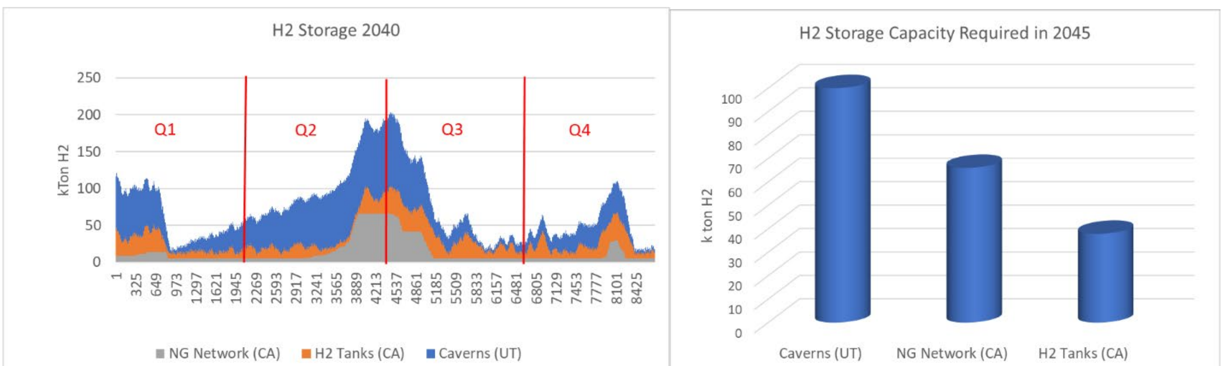

Fig. 26: The total seasonal storage required is much less in wind-heavy case, specially with the wind pattern in WY. The total storage capacity required in this case is only 200kton relative to the optimal case that required 300 kton H2 storage.

Future Study

Future study would be improving the LDV and HDV transportation sector characterization (total costs and charging behavior), adding CCS to the gas power plants towards emission free grid. Complete run to include all 5 major regions in California. Adding time periods 2030, 2035, 2040 for better understanding interim policies. Add hydrogen LCFS credit and possible policy for a cost minimum policy towards an optimum carbon free 2045 economy. Adding other industrial sectors, residential sector and commercial sector to H2 end-use consumers.

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