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Evaluating co-benefits of battery and fuel cell vehicles in a community in California

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ABSTRACT

Battery vehicles and fuel cell vehicles can facilitate the use of low-carbon energy sources in stationary applications, as well as for transportation. For instance, battery vehicles might enable peak load shifting and short-term electricity storage when connected to the electric grid. Hydrogen infrastructure that provides refueling of fuel cell vehicles might also absorb peak solar generation, and provide hydrogen to the natural gas network. Here, the cost and emissions impacts of these system-level effects are integrated into an overall cost-benefit analysis of battery vehicles and fuel cell vehicles.

An integrated analysis of a community energy system under various electric vehicle penetration scenarios is conducted, using a linear cost optimization model. The model determines the cost-optimal energy infrastructure mix in different penetration rate scenarios, using hourly time series data for the community's power generation and energy demand. The optimization considers a wide variety of technical and economic parameters, and determines results for 2025 and 2035.

The findings show, that while both battery vehicles and fuel cell vehicles can modestly reduce the community's overall carbon dioxide emissions, the latter carry higher overall costs, primarily due to the hydrogen generation infrastructure. Battery vehicles are therefore a more cost-efficient choice for reducing CO_2 emissions.

1. Introduction

Battery electric vehicles (BEVs) and fuel cell vehicles (FCVs) have attracted attention as environmentally friendly transportation alternatives to internal combustion engine vehicles (ICVs), because they produce no carbon dioxide emissions during operation. Both BEVs and FCVs require substantial investments in a public charging or hydrogen refueling infrastructure. While the introduction of BEVs is facilitated by the availability of electricity in most places, the widespread deployment of FCVs requires construction of a new (renewable) hydrogen generation and distribution infrastructure, with significant capital costs and administrative challenges. So far, more than 92 million USD have been awarded by the Californian Energy Commission to build or upgrade 50 hydrogen refueling stations [1]. In Germany (which is slightly smaller than California), the cost for an initial hydrogen refueling network with 400 stations is estimated to 400 million EUR (≈ 450 Mio. USD) [2]. Policymakers considering such an investment in hydrogen infrastructure to support FCV deployment will therefore benefit from a comprehensive evaluation of its potential benefits. FCVs currently have two distinct advantages for the driver: longer range and faster refueling. Comparing the technical characteristics of the vehicles themselves, however, may provide an incomplete assessment of their relative benefits, because the emissions impacts of BEVs and FCVs may extend beyond the transportation sector. In particular, the hydrogen infrastructure that would accompany a FCV fleet may enable an overall larger share of intermittent renewable energy sources (RES) in the energy system than would otherwise be the case, as a result of two potential co-benefits: (1) grid storage and (2)

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providing hydrogen to the natural gas supply (Power2Gas, P2G).

Likewise, BEVs that are connected to the grid can be both a storage and a flexible load resource. Under a suitable "smart charging" regime, these vehicles could be utilized by a grid operator as a demand response mechanism. They might also be called on to dispatch power back to the grid during high demand (Vehicle-to-Grid, V2G). As early as 2004, Kempton and Tomić argued, that V2G "should be tapped" to complement the electricity sector [3]. In 2012, Kuhn et al. found that "smart charging" has the potential to significantly reduce the necessary storage capacity in Germany in 2050 when 80% of the electricity demand are met by RES [4]. In the same study, V2G was found to be of little additional value. The latter result is supported by a literature review conducted by Richardson in the same year, which concludes that "V2G plays a limited role in improving the penetration of renewables in the literature, most likely due to excessive battery degradation which results in a relatively high cost of providing V2G power". [5].

To provide low-carbon hydrogen fuel for an FCV fleet, electric power from renewable sources would be directed to a water electrolyzer. This system could provide a strategy for managing the intermittent power output from these power sources, since hydrogen could be generated when power is plentiful and then stored for later use in FCV refueling. This system could also act as an electricity storage device when equipped with a stationary fuel cell to convert hydrogen back into electricity. In a recent study (2015) by Ayodele and Ogunjuyigbe on mitigation of wind power intermittency, the authors found, that the "use of hydrogen for electricity generation is presently not attractive [...] because of its high capital cost and low storage conversion efficiency" [6]. In the same year, the round-trip efficiency of an experimental solar hydrogen electricity storage system could be determined to 32% by González et al. [7].

Finally, the hydrogen could also be blended into the natural gas supply, thereby providing a renewably-sourced combustion fuel to the building sector or using the natural gas grid as a storage system which generates electricity in a gas turbine or fuel cell at a later point in time. Around the globe, more than 40 pilot projects have been realized to evaluate the potential of this technology [8]. The approach has also received attention in the U.S., where Melaina et al. found that P2G "has the potential to increase output from renewable energy production facilities in the near term." [9]. Similarly, Winkler-Goldstein and Rastetter state that P2G "is becoming more popular in Germany and also other European regions", albeit promising business models are difficult to find as improvements "on electrolysis, methanation process, as well as up scaling" are needed [10]. These opinions are further supported by two different studies performed by Regett et al. for Germany [11] and de Joode et al. for the Netherlands [12] which independently came to the conclusion that a positive business case for P2G is unlikely at least until 2030. Another point of view was expressed by Sterner et al., in 2015, who argue that storage systems – among which P2G is claimed to be of particular importance – will be "structurally indispensable" to cope with the increasing share of intermittent RES generation as a result of the German energy transition [13]. According to the authors, societal benefit could be as high as 1.4 billion EUR (1.6 billion USD) in 2035 and is set to gradually increase to 12–18 billion EUR (13–20 billion USD) by 2050. In contrast, Heilek argues, that the integration of intermittent RES could turn out to be a smaller challenge than expected as surplus electricity in the power sector can be easily integrated into the heat sector. He concludes that "the tighter coupling of the power sector and the heat sector offers a significant cost reduction potential for the power supply and reduces the future need for electrical storage systems" [14].

Evaluating the total emissions impact of BEVs and FCVs and their related infrastructure requires an integrated assessment that models all energy infrastructure components, including both the transportation and non-transportation sectors. Previous studies have compared the emissions and energy impacts of BEVs and FCVs: Campanari et al. [15] provide a comparison of well-to-wheel (WTW) CO_2 emissions of battery and fuel cell vehicles (hydrogen from natural gas) which sees either vehicle in favor depending on the grid emissions CO_2 intensity. Another literature review [16] shows that BEVs currently have a slight WTW emissions advantage compared to FCVs but expects that this will change in favor of FCVs in the future. A comprehensive analysis [17] of the WTW emissions for ICVs, BEVs and FCVs showed that depending on the energy pathways, either vehicle could be favorable. None of these studies consider the potential co-benefits of using BEVs or FCVs for the energy system.

Caumon et al. [18] have investigated flexible hydrogen generation to prevent RES curtailment in Europe and came to the conclusion that operation could become profitable after 2030. Juul [19] showed that the integrated analysis of power and road transport system leads to overall lower cost due to smart charging and V2G but did not include hydrogen vehicles for comparison. Komiyama et al. found in 2015, that hydrogen storage is cost-competitive to rechargeable batteries and be furthermore used as mid-to long-term grid storage of wind surplus energy in Japan [20]. However, a recent analysis (2016) of hydrogen systems in California by Eichman et al. found that "producing and selling hydrogen was found to be much more valuable than producing and storing hydrogen to later produce electricity" due to the hydrogen systems' low round-trip efficiency compared to alternative technologies like batteries [21].

To date, however, no study analyzes how addition of BEV and FCV will change energy demand and the individual co-benefits regarding the integration of distributed RES. This study fills that gap by evaluating this topic using an established approach for an integrated analysis of electricity, heat and transportation sector based on the simulation model VICUS/URBS. The model is applied to evaluate whether the two benefits (grid storage and Power2Gas) are likely to be realized if FCVs and the accompanying hydrogen infrastructure are deployed in a small California community. The simulation model uses linear optimization to determine the cost-optimal mix of different technology options to meet the community's energy demands. The simulation incorporates consensus values for electric vehicle (EV) penetration rates (13% EVs in 2025 and 38% in 2035) and technology learning rates to project systemwide impacts of BEV/FCV deployment in the years 2025 and 2035. This integrated assessment incorporates the potential co-benefits of BEV/FCV infrastructure into a quantitative cost-benefit comparison of these two clean transportation technologies.

2. Methods

The VICUS simulation model was used to determine the cost-optimal mix of different technology options to meet the energy demands in the community of Los Altos Hills, California using linear optimization. A scenario was developed to account for future electric vehicle penetration rates as well as technical and economical learning curves of the energy conversion and storage technologies (compare supplementary information). To provide a comparison of battery and fuel cell vehicles, the model determined results for three electric vehicle cases (BEV, MIX, FCV) and an all-ICV reference case for 2025 and 2035. The rationale for this time frame is twofold: First, to allow a deeper EV penetration which in turn increases the absolute difference between the BEV and FCEV cases. Second, to provide a realistic time frame for further technology developments (cost/efficiency) which could lead to different results compared to today given that a lot of the technologies are currently used on a comparably small scale and therefore expensive and/or not highly efficient.

2.1. VICUS

VICUS is a 1-node version of the Urban Research Toolbox: Energy Systems (URBS) [22] which was first developed by T. Hamacher and S. Richter [23]. The simulation model (compare Fig. 1) relies on the linear CPLEX solver provided by the Generic Algebraic Modeling System (GAMS) to determine the cost-optimal way to meet the community's energy demands. URBS/VICUS provide a proven toolset which has been previously applied in various other studies such as the “Integration of Variable Renewable Energies in the European power system” [24] or the “Electricity system optimization in the EUMENA [Europe, the Middle East and North Africa] region” [25].

The input parameters consist of two parts: time series - to account for the dynamics of power generation and demands - in an hourly resolution for both the energy demands (Building electricity and heating, BEV charging and FCV fueling profiles) as well as the availability of renewable energy sources (e.g. solar irradiance, wind speed). Process and storage datasets - to provide the resources to cover the demands - consist of technical and financial parameters (efficiency, system lifetime, investment/fix/variable cost, etc.) on the available technologies. A detailed overview of the input parameters and assumptions is given in the supplementary information.

GAMS then creates a linear programming problem based on these input parameters. The third step is the optimization of the problem: the CPLEX solver uses a simplex algorithm to determine the cost-optimal solution to meet the three energy demands (electricity, heating and in the MIX/FCV case - hydrogen) in the community. The output of the optimization includes both the cost-optimal set of process and storage technologies and their hourly dispatch profiles.

Gasoline and diesel costs and vehicle capital costs are added to the output of the simulation, since these do not depend on other energy demands or renewable generation profiles.

One- and three-way sensitivity analyses were conducted (supplementary information) to ensure the validity and robustness of the results.

2.2. Key assumptions and model limitations

1. **Regional vs. nation-wide scope** – In the light of an increasing decentralized power generation, single communities are investigated. This balancing group allows to consider all co-benefits (P2G, H_2 grid storage and V2G) while allowing a focused comparison of the impact of BEVs and FCVs. An analysis of a larger entity, i.e. Germany or Europe, will result in considerably lower amounts of local RES installations (e.g. as other areas provide better potential for wind turbines) and surplus electricity (because of smoothing effects, compare [26] for further detail).
2 **Combined-heat-and-hydrogen** – Waste heat utilization of the electrolyzer could offset the cost of hydrogen, but the attainable temperatures are currently too low for a profitable heat utilization. This could change with solid oxide electrolyzers, which however have the disadvantage that they are not as well suited for dynamic operation. As furthermore a heating grid would be necessary for distribution of the heat, this possibility was not investigated further.
3 **Surplus & Interconnectedness** – It is assumed, that surplus energy could not be sold as it seems likely, that if one community has a surplus due to high local RES generation, due to proximity, neighboring communities with a similar infrastructure would face the same challenge. The transfer of electricity between communities might result in an offset of the absolute

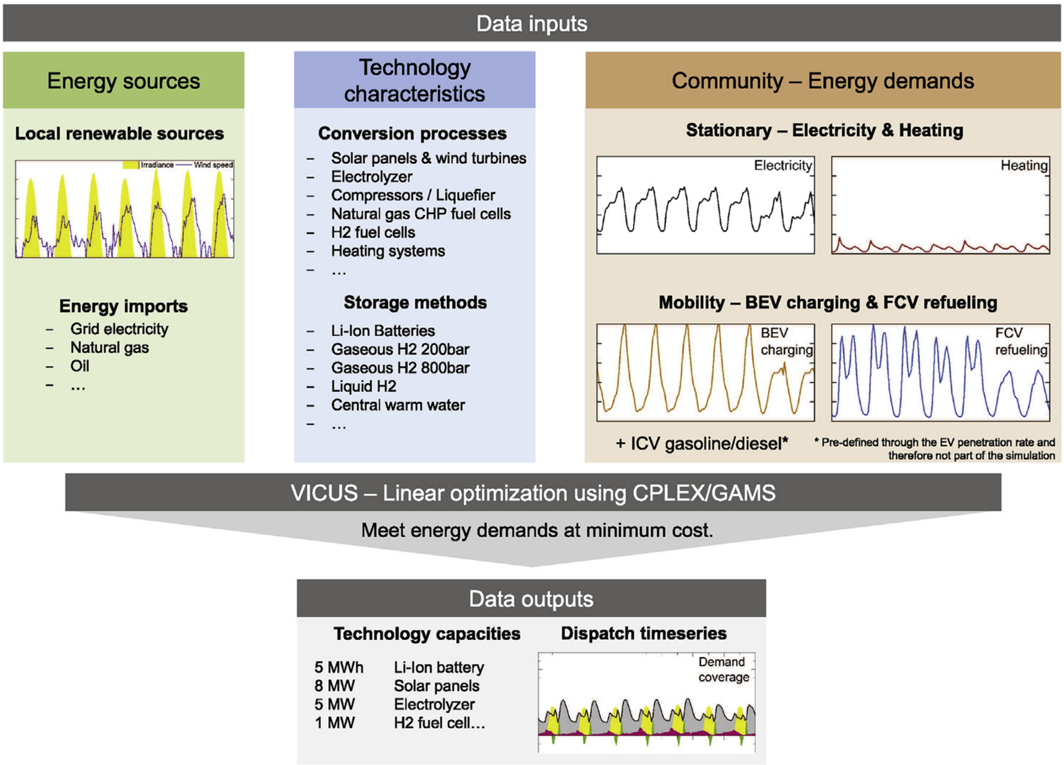

Fig. 1. Schematic overview of the simulation model VICUS.

results (costs and CO_2 emissions for the different cases). However, the overall result - the relative difference between BEVs and FCVs - is expected to be similar, as the energy efficiency gap between BEV and FCV would still prevail.

4 **Macro-vs. micro-economy** — This simulation model determines the macro-economic cost-minimum for a single entity “the community” assuming that residents and local industry would share a single budget to cover their demands for electricity, heat and mobility.

5 **Nationwide infrastructure** — In order to limit the scope of this analysis, all charging and refueling events were assumed to take place in the community. The necessary nation-wide network of charging and refueling possibilities was beyond the scope of this analysis.

6 **Transportation demand** — It was assumed that BEV and FCEV are capable to cover similar driving patterns as ICVs by 2025. It is further assumed that all charging and refueling events take place in the community. The cost of charging infrastructure or hydrogen refueling stations is not considered.

2.3. *Model community, scenario and the electric vehicles cases*

This analysis was tailored to Los Altos Hills (LAH), California, a small community of about 8000 residents located about 60 km southeast of San Francisco. LAH is distinguished by (1) an unusually high solar generation capacity [27] and (2) is located in the county with the highest share of electric vehicles [28] in California. A detailed overview on the building sector energy demands and other parameters for Los Altos Hills is given in the supplementary information. Since LAH is located in a densely populated area, the installation of wind turbines seemed too unlikely and was therefore not considered.

The forecast for future penetration rates was developed based on an extensive literature research [28–33]. This forecast was combined with projections for technical developments and financial learning curves to build a scenario for 2025 and 2035. In order to compare the impact of battery and fuel cell vehicles on the overall cost and CO_2 emissions, three fleet mix cases, were introduced (see Fig. 2) and compared to the all-ICV reference case.

3. Results

Even with significant FCV penetration, neither of the anticipated co-benefits of H_2 infrastructure - storing grid power in H_2 or feeding H_2 into gas grid - are cost effective. To achieve lowest total system cost, the hydrogen system would be almost entirely used to supply hydrogen to FCVs, not to a stationary fuel cell or to the natural gas grid. Because of the high cost of the hydrogen infrastructure, and the inefficient conversions between electrical energy and hydrogen, FCVs are less attractive than BEVs when considering cost and emissions simultaneously.

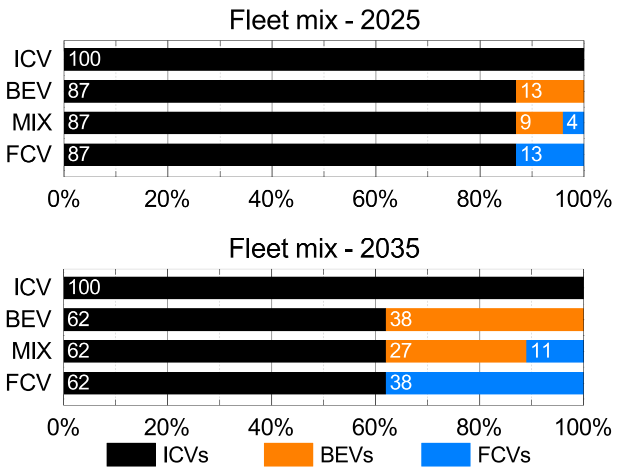

Fig. 2. The fleet mix in the electric vehicle (BEV, MIX and FCV) cases and the ICV reference case.

3.1. *CO_2 emissions reductions and annualized system cost*

The model projects that in the all-ICV reference case, the community's overall costs for electricity, heating and transportation (Fig. 3) in 2025 and 2035 are similar to the 2015 level. The all-ICV reference case assumes exclusive use of conventional vehicles and no electric vehicles in the vehicle fleet. CO_2 emissions in the all-ICV reference case decrease by 33% by 2035 due to efficiency improvements in the ICVs. The deployment of electric vehicles will decrease CO_2 emissions by 40% (BEVs) and 41% (FCVs) compared to 2015. In the BEV case, this can be achieved at almost no additional cost from 2025 onward. However, in both 2025 and 2035, the FCV case is significantly more expensive than the all-ICV reference case, and provides almost no co-benefits (grid energy storage or Power2Gas).

For the all-ICV reference case, the overall costs for the years 2025 and 2035 decrease slightly below the 2015 level (−3% lower in 2035) for two main reasons. First, the total costs for electricity and natural gas (NG) decrease slightly due to a combination of decreasing energy consumption and increasing NG and electricity prices. Second, the cost for transportation remains almost unchanged for a similar reason: vehicle and gasoline price increase, but lower fuel consumption (due to increasing fuel efficiency) offsets this increase and results in lower overall fuel costs. For the all-ICV reference case, overall CO_2 emissions decrease by 21% in 2025 and 33% in 2035. The major share of the emissions reduction is accomplished by the increased fuel efficiency of the vehicles (34 mpg, +48% by 2035 — mainly driven by the CAFE (Corporate Average Fuel Economy) and GHG (Greenhouse Gas) emissions standards [34–36]) in combination with the increased use of renewable energy sources in the electricity grid (50% by 2030, per California state renewables portfolio standard goals [37,38]). In all scenarios, the largest contributor to systemwide emissions in the reference community Los Altos Hills is not the transportation sector but the building sector, as the community's NG consumption is about a two-fold higher [39] than the average consumption in California [40] and NG remains the most cost effective method for building heating. The cost-optimal configuration also includes a small quantity of NG-powered residential fuel cells (1% of buildings) to meet building heat and electricity demand in 2035.

Compared to the all-ICV reference case, every EV case has higher capital costs for both energy conversion infrastructure (e.g. solar panels, electrolyzers, NG-powered fuel cells - see supplementary information for details) and energy storage infrastructure. The FCV case is more expensive than the BEV case for two reasons. The first is the cost of electrolyzer, compressors, hydrogen storage, and FCVs (which are more expensive than BEVs). Second, because of the lower efficiency of the hydrogen path (compare Fig. 7), more energy must be provided to the transportation sector in the form of hydrogen than would be provided in the BEV case as electricity in order to meet the same transportation demand. This requires substantial solar power generation capacity in order to meet the electricity demand for providing this hydrogen (19 MW vs. 10 MW in the BEV case, Fig. 5).

Notably, this analysis finds that in spite of the higher capital investment per vehicle required, BEVs will not only provide a

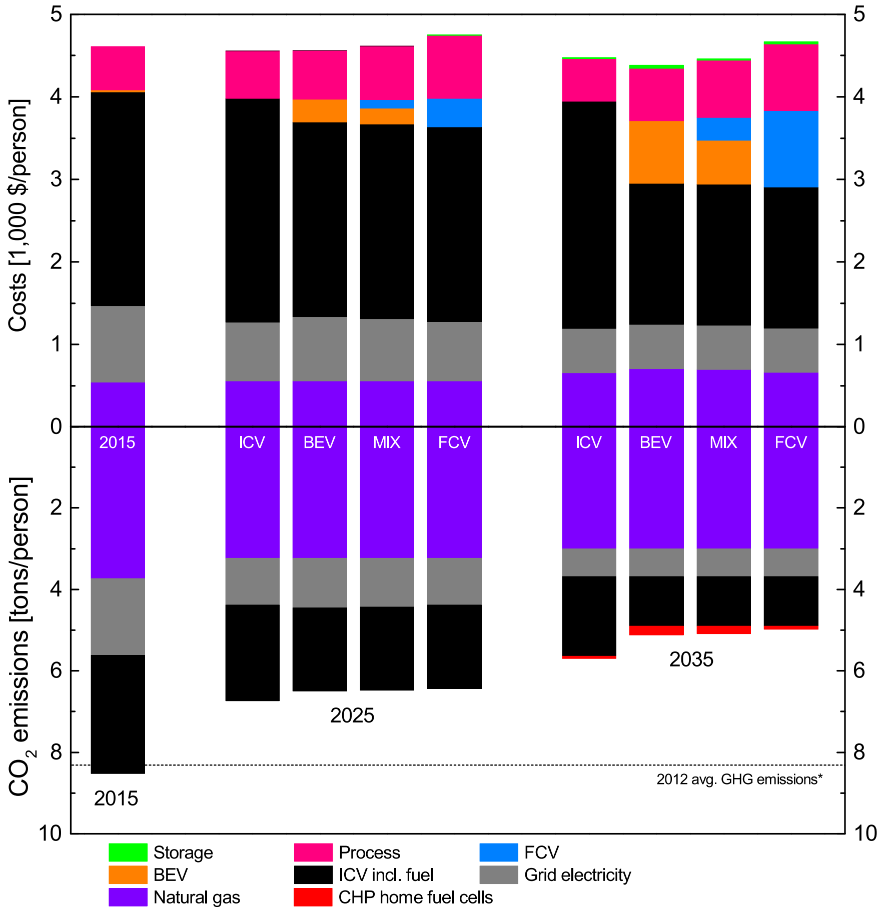

Fig. 3. Breakdown of the annualized costs in the community for different time frames and vehicles penetration rates. Process costs include any investments associated with the installation and operation of energy conversion infrastructure (e.g. solar panels, electrolyzer, compressors, heating systems). Storage costs comprise the expenses for stationary battery systems, hydrogen storage systems and variable costs for vehicle-to-grid due to increased battery aging. (*) The dotted line indicates 2012 GHG emissions per capita in California, excluding industrial and agricultural emissions [41].

lower-emissions solution than ICVs, but will also be cost-competitive with ICVs from 2025 onward. This development results from the elimination of fuel costs in combination with decreased BEV costs and the availability of vehicle-to-grid for electric load management (compare Fig. 3 And 5).

The increasing proportion of electric vehicles anticipated in our scenario lead to lower overall system emissions than the all-ICV reference case in both 2025 and 2035, with slightly higher emissions in the BEV case than the FCV case. Under the current projections for the EV penetration rates (13% EVs in 2025 and 38% EVs in 2035), the use of electric vehicles would result in an additional reduction of the CO$_2$ emissions by 3% (2025MIX) and 7% (2035MIX) compared to the ICV case. Interestingly, in both 2025 and 2035, the CO$_2$ emissions are slightly lower in the MIX and FCV cases than in the BEV case. This is a result of the greater share of low-emissions RES in the electricity consumption in the FCV case.

However, this CO$_2$ reduction comes at significantly higher cost per ton of CO$_2$ avoided than in the BEV case. Fig. 4compares each scenario (BEV, MIX and FCV) to the all-ICV reference case, quantifying how the change in cost compares to the change in CO$_2$ emissions. This analysis identifies the aggregate cost at which the CO$_2$ emission reductions can be realized under the technological and economic developments assumed in the scenario (detailed in the methods section and supplementary information).

The BEV and the MIX cases (70% BEVs, 30% FCVs) are the only cases that achieve both lower CO$_2$ emissions and lower costs by 2035. The FCV case achieves slightly lower overall CO$_2$ emissions (Fig. 3) than the BEV case, but at significantly higher costs. As a result, BEVs are the more favorable solution from both a financial (lower overall costs, Fig. 3) and environmental (lower cost per CO$_2$ reduction, Fig. 4) perspective.

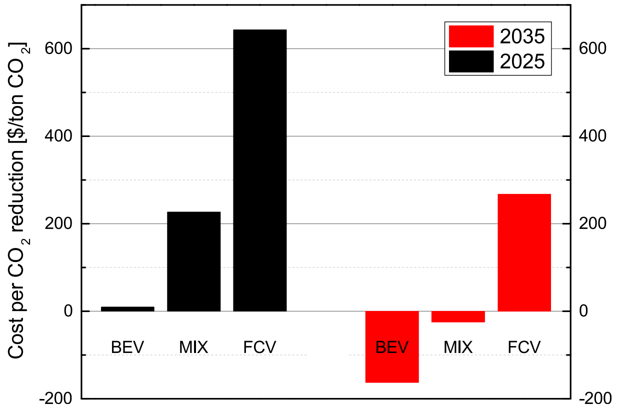

Fig. 4. Cost per ton of CO$_2$ reduction in the community for the different EV cases compared to the all-ICV reference case.

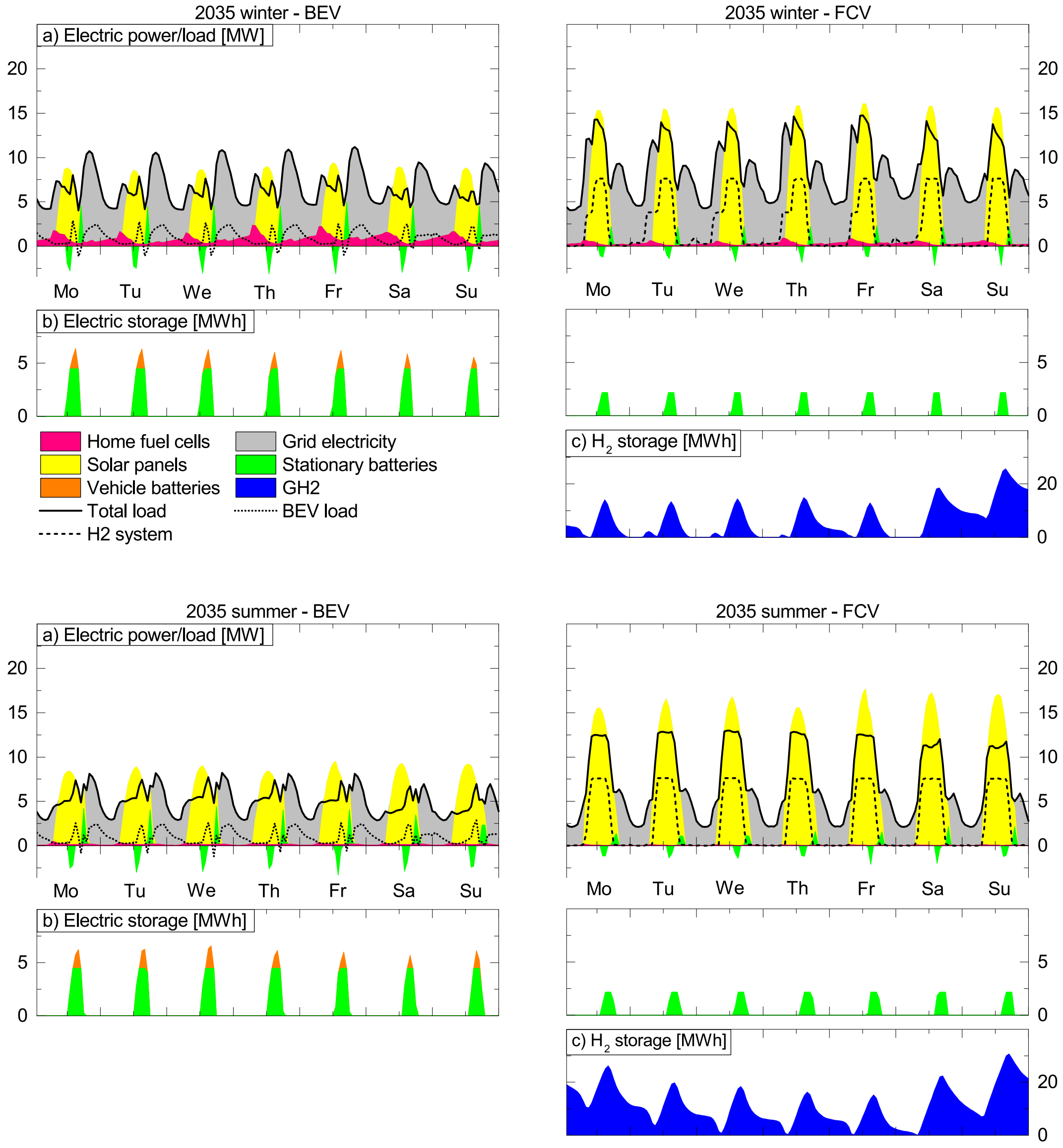

Fig. 5. 2035 BEV and FCV time series for the second week of January and July. a) Electric power generation and load profiles. b) State-of-charge of the electric storage systems. c) State-of-charge of the hydrogen storage system.

3.2. Power generation, grid storage and Power2Gas

Distributed photovoltaic power is a significant proportion of the cost-optimal electricity generation mix in both the BEV and FCV scenarios (Fig. 5). In the FCV case, about 19 MW of distributed solar panels are required in order to meet the large energy demand, while 10 MW are sufficient in the BEV case. Although the model has the option of including a centralized hydrogen fuel cell power plant for electricity generation, it determined that this option is not cost-efficient. The model also found it economically unfavorable to add additional electrolyzer capacity that would produce hydrogen for feed-in to the natural gas grid (Power2Gas). Instead, purchasing natural gas is more cost-efficient. As a result, solar hydrogen blended into the natural gas supply via Power2Gas contributes only 1% of the gas-fired building heating demand in the FCV case.

By 2035, in either case, the community would use large quantities of local solar power generation to provide electricity during daytime, but rely on grid electricity during the nighttime. In the FCV case, the losses associated with the energy conversions (electricity-to-H_2-to-electricity) result in larger electricity demand, and larger solar panel capacity, than the BEV case. Consequently the share of local RES generation is higher in the 2035 FCV case (52%) than in the BEV case (34%). The results indicate that combined heat and power from NG-powered residential fuel cells would cover up to 30% of the hourly electricity demand in the BEV case in peak winter hours. In contrast to this, in the FCV case, electric heating systems would be favored, to make best use of the vast amounts of solar panels.

In both cases, stationary batteries would primarily be used for intra-day load shifting, rather than mid- or long-term grid storage. In the FCV case, the buffering of hydrogen in storage tanks makes it possible to generate most of the hydrogen during daytime, using solar power, and refuel it at a later time. Due to this flexibility, stationary batteries add limited value. The FCV case calls for 2 MWh of stationary battery storage, which are used to maximize the use of the local solar power generation and minimize the consumption of grid electricity from higher priced tiers.

In the BEV case, peak electricity generation is less easily shifted

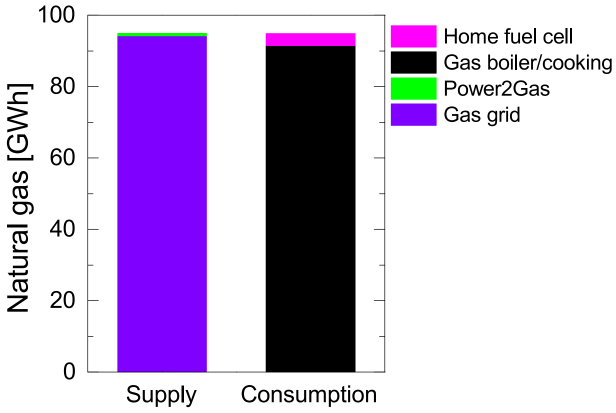

Fig. 6. Natural gas supply and demand in the 2035 FCV case. Less than one percent of the gas demand would be covered by Power2Gas.

to meet transportation needs at other times. This is because BEVs must be grid-connected in a low state-of-charge to receive electric charge. As only 5% of the vehicles were allowed to shift their charging load, the majority of the vehicles would charge similar to current BEVs - during evening or nighttime hours [42]. Therefore, stationary batteries are significantly more valuable in the BEV case, which uses twice the storage capacity (4MWh) to buffer the solar power generation. Vehicle batteries provide an additional storage capacity of 11MWh. However, due to the variable costs associated with the increased battery aging in the vehicles, this capacity is only utilized once the stationary batteries are fully charged.

In the FCV case, the hydrogen system operation will closely track solar power generation in order to avoid using more expensive grid electricity to generate hydrogen. As a result, in the FCV case, the electric load profile would be strongly influenced by the hydrogen generation, while BEVs have a smaller impact on the load profile. (Although fast charging of BEVs was not included in the model, this could lead to a rapid load ramp-up in the BEV case.)

As hydrogen is not used for centralized electricity generation in the cost-optimal solution, the first co-benefit for the hydrogen infrastructure — grid storage — is not realized. Instead, the hydrogen storage system (32MWh of compressed gaseous hydrogen storage capacity, approx. 1 ton of H_2) is used exclusively to meet the hydrogen demand of the FCVs.

The second anticipated co-benefit of the hydrogen system, capturing solar overgeneration, also has little impact in the cost-optimal solutions. The electrolyzer (5 MW power rating) can be used as a Power2Gas system, to generate hydrogen from solar overgeneration and feed it into the natural gas (NG) grid. In the FCV scenario, only 6% (800MWh or 24 tons) of the overall hydrogen generation is fed to the NG grid, corresponding to 0.8% of the NG demand in the community (Fig. 6). This small magnitude of Power2Gas is due to low NG prices: the additional electrolyzer capacity that would be required to capture the solar overgeneration as hydrogen is more expensive than purchasing the same energy content as natural gas.

3.3. *The value of efficiency - energy demand per distance traveled*

The large distributed solar generation capacity in the FCV case (19 MW) results in a higher share of low-emissions RES (52%) as compared to the BEV case (34%).

For the FCVs, more than 80% of transportation energy would be sourced from local solar power generation (Fig. 8). In contrast, BEVs would primarily charge during evening and nighttime hours, when low or no solar generation occurs, and would therefore use more grid electricity. While smart BEV charging could result in a higher fraction of daytime charging with PV, this would depend both on consumer choice and the availability of workplace charging. This choice may be influenced by battery capacity, electricity price and geographic coverage of charging stations. To provide a reasonable comparison between FCVs and BEVs, conservative assumptions about the extent of smart charging in 2035 (5% of the daily BEV demand can be shifted) were used. As a result, the 2035 load profile is fairly similar to the 2015 load profile, and corresponds to a low proportion (16%) of solar energy in the total BEV transportation energy mix.

Since both vehicle types are powered by electric drivetrains, about the same amount of energy is required to provide the propulsion for a BEV and a FCV of similar weight. However, due to the energy losses along the hydrogen energy chain, a FCV requires

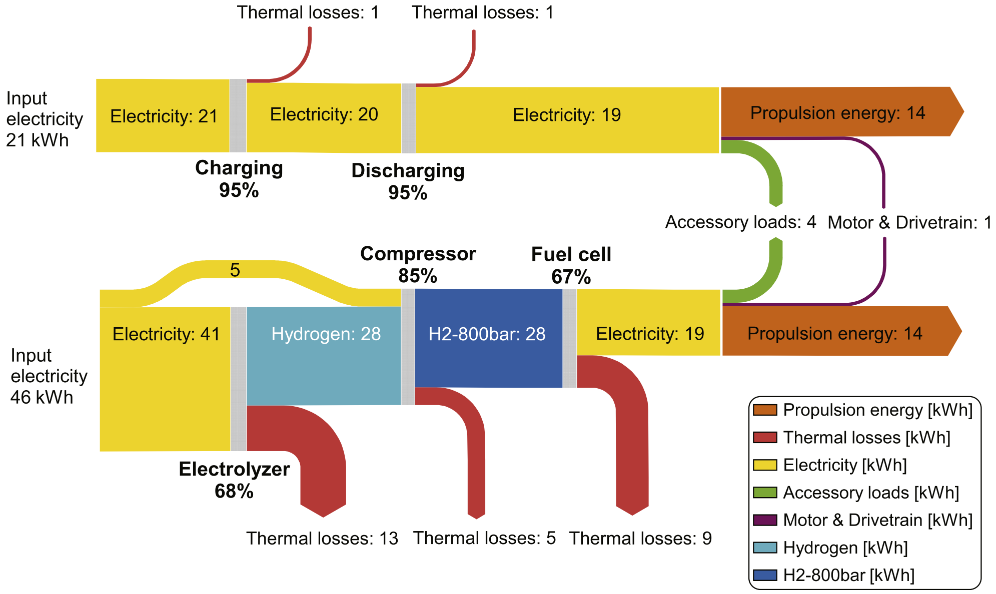

Fig. 7. Sankey diagram on the energy flows per 100 km traveled for BEVs and FCVs on an electricity-to-wheel basis. The projections for 2035 are estimates based on current data: Motor&Drivetrain [43], Accessory loads [44,45]. BEV: Charging efficiency [46], Battery discharge [43,47,48] FCV: Electrolyzer [49,50], Compressor [51,52], Fuel cell [53].

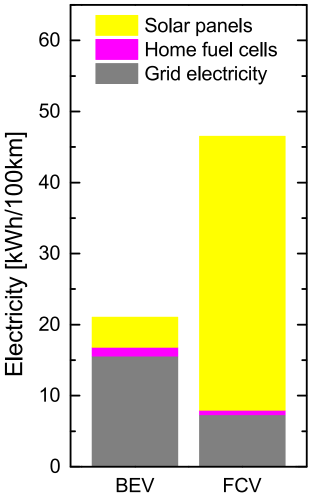

Fig. 8. Electricity energy demand and generation source, to travel 100 km in the 2035 cases based on the electricity generation mix during BEV charging or hydrogen generation and compression (FCV).

about 2.2 times more initial electric energy per distance traveled than a BEV (estimates for 2035, Fig. 7).

4. Conclusion – implications for electric vehicles in California

This study quantifies the reductions in transport sector CO_2 emissions that would result from market penetration of BEVs and/or FCVs into the light-duty vehicle fleet. The results of our study provide three key insights:

First, BEVs are a cost-competitive alternative to conventional vehicles from 2025 onwards, mainly because of decreasing BEV costs and increasing ICV and fuel costs. BEVs therefore offer an opportunity for reduced CO_2 emissions accompanied by lower costs. Second, if the community relied on FCVs instead of BEVs, about twice as much photovoltaic generation capacity would be required to achieve a similar CO_2 emissions reduction, which leads to higher cost.

Third, in the FCV case, the economic benefits of grid storage and Power2Gas are not sufficient to compensate the significantly higher expenses for the hydrogen infrastructure and additional solar panels. The sensitivity analyses (supplementary information) suggest that the results are robust under a wide range of conditions (e.g. vehicle price, PV panel cost, natural gas and grid electricity price). Hence a different conclusion seems unlikely unless a significant increase of both electrolyzer and fuel cell efficiency closes the efficiency gap between FCVs and BEVs. With driving ranges exceeding more than 400 km (250 miles) for current BEVs, quick-refueling remains the sole advantage of FCVs from a driver's perspective.

Because this analysis incorporates meteorological, policy and energy cost data that are specific to California, these results are only valid for a community in California. Further research might explore other locations with different conditions for energy prices (especially natural gas prices for P2G competitiveness) and solar power generation (seasonal change of the solar irradiation) and include wind in the local renewable generation mix. Research is also needed to determine how the grid electricity price design (tiered pricing, demand-pricing, etc.) affects the total cost of ownership of solar panels in combination with stationary batteries and electric vehicles.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2016.08.014.

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