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Economic and environmental prospects of battery and fuel cell vehicles for the energy transition in German communities.

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Abstract

The CO_2 reduction potential of battery and fuel cell electric vehicles (BEV/FCEV) is linked to the success of the energy transition. Both vehicle types can facilitate the integration of intermittent renewables. H_2 generation and storage infrastructure to support FCEVs is a promising opportunity for synergy between the transportation and building sectors in renewables integration, through grid storage and Power2Gas (i.e. blending H_2 into the natural gas supply). However, as FCEVs also require more than twice as much electric energy per distance traveled than BEVs, an integrated analysis is necessary to evaluate which electric vehicle (EV) offers the lowest cost for reducing CO_2 emissions.

We use an integrated analysis to determine the overall cost and CO_2 emissions when BEVs or FCEVs are deployed in two communities in southern Germany. Based on a comprehensive scenario for future cost and technology developments for 2025 and 2035, the cost-optimal mix of energy generation and storage technologies is determined to meet all energy demands (heating, electricity and transportation) in the communities.

This integrated analysis finds, that the higher energy consumption of FCEVs could not be compensated by system benefits like Power2Gas and grid storage. The result is consistent with a similar analysis of a community in California. The simulation results reveal, that while the two vehicle types enable similar CO_2 emission reductions, these can be realized at lower costs with BEVs than with FCEVs. The most striking observation was, that in the event seasonal H_2 grid storage becomes necessary, FCEVs would in fact be less favorable than BEVs, which require less energy per km traveled and therefore leave more energy available for stationary applications.

Keywords: energy transition, battery vehicles, fuel cell vehicles, Power-to-Gas, hydrogen infrastructure

1. Introduction

Battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) both offer convenient personal mobility with no tailpipe emissions. Their potential to reduce CO_2 emissions in Germany depends on providing them with energy from a low-carbon source - in other words, on the success of the German energy transition. However, they both offer interesting co-benefits for the integration of intermittent renewable energy sources (RES) such as wind and solar power that may facilitate the transition.

When connected to the grid, BEVs can contribute via smart charging (load shifting to times of high RES generation) [1, 2, 3, 4] or as short-term energy storage (vehicle-to-grid, V2G [5]). When considering FCEVs, the hydrogen infrastructure consisting of electrolyzer (H_2 generation) and gaseous or liquid storage tanks, is particularly interesting for the energy system. For one thing, hydrogen could be generated during renewable power generation and converted back to electricity in a stationary fuel cell at a later point in time. Compared to V2G and stationary batteries, considerably more electricity could be stored [6]. Second, would it be possible to convert renewable (over-)generation, that would otherwise be curtailed, to hydrogen and feed it into the natural gas grid (Power2Gas, P2G) - thereby linking electric power and heat sector.

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Nomenclature

BEV	Battery powered electric vehicle
EV	Electric vehicle, powered by an electric motor
FCEV	Fuel cell powered electric vehicle
ICV	Internal combustion vehicles, usually powered by gasoline or diesel fuel.
NEU	Neumarkt i.d.OPf., Germany
P2G	Power2Gas - hydrogen infeed to the natural gas supply
PUT	Putzbrunn, Germany
RES	Renewable energy sources
SI	Supplementary Information
V2G	Vehicle-to-Grid, short-term electricity storage using BEVs

In this study, the cost and CO_2 emissions impact of BEVs or FCEVs together with their accompanying infrastructure was investigated in the communities Putzbrunn and Neumarkt i.d.OPf. (PUT/NEU) in order to evaluate the potential benefits of either technology. The aim of the analysis is to determine if the potential co-benefits Power2Gas and H_2 grid storage from the use of hydrogen for transportation can compensate for the two- to threefold higher electric energy consumption of FCEVs compared to BEVs per distance traveled [7, 8, 9] (compare fig. 1).

The results were obtained with the simulation model VICUS [7] which uses hourly data[1] on RES availability and the energy demands in the community (Heat, Electricity and Mobility) as well as a comprehensive scenario on the further development of the energy vectors and available technologies.

For the years 2025 and 2035, the cost-optimal way to meet the energy demands was determined in three scenario cases: First, the all-ICV reference case (100% Internal combustion vehicles, no EVs); second, a BEV case with 13% (2025) and 38% (2035) BEVs in the vehicle mix; and finally a similar FCEV case[2].

The first part of the paper provides an overview on the overall costs and corresponding CO_2 emissions in the different cases. Second, the benefits of Power2Gas are investigated, prior to the third and final part, where the implications of hydrogen as a large-scale grid storage system are analyzed for a scenario with limited grid power in 2035.

2. Methodology – Simulation model, Input Data & Sensivity analyses

For this study, the same method as described in [7] was used to “determine the cost-optimal mix of different technology options to meet the energy demands” in the two communities. In [7], “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, SI). For the comparison of battery and fuel cell vehicles, the model determined results for three electric vehicle cases (BEV, MIX, FCEV) and an all-ICV reference case for 2025 and 2035.”

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[1] for one year ≙ 8760 timesteps

[2] 2025 and 2035 ICV cases: 100% all-ICV, no electro-mobility
2025 BEV / FCEV cases: 87% ICV + 13% BEV / 87% ICV + 13% FCEV
2035 BEV / FCEV cases: 62% ICV + 38% BEV / 62% ICV + 38% FCEV.

Because the analysis in [7] was based on a community in California, some adaptions to the parameters in the scenario had to be made in order to apply the scenario to Germany. However, in order to enable a comparison between the calculations made for California and this work, the same electric vehicle penetration rates (13% in 2025 and 38% in 2035) were used – which is rather optimistic for Germany given the current state of EV penetration [10].

Figure 1 presents the change in the overall energy demands, when 38% of the vehicles were either battery- or fuel-cell-powered by 2035 in NEU. Since transportation has no (immediate) impact on the heating demand, and transportation fuel demand reduction is identical for BEVs and FCEVs[3], the sole differentiator on the demand side is the overall electricity demand. While BEVs lead to an increase in the electricity demand by 11%, would the deployment of FCEVs result in a more than twofold higher (27%) demand increase.

2.1. VICUS - excerpt from [7]

VICUS is a 1-node version of the Urban Research Toolbox: Energy Systems (URBS) [11] which was first developed by T. Hamacher and S. Richter[12]. The simulation model (compare fig. 2) 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.

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 FCEV 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/FCEV 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. – end of excerpt [7].

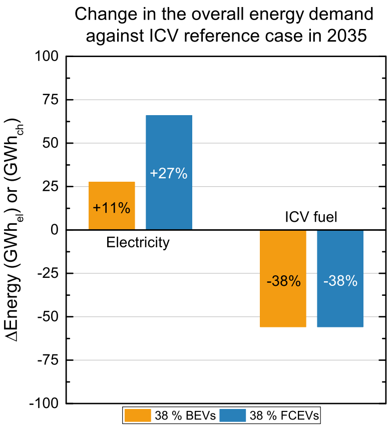

Figure 1: Change in the energy demand of the community, if 38% of the vehicles were either BEVs or FCEVs in Neumarkt i.d.OPf. by 2035.

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[3] as in either case 38% of the ICVs would be replaced in comparison to the all-ICV (100% ICVs) reference case

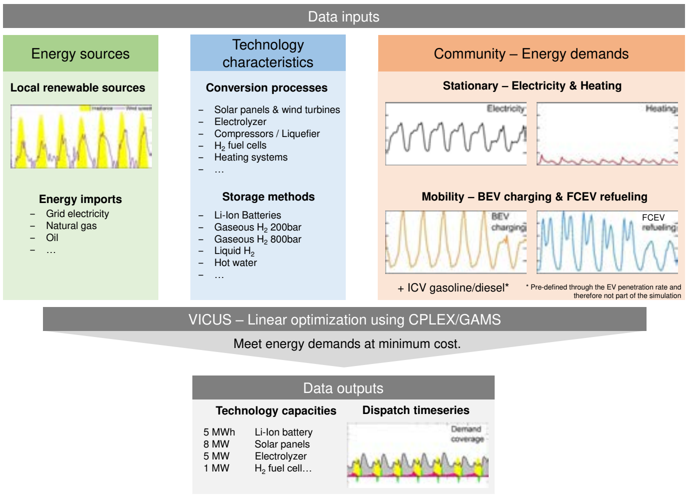

Figure 2: Schematic overview of the simulation model VICUS.[7]

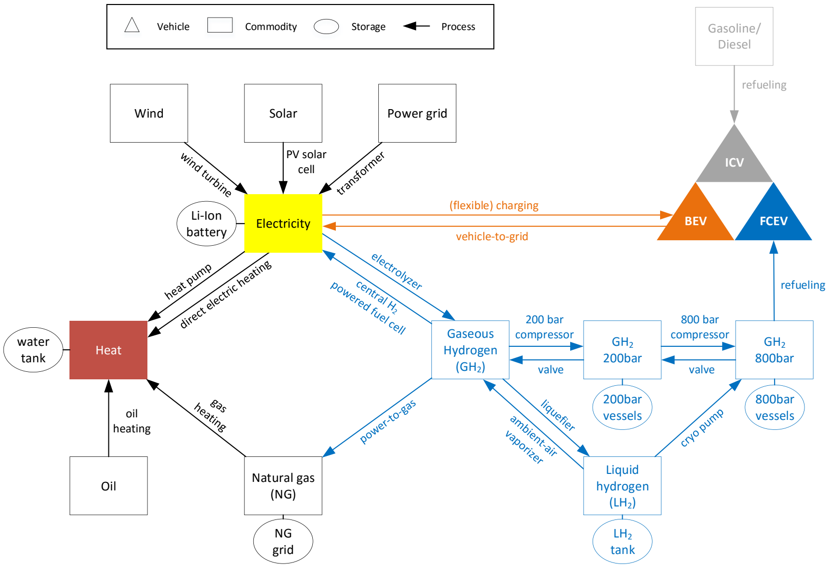

Figure 3: Overview on the energy vectors/commodities, processes, storage technologies that were considered within this analysis.

2.2. Communities & scenarios

Two different-sized communities, Putzbrunn (6,300 residents, PUT) and Neumarkt i.d.OPf. (41,300 residents, NEU) in Southern Germany were investigated. Both communities have a similar vehicle penetration (≈ 600 vehicles/1,000 residents) but distinguish themselves in (1) electricity, heating and transportation energy demand and load profiles (2) distribution of residential and industrial electricity demand[4] and (3) availability of RES potential, particularily wind energy[5]. Figure 3 provides an overview on the technologies that were considered within this analysis.

3. Results & Discussion

Under the current projections, overall cost will increase by approximately five to ten percent from 2015 to 2025 for all fleet mix scenarios, primarily caused by (1) the increase in the ICV vehicle prices and fuel expenses (gasoline/diesel) and (2) altogether increasing cost for energy vectors[6] which will not be entirely compensated by the increase in the energy efficiency (fig. SF1 in the SI provides a cost breakdown). As BEV and FCEV prices decline and ICV prices stagnate between 2025 and 2035, overall costs decline. This development is further supported by the increasing competitiveness of local solar and wind power generation, which provides almost two thirds of the overall electricity generation by 2035. This moreover promotes the energy transition in the heating sector as the existing oil heating systems (and some of the gas-powered heating systems) will be replaced by electric-powered heatpumps by 2035.

3.1. Overall cost & CO_2 emissions

In contrast to the BEV case which will almost be at cost parity to ICVs in 2025 and 2035, the FCEV case results in the highest costs. This is caused by the higher FCEV prices[7] in combination with the higher energy demand for the supply of hydrogen, which results in higher expenses for the supply of electricity and the H_2 infrastructure (H_2 generation & storage) compared to ICVs and BEVs. Figure 5 provides a detailed cost-breakdown for the BEV and FCEV cases in comparison to the all-ICV base case at the example of 2035 in Neumarkt i.d.OPf. The data shows, that transportation costs[8], H_2 system[9], and increased power generation are the main distinctions between the BEV and FCEV case.

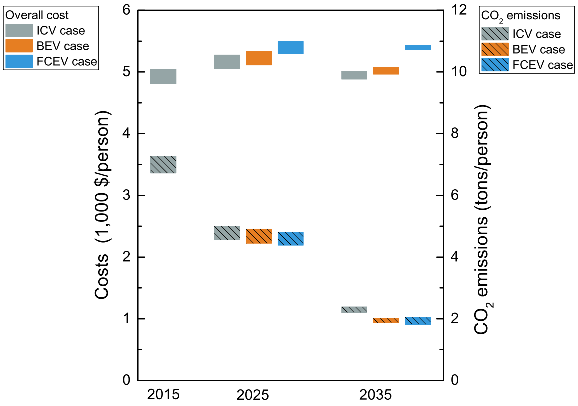

Figure 4: Overall cost and CO_2 emissions per person. Lower/upper boundaries of the bars are the data points for Putzbrunn (lower) and Neumarkt (upper). A more detailed cost breakdown is provided in figure SF1 in the supplementary information (SI).

The significant decrease in the overall CO_2 emissions (about one third by 2025 and two thirds by 2035) can be traced back to three main developments: First, the largest contribution comes from the reduced use of grid electricity[10], followed by the replacement of fossil-powered heating systems through heatpumps, and third, the increased fuel efficiency of conventional

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[4] which affects not only the load profiles, but also the average cost of the energy vectors, given that residential energy prices are often considerably higher. See Supplementary information (SI) for details.

[5] Annual energy output: solar panel PUT/NEU: 1170 / 1145 kWh_{el}/(kW·a); Wind power PUT/NEU 1200 / 2000 kWh_{el}/(kW·a)

[6] the recent decline in oil and gas prices has not been included in the calculations as the projections are based on a long-term forecast [13], compare SI for details

[7] vehicle price in thousand dollars per vehicle for 2015-2025-2035: ICV 29-32-32; BEV 50-45-43 and FCEV 61-56-52, see SI for details

[8] include the cost of vehicles, charging/refueling infrastructure and the ICV fuel cost

[9] which in the ICV and BEV case is about an order of magnitude smaller and would be used exclusively for Power2Gas

[10] which furthermore will be less carbon-intense

vehicles[11] (see fig. SF1 in the SI for details). It is evident from figure 4 that the use of electric vehicles will further decrease the CO_2 emissions, however to a smaller extent than the aforementioned factors.

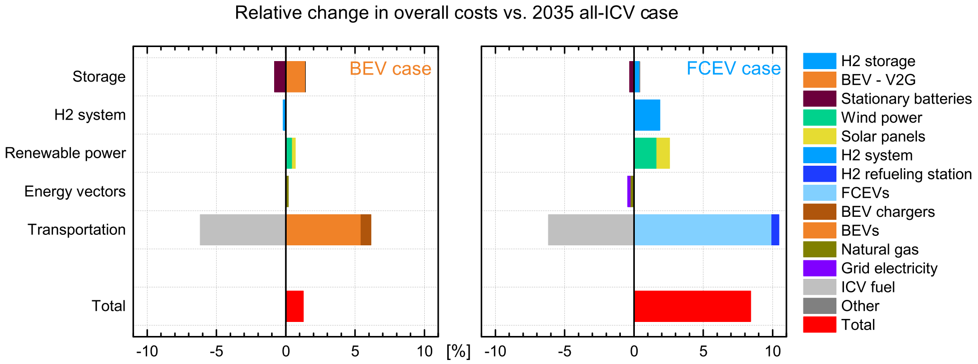

Figure 5: Comparison of the overall cost for Neumarkt i.d.OPf. in the 2035 BEV and FCEV case (62% ICVs; 38% of the vehicle fleet would be either battery- or fuel-cell-powered) to the all-ICV base case. The cost of the vehicles is the most dominant factor, followed by the hydrogen system (FCEVs) and the cost of additional Renewable power generation. [Transportation: cost of vehicles, charging/refueling infrastructure and the ICV fuel costs. H_2 system: H_2 generation and compression/liquefaction, excluding storage.]

The following conclusion can be drawn from the data provided in figures 4 and 5: Under the current projections, both FCEV and BEV lead to lower CO_2 emissions than ICVs. Using BEVs is cost-competitive to the all-ICV case from 2025 onward. However, FCEVs would lead to higher expenses without a significant additional CO_2 emissions reduction. These results are consistent with similar calculations for a community in California [7]. To further illustrate the difference between the BEV and FCEV case, figure 6 presents the cost per ton of CO_2 avoided in comparison to the all-ICV case based on equation 1 (from [7]).

$$\text{Cost per CO}_2\text{ reduction} = \frac{\text{Added cost EV case}}{\text{CO}_2\text{ reduction EV case}} = \frac{\text{Cost(EV)} - \text{Cost(ICV)}}{\text{CO}_2\text{(ICV)} - \text{CO}_2\text{(EV)}} \tag{1}$$

Under the current projections, BEVs enable a less expensive decarbonization than FCEVs, even if BEV and FCEV prices were equal (data point FCEV-inv = BEV-inv in fig. 6). This leads to the question which role Power2Gas and grid storage play in these energy systems and under which circumstances FCEVs would provide less expensive emission reductions than BEVs.

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[11] provided that 87% (2025) and 62% (2035) of the vehicles are still conventional ICVs in the BEV and FCEV cases, compare section 2.

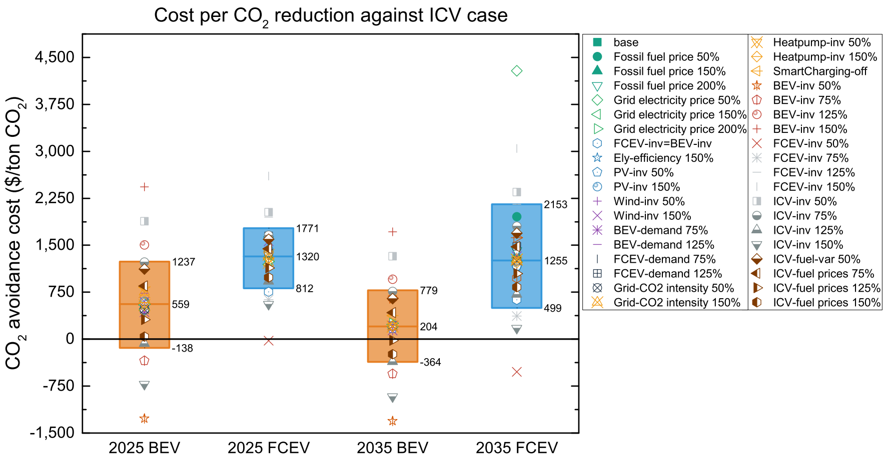

Figure 6: Cost per ton of CO_2 avoided in the BEV and FCEV cases versus the all-ICV case (PUT/NEU-average). The size of the boxes is defined by the standard deviation of the sensitivity studies shown in the legend. [The parameters for the base case (100%) are provided in the SI. For each scenario, the percentage values in the legend, indicate how the respective parameter variable was modified relative to the base case. Fossil fuel = Fossil heating fuels natural gas and oil / Ely-efficiency = Electrolyzer efficiency / PV = photovoltaic solar panels / Wind = wind turbine / inv = investment cost.]

3.2. Power2Gas

The data in figure 7 shows the impact of P2G at the example of the 2025 FCEV case. Over a wide range of assumptions on the future cost of the most relevant energy vectors, P2G results in cost reductions of only up to 0.75% for NEU and more than twofold higher energy vectors than in the anticipated 2025 base scenario (compare SI). Regarding the CO_2 perspective however, the benefits are about an order of magnitude higher, with a reduction of 0 to 5% as long as P2G does not promote a continued preference for gas-powered heating systems (NEU 250%/200%)[12] instead of conversion to electric heatpumps. It is also apparent from figure 7, that the benefit of P2G correlates to the fossil fuel (particularily natural gas) and grid electricity prices (due to increasing RES capacities which generate more surplus energy).

3.3. Hydrogen grid storage

Hydrogen could play an important role should “seasonal storage” become necessary to compensate the reduced electricity output of solar power during the winter. Hence, one might expect, that a community that already uses hydrogen for transportation would prove more favorable in this case than a community with BEVs. To reconstruct a situation where seasonal storage becomes necessary, an energy system with high RES and limited backup from the power grid[13] was modeled (fig. 8).

As shown by the surplus of energy supply compared to energy demand (10 - 15% surplus) in figure 8, renewable overgeneration provides the low-cost solution to resolve the grid power bottleneck before installing massive amounts of storage (compare [14]).

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[12] P2G OFF (91% of heat covered by heatpumps, 9% by gas-powered boilers) – P2G ON (77% heatpumps and 23% gas) - for reference: in 2025 base case (ON/OFF: 57% Gas and 43% oil)

[13] the output of the power grid was limited to 10% of the building peak electric load

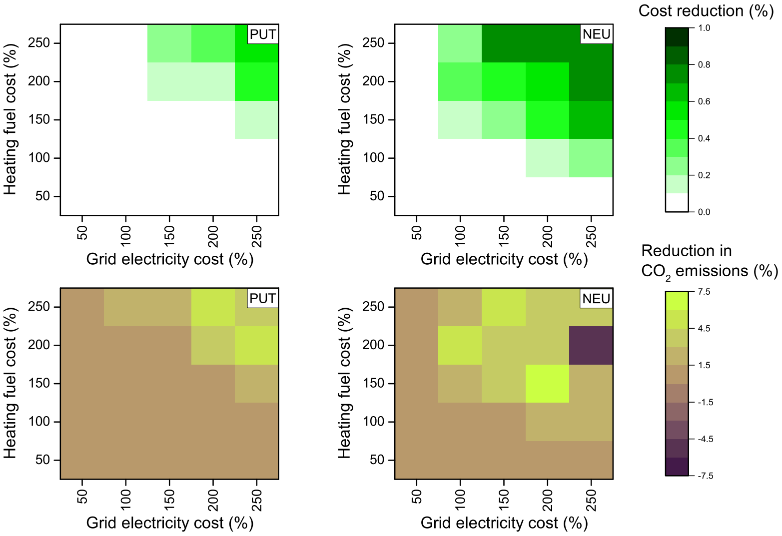

Figure 7: Cost and CO_2 emission reduction from Power2Gas. The diagrams show the relative change in the 2025 FCEV case with and without the availability of Power2Gas as a process to the simulation model (fig. 3). Power2Gas leads to lower CO_2 emissions as long as it does not reach a scale that would promote the extended use of gas-powered heating systems instead of electric heatpumps. (NEU 250%/200%)

In both communities, the BEV case turns out to be 5 - 6% less expensive than the FCEV case[14]. This difference remains even if FCEVs could be offered at the same price as BEVs, though it is smaller (1 - 2%). As a result, the major share of the cost difference can again be explained by the different cost of the vehicles, while the remainder is related to the different energy demands.

While both BEV and FCEV case use a hydrogen system[15] to backup the renewable generation during the winter, there's a significant difference in how the communities can benefit from it: In the FCEV case, the H_2 systems' primary purpose by order of magnitude is to cover the demand of transportation, before "stationary use" in the form of grid storage and P2G. As the transportation demand for electricity is cut more than in half in the BEV case (fig. 1), this otherwise "lost energy" is now available to provide a greater proportion of "stationary use".

Surprisingly, in the case that hydrogen-based grid storage becomes necessary, FCEVs turn out to be a less favorable partner for the energy system than BEVs.

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[14] over the same range of parameter variations for grid electricity and fossil fuel (natural gas/oil) prices as in figure 7

[15] consisting of electrolyzer, liquefier, liquid hydrogen (LH_2) storage tanks, vaporizer and stationary H_2 fuel cell

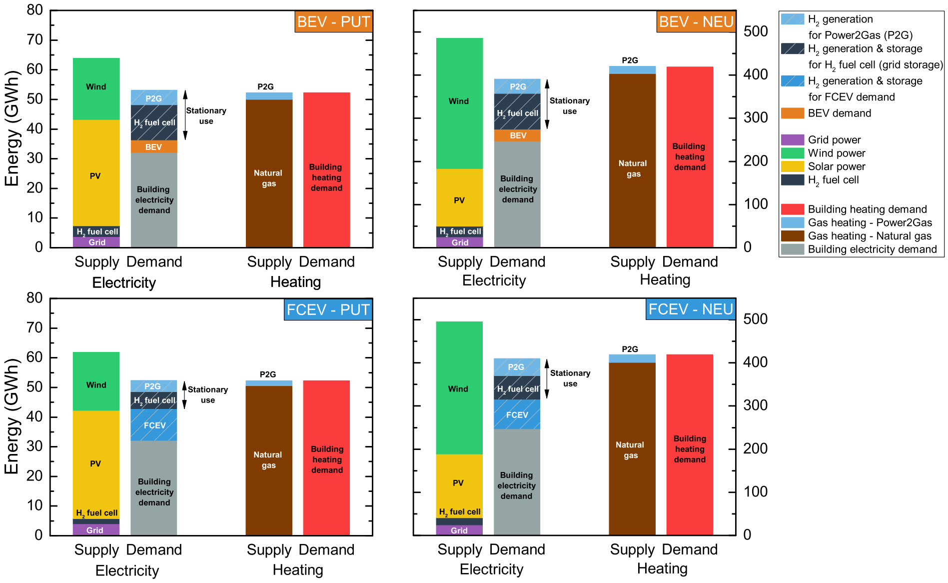

Figure 8: 2035 BEV and FCEV case with grid power limited to 10% of building electricity demand. As a result of the higher wind potential, more wind than solar power would be installed in NEU while the opposite is true for PUT. While in the base case (unconstrained use of grid electricity) a vast majority of the heating demand would be covered by heat pumps, the power limitation results in the continued use of natural gas. To compensate for the limited grid capacity, both BEV and FCEV case would rely on a H_2 grid storage. Surprisingly, the BEV cases provide up to twice the benefits to the community than the FCEV case as less energy is required for transportation. (The model decides to use LH_2 storage tanks for seasonal storage, which - in addition to thermal losses in electrolyzer and fuel cell - adds further losses from liquefaction to the "input energy" of the H_2 fuel cell which is more than three times higher electric output energy.)

3.4. Further research

The following section provides some thoughts on the scope of the analysis and elaborates on some additional factors, that need further investigation:

1. **Regional vs. nation-wide scope** – We chose to investigate single communities for two main reasons:
   First, the scope is large enough to evaluate co-benefits like Power2Gas and H_2 grid storage but still allows a high level of detail to analyze the impact of electric vehicles in detail.
   Second, local renewable generation is a political and social goal in many communities [15, 16, 17, 18] (incl. PUT [19] / NEU [20]) which have set up detailed action plans to reduce dependency of fossil fuels and increase local RES generation. In case FCEVs and the corresponding co-benefits provide an overall more economic solution than BEVs in the communities, this could accelerate the roll-out of a widespread FCEV refueling network.
   A nation-wide analysis might come to different results in the amount of local RES installations (i.e. as other areas provide better potential for wind turbines and because of smoothing effects in the load curves), total cost and CO_2 emissions. However the key distinction between BEVs and FCEVs would remain unchanged: FCEVs would still require more than twice as much energy per km traveled and result in a higher transportation energy demand.
2. **Hydrogen import** – Due to the local focus of this analysis, an import of hydrogen (e.g. sourced from surplus electricity in Northern Germany [21] delivered by trailer) was not considered.
3. **Combined-heat-and-power** – Waste heat utilization of electrolyzer and stationary fuel cell could offset the cost

of a hydrogen system, but the attainable temperatures are currently too low for a profitable heat utilization[16]. As furthermore a heating grid would be necessary for distribution of the heat, this possibility was not investigated further.

4. **Surplus & Interconnectedness** – We 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 results (costs and CO_2 emissions for the different cases). However, the overall result - the relative difference between BEVs and FCEVs - is expected to be similar, as the energy efficiency gap between BEV and FCEV would still prevail.
5. **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. Future work might explore this topic for individuals owning a BEV or FCEV to determine the specific cost and emissions benefit per vehicle.
6. **Customer preferences** – The results of this work indicate, that from a technical and economic perspective, BEVs are superior to FCEVs. However, costs set aside, the satisfaction of customer needs is decisive for a wide-spread adoption of electro-mobility. For this analysis, it was assumed that all EVs were capable to cover similar driving patterns as ICVs by 2025. While the range of BEVs is continuously increasing, their recharging rate (km/min) will remain about an order of magnitude below FCEVs and ICVs for the foreseeable future. More studies are needed to quantify how the difference in the recharging/refueling time affects consumer choice in deciding between BEV and FCEV.
7. **Nationwide infrastructure** – In order to limit the scope of this analysis, all charging and refueling events were assumed to take place in the community. While the cost of local charging and refueling infrastructure is included in the calculations, the necessary nation-wide network of charging and refueling possibilities was beyond the scope of this analysis.

4. Conclusion & Outlook

In this assessment, we have evaluated whether the co-benefits Power2Gas and H_2 grid storage could offset the lower energy efficiency of FCEVs compared to BEVs and provide an overall less expensive decarbonization.

Both BEVs and FCEVs enable lower CO_2 emissions than an all-ICV scenario (fig. 4). Compared to a reduced consumption of carbon-intense grid electricity or the replacement of fossil-fueled heating systems, the overall impact of electro-mobility on CO_2 reductions is however rather modest.
Within the scope of this analysis (sec. 3.4), CO_2 emissions reduction with BEVs comes at lower costs than with FCEVs, as the co-benefits Power2Gas and H_2 grid storage are not able to compensate the higher energy demand. First, Power2Gas provides very little cost savings (fig. 7). Second, in case H_2 storage becomes necessary to balance seasonal loads, BEVs turn out to better complement the energy system than FCEVs (fig. 8). The additional amount of electrical energy that is required for FCEV to cover the same transportation demand (fig. 1) is available for other uses in the BEV case and can be deployed to increase the benefit from Power2Gas and Grid storage for the community.

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[16] This could change with SOFCs, which however have the disadvantage that they are not as well suited for dynamic operation as PEM fuel cells.

fruitful technical discussions. We would all like to thank the BMW Group and the Global Climate and Energy Project at Stanford University for their support of this project. The results of this work do not necessarily reflect the view of the BMW Group or Stanford University.

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