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Exploring the Feasibility of Battery Electric and Fuel Cell Electric Vehicles as Peaker Plant Substitutes at Low Wind and Irradiation Conditions

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Abstract

In this paper a comparison between the use of Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs) to span cold dark doldrums ("Dunkelflaute") in a future energy system with a high penetration of renewable energy supply is presented. A big problem with the cold dark doldrums is the rareness of the situation. Any power plant built to specifically be used during those special weather conditions will be operated only 0.1 % of the time according to a study on the energy demand in Germany in 2050 Aurora (2021) even though 10 GW are required to meet the demand. A prototype FCEV docking station to measure power transfer efficiencies was built. By this, we investigated supplying a district with energy via FCEVs by simulating a district with varying amounts of BEVs present. It is possible to supply a district with a low number of FCEVs although a stationary hydrogen connection would be beneficial. The efficient transfer of energy from a FCEV to a building requires a careful design of the plate heat exchangers and depends on the temperature level of the supplied building.

Keywords: mobile CHP, fuel cell vehicles, power supply, cold dark doldrums

1. Introduction

As the penetration of renewable energy sources increases, the need for flexibility in the electricity grid becomes more demanding. With the transition from fossil fuels, such as natural gas and oil, to more sustainable options for heating like heat pumps, electricity demand is expected to rise during cold periods. A study conducted by Aurora (2021) predicts a difference of 10 GW in peak power generation demand for a year with low wind and PV generation, i.e. a cold dark doldrums (cold "Dunkelflaute") condition, compared to an average weather year in Germany by 2050.

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This demand cannot be met by traditional load shifting methods alone, but needs expensive peaker power plants (which only operate a few hours a year) or multi-purpose facilities.

One potential strategy for these energy systems is the integration of Battery Electric Vehicles (BEVs) with bidirectional charging functionality for households and heat pumps investigated by Tiedemann (2022). This approach leverages the energy stored in BEVs to meet increased demands for electricity and heat. An alternative solution involves the use of Fuel Cell Electric Vehicles (FCEVs) to convert stored green hydrogen into both, electricity and heat. The FCEV solution benefits from access to chemically stored energy in the form of hydrogen, whereas BEVs rely on available energy that is already stored in the battery, and would be limited in situations with a lack of renewable energy generation. These dual-use cases of vehicles have the added benefit of increasing the energy system's resilience, while, in the case of FCEVs, at the same time the waste heat of hydrogen reconversion can be utilized for an increased overall efficiency.

2. Methodology

For the determination of thermal and electric energy transfer efficiencies from an FCEV to a building energy system, a docking station prototype was set up in the laboratory of the German Aerospace Centre in Oldenburg. The docking station can be seen in Figure 1, key components are marked in roman numerals with description in the following text. The thermal setup includes a plate heat exchanger (PHE), ultrasonic and magnetic-inductive flow sensors, temperature and pressure sensors, valves, and pumps. These components are used to transfer thermal energy from the FCEV's high-temperature cooling circuit to a thermal sink via a set of independent circulation systems (I) and a heat storage water tank (II). The electrical components include a DC power connector (III), a DC switch, and a DC sink, which are used to transfer direct current out of the FCEV and to control the power output. All sensor data is displayed in real time (IV). Measurements at different DC-power output levels and cooling inlet temperatures were performed, a detailed description of the setup can be found in Tiedemann (2023).

Furthermore, the use of regenerative FCEVs supplying a neighborhood was simulated in the Python framework OEMOF, which optimizes energy flows in a cost-controlled manner. The virtual neighborhood considered in the simulation consists of 19 buildings, inhabited by 252 persons, with the different types of residents determined from statistical data (e.g. working dayshift, working nightshift, retiree). Electric and thermal load profiles of each building were generated for a time period of one year, considering the individual behavior of the residents using the software "LoadProfileGenerator". Heating load in this simulation is set at 25 kWh/m²/a for comparison reasons, which is lower than the heating load used in a prior publication from Tiedemann (2022), because we wanted to simulate a district with improved average insulation. The simulations examine different scenarios, including scenarios with increasing numbers of BEVs used by the residents, leading to a higher demand of electricity for charging, based on an average commuting distance in Germany and an average BEV consumption of ~170 Wh/km. A detailed description of the simulation setup can be found in Tiedemann (2023).

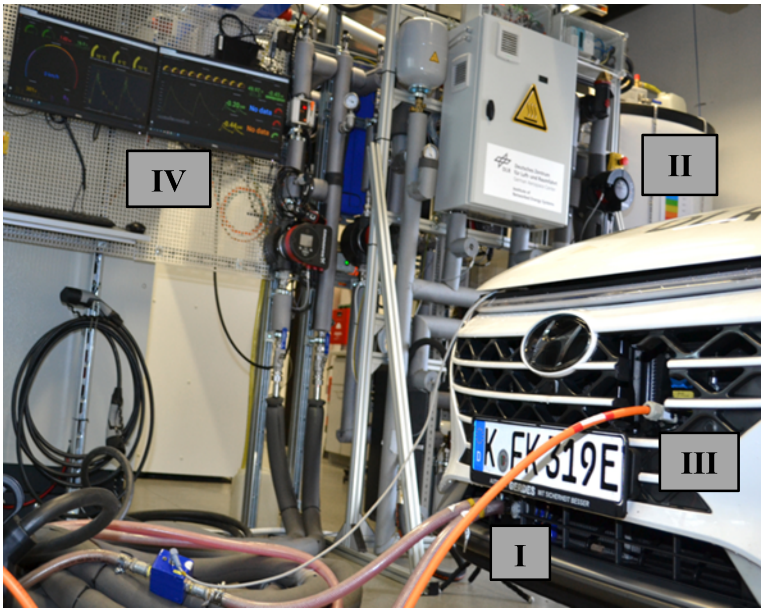

Figure 1: Prototype of the FCEV Docking Station. The vehicle is thermally coupled via hose connectors (I) to a stratified water tank (II) and electrically via a DC-connector (III). Measurement data is displayed in real time (IV).

3. Results and Discussion

3.1. Transfer Efficiencies of Heat and Electricity

In order to experimentally evaluate the transfer efficiencies for heat and electricity, DC sinks were used to transfer electrical power from the docking station at different power levels ranging from 1 kW to 9 kW. While delivering power we used the PHE of the FCEV to withdraw the heat to a storage tank of the docking station. The temperature of the coolant going into the PHE in the FCEV is crucial to the amount of thermal energy that can be withdrawn. 20, 40 and 50 °C coolant temperatures were used in order to simulate different heating demands. A building with bad insulation and old radiators will need a higher temperature than 50 °C to be able to supply heating. The model Hunday Nexo is limited to 60 °C in the fuel cell cooling circuit although optimum working temperature of the fuel cell stack should be around 65 °C. The cars radiator is programmed by the manufacturer to switch on when reaching that temperature, transferring excessive heat to the ambient.

The heat that can be transferred from the fuel cell will be at a low temperature levels well below 50 °C (especially when used at high electrical output). Therefore, the optimum use cases are at well insulated houses with space heating. For supplying higher temperature levels, an additional heat pump has to be utilized that can be operated by the supplied electrical energy as well.

The temperature and hydrogen tank pressure was measured constantly while using the docking station to determine the hydrogen consumption during the experiments. The equations to calculate the amount of hydrogen used can be found in Tiedemann (2023). The resulting net electrical efficiencies started at approximately 35 % at 1 kW electrical power and saturated at slightly more than 50 % efficiency for electrical power outputs of 5 kW or more regardless of external cooling temperature. The lower efficiency at lower DC outputs is related to losses caused by auxiliary electric consumers and units, like the air compressor, fuel cell electronics, and DC to DC conversion losses due to the fact that the fuel cell is operated in a pulsed mode at a minimum of 9 kW electrical output. Electrical power output at low power levels is therefore mainly supplied by a high-volt buffer battery whose state-of-charge will determine the duty cycle of the fuel cell. Not included are additional conversion losses that will occur when the DC power supplied by the FCEV is converted to AC for use in household appliances. This additional DC to AC converter, needed to supply the building, is one of the main components of an integrated docking station next to the heat transfer components and possibly a heat pump for higher temperatures.

While looking at the heat transfer efficiency at $T_{coolant}$ = 20 °C docking station coolant temperature, a net thermal efficiency of slightly above 50 % at 1 kW electrical output decreasing to approximately 35 % at 9 kW electrical output was measured. The two efficiencies combined result in an overall efficiency of close to 90 % with a peak of 95 % at 5 kW electrical output. Detailed tables of additional measurments can be found in Tiedemann (2023). With the same argument as before, overall efficiency should increase at higher loads because the amount of parasitic losses should remain almost constant. For higher coolant temperatures parasitic losses increase: The average thermal efficiency for $T_{coolant}$ = 20 °C is at 42 % whereas the average efficiency for $T_{coolant}$ = 40 °C is at 23 % and 18 % for $T_{coolant}$ = 50 °C.

To prove the initial estimation of increased losses due to cooling by the radiator of the FCEV, the thermal components and calculated heat transfer efficiencies based on temperature differences between external and internal coolant, plate heat exchanger surface area and mass flow were simulated. Figure 2 shows a variation of PHE surface area (number of plates), pump speed in rpm and internal coolant mass flow in kg/s. At higher DC loads and higher external coolant temperatures of e.g. 50 °C, a larger PHE surface area and mass flow is needed to remove enough heat to avoid triggering the use of the radiator of the FCEV, loosing heat to the exterior. As shown in figure 2, with the boundary conditions set for the simulation, a maximum of 71 % (10.4 kW) of the heat can be transferred. To find conditions for 100 % heat transfer, we looked at conditions outside our simulation parameters: An increase in the temperature when the radiator switches on to 70 °C, a transfer efficiency above 90 % can be reached with only 30 plates for the PHE (not shown in the figure). Careful dimensioning of flows, cooling temperatures and PHEs is therefore key to reaching overall efficiencies above 90 % at higher DC loads when designing a docking station for a FCEV.

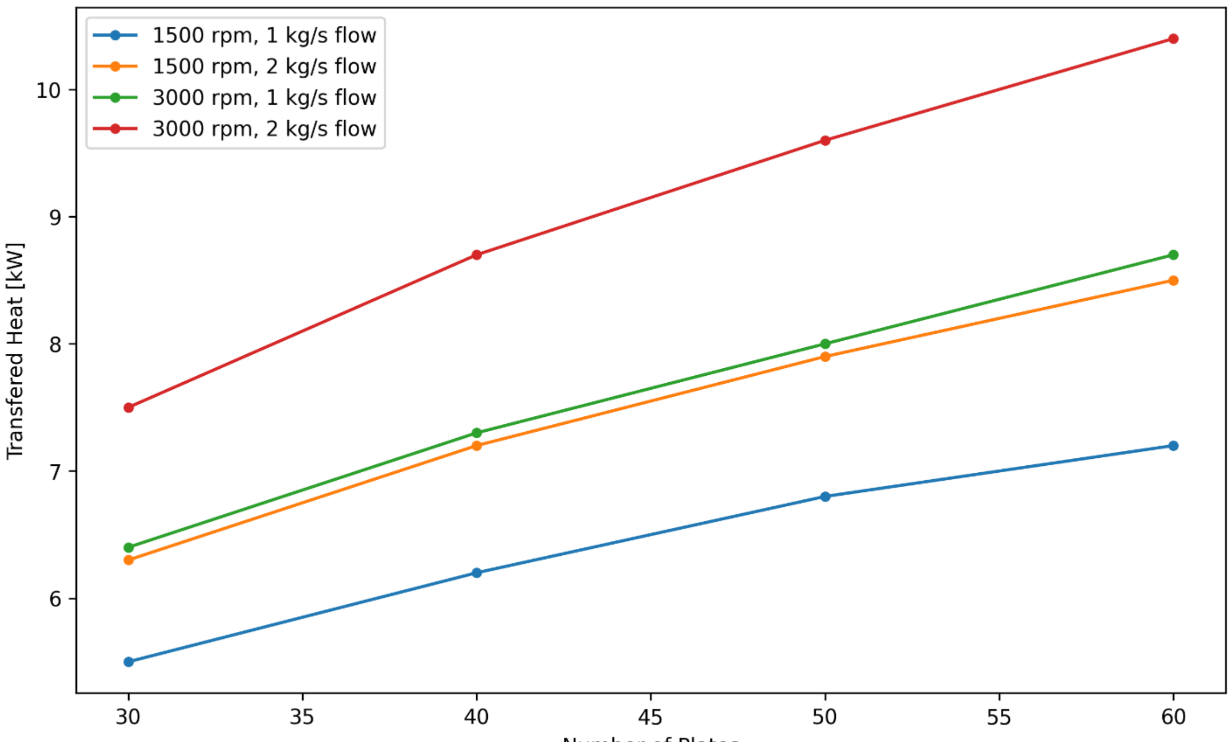

Figure 2: Simulated Heat output for different PHE sizes at 30 kW electrical load and 50 °C external coolant temperature

3.2. Distributed Backup Power Plants

In a future energy system with a high penetration of decentralized wind and photovoltaic power plants a method of supplying energy for wind lulls in winter will be needed. With the planed shift in Germany from oil and gas heating to electricity-based heat pumps, a power supply source has to be available for the few days every couple of years where no renewable energy generation is available and the energy demand is high due to cold outside temperatures. At utilization hours of 9 h in average a year, an oil peaker plant would require 9 k€/MWh to finance itself Aurora (2021). 10 GW is still an optimistic estimate since the average residual load was above 72 GW for two weeks in 2006 and 2012 Brainpool (2017).

Different and more sustainable options would be to use stored surplus renewable energy or imported green hydrogen. Instead of curtailing surplus wind energy for example, it could be converted to hydrogen via electrolyser and stored in salt caverns. In times of insufficient energy supply by renewable sources, the hydrogen could be used in cheap gas turbine peaker plants adjacent to the caverns.

An even better way to provide backup power for the cold dark doldrums would be to use decentralized machines, which are used for a different purpose the rest of the year. One option would be to use the remaining charge stored in all the electric vehicles available at that time. With the advent of bidirectional charging it is reasonable to create a scenario where bidirectional BEVs feed their remaining stored power to the grid, incentivized by high tariffs. To reach 10 GW as a distributed power plant, one million BEVs feeding in with 10 kW of electricity would be needed – a reasonable assumption for residential wallboxes. In 2030, the German government plans to have 7 to 10 million electric vehicles (including PHEV) registered BMuV (2023). At least 20 million BEVs by 2050 as a conservative estimate for calculations can be extrapolated from that. To span cold dark doldrums of 14 days that will occur every two years in average Brainpool (2017), approximately 3.4 TWh of backup power supply is needed. Distributing that to the 20 million BEVs would mean a required remaining charge of 168 kWh in every single BEV. Even with double the amount of BEVs the required charge would still be at an unreasonable level of 79 kWh. Additionally, using the total charge remaining in the battery would mean no mobility of those vehicles for 14 days. Therefore, bidirectional BEVs can be a small part of a distributed power plant at best and their future bidirectional capability will probably be employed for short-time grid services like peak-shaving and maximizing own-consumption of renewable energy. Satisfying mobility demands with BEVs requires constant electric energy input.

The second option would be to couple the sectors transportation, heating and energy by using FCEVs connected to districts in order to reconvert the stored hydrogen to electricity and heat. This decentralized option has the added benefit of usable waste heat contrary to the solution of using gas turbines close to the few salt cavern storage facilities. A simulation to evaluate this solutions potential was performed, challenges of this method will be addressed in section 4.

In order to simulate supplying a district with heat and electricity, the beforementioned docking station to measure transfer efficiencies was built. With those validated efficiencies, the model of Tiedemann (2022) was improved. The ”LoadProfileGenerator” (LPG, V10.4.0.40) Pflugradt (2022) was used to generate a district of 19 buildings inhabited by 252 people of representative age and occupations for Germany based on data from 2019. With the changes in the amount of work from home, which is now possible due to covid, future simulations should incorporate more “retired” people because that category of people generate a load profile closer to “work from home” occupants that were almost not existent in Germany before. The location and weather used to generate the profiles was set at Hamburg in the year 2007. More details on the composition of the district can be found in Tiedemann (2023). The generated load profiles were fed to the Python modelling framework OEMOF, where the heat and electricity transformation efficiencies that were obtained with the docking station were used to represent FCEVs supplying the district in the model. In this research, the amount of BEVs used by the people working in the district were varied from 0 to 75 %, since that is a main factor for electricity consumption besides the electricity needed for heat pumps. The simulation results show, that using the waste heat of the fuel cells to supplement the heat generation with heat pumps can reduce the electricity demand by 14 % regardless of the amount of BEVs present. The required amount of stack power (and therefore number of FCEVs) is dependent of the amount of charging BEVs and varies at night (when most BEVs will be charging) from 80 kW where no BEVs are present in the district to 170 kW at 75 % interspersion. With the rated nominal continuous electric power output of 32 kW of the before mentioned Hyundai Nexo, only 6 vehicles at maximum are needed to supply the district. The required stack power during daytime is constant at around 145 kW regardless of interspersion with BEVs. The daily demand of hydrogen varies from 78 kg with no BEVs present to 100 kg with 75 % of vehicles being BEVs.

3.3. Using Hydrogen in Agriculture for Backup Power Infrastructure

While the shift from internal combustion engine (ICE) passenger cars to more sustainable modes of transportation is dominated by BEVs, there is certainly a case for other types of vehicles. Because there is an upper weight limit for trucks, it makes more sense to use a fuel cell instead of filling the limited weight capacity with batteries. Future self-driving capabilities will reduce the availability of trucks for backup power plant operations even further.

Agricultural machinery like harvesters and tractors on the other hand have a lot of advantages for this use case. Most of the machines are not in use during the relevant time period. A significant portion of farms are already energy suppliers with large photovoltaic (PV) arrays on barn roofs. Since farmers were early adopters of photovoltaic technology (called “energy farmer” in Germany) many plants reach the end of the 20-year subsidy contract with the German government and are therefore looking for new applications of the PV energy. One possible way to go with the energy would be to produce and store hydrogen. With agricultural machinery running on hydrogen this would enable the farmers to reduce the carbon footprint of their agricultural produce. With large PV inverters already present, input for the inverters could be switched from PV to the fuel cell electric harvester or tractor while using the waste heat of the fuel cell in greenhouses or barns. Waste heat usage could be done as easy as parking the machine in the greenhouse during operation. The additional infrastructure requirements for operating agricultural machinery as backup power plant can therefore be quite low.

There are around 30 000 new tractor registrations every year in Germany Statista (2023). With an average power output of 300 kW, a potential 9 GW of backup power could be added each year in case those were FCEVs. The higher investment costs for the FCEV could be returned by offering its grid service capacity on the spot market. If energy farmers offer their capacity at a quarter of the beforementioned price of 9 k€/MWh, 2.25 k€/MWh (to get an offer at cold dark doldrums before costly fossil peaker plants) a FCEV tractor with 300 kW output could convert hydrogen into 100 MWh of electricity over the course of the 14 days doldrums. That would result in an income of 225 k€ every two years for the energy farmer. With the efficiencies obtained with the docking station, that relates to 200 MWh of hydrogen or roughly 6000 kg at 33.3 kWh/kg. An electrolyser running at 70 % efficiency and an input of 150 kW would produce around 2 kg/h of hydrogen, with roughly 2000 sun hours a year it is feasible for a farmer to produce that amount by himself. Challenges are compression and large-scale hydrogen storage at high pressures. Because weight is not a concern for storage in application scenario, metal hydrides could be used to store that amount of hydrogen safely Depken (2022). Because there is no need to compress the hydrogen for static grid service operation, there would be no need for a compressor. For storage in a compressed state at 350 or 700 bar on the other hand and to be able to fuel vehicles a compressor would be needed. Metal hydrides could be used to find a solution, since it is also possible to build a compressor von Colbe (2019) which has no moving parts and could be built at a small scale since the amount of daily hydrogen compression is rather small.

4. Conclusion

Future high penetration of renewable energy production will require flexibility options on a GW scale. There are three options to span cold dark doldrums:

1. Use existing fossil fuel peaker plants
2. Store green hydrogen from surplus renewable energy production in caverns and reconvert the hydrogen with gas turbines as needed
3. Use FCEVs to decentralize green and flexible hydrogen reconversion

A decentralized reconversion would enable the use of the waste heat that is lost with option two. Leftover battery capacity in BEVs is not sufficient to buffer the amount of energy needed to span those doldrums. Especially since mobility with the BEVs would not be possible any more in this time. We successfully connected a FCEV to a prototype docking station and measured a hydrogen to electricity transfer efficiency of about 50 %. With careful design of the heat transfer system and an optimized operation scheme, combined efficiencies above 90 % can be reached for the conversion and transport from hydrogen to electricity and heat to the building.

A simulation of the energy supply of a district with FCEVs during cold dark doldrums showed a reduction of 14 % in required electricity because of use of the fuel cell waste heat. The amount of charging BEVs has a big impact on the energy requirements. With 75 % of the working people owning BEVs, ~20 % more hydrogen is needed compared to no BEVs present in the district. Hydrogen supply is a big challenge of this backup power plant idea, requiring multiple trips of each FCEV to a refuelling station every day: The tank capacity of the Hyundai Nexo for example would require at least 13 trips to a refueling station for the 78 kg of hydrogen not considering the amount of hydrogen used for the trip itself. A stationary connection of the FCEVs or vehicles with larger tanks would therefore be required for an increased feasibility of this approach. In addition, a docking station for each FCEV has to be build where the car is connected electrically (requiring an inverter) and thermally, making modifications of the building and car necessary.

Because passenger fuel cell car sales are not accelerating in comparison with ICE and BEV passenger car sales and adding a thermal connection, an inverter and at best a stationary hydrogen supply of high purity required for fuel cells is a lot of investment, other types of FCEVs might be a better option. Agricultural machinery could step in because of their typical idle times during winter. Also, large PV plants are often already present for hydrogen production and also PV inverter connection capacity during the winter. Selling flexibility could be a viable option for farmers in the future. The latter topic needs further investigation and research. In general, the success of such applications is very dependent on electricity market design and subsidies provided by the governments.

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