Fuel cell electric vehicle to grid & H2

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Fuel Cell Electric Vehicle to Grid & H_2: Balancing national electricity, heating & transport systems

A scenario analysis for Germany in the year 2050

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***Abstract*— In a 2050 fully renewable national electricity, heating and road transport system primary energy supply comes from non-dispatchable power generation such as solar and wind energy. Both negative and positive dispatchable balancing power plants need to balance the system. This work investigates whether parked and grid connected (Vehicle-to-Grid) Fuel Cell Electric Vehicles (FCEVs) fueled with pure hydrogen can replace positive dispatchable balancing power plants. These power plants, often gas turbine based, are likely to operate at low capacity factors in future. A simulation for a 2050 scenario is based on German 2015 renewable electricity data and assumes a passenger car mix of 40% FCEVs and 60% Battery Electric Vehicles. On average 0.9 million FCEVs with Vehicle-to-Grid (V2G) output of 10 kWe would be required during evening and night time and approximately 6 million during the annual peak shortage hour to balance the system at all times. These numbers represent respectively 2% and 14% of the total 2015 German passenger car stock and have the potential to replace all positive dispatchable power plants in future.**

Keywords—component; hydrogen, fuel cell electric vehicles, vehicle-to-grid, energy storage, demand response heating, national energy systems

I. Introduction

In a 2050 fully renewable national energy system, where primary energy supply mainly comes from non-dispatchable power generation such as solar and wind energy, negative and positive dispatchable balancing power plants need to balance the system. A scenario analysis for the year 2050 of the German national energy system with a 90% reduction of energy-related CO_2 emissions compared to the reference year 1990 by Fraunhofer et al. [1] shows that 175 GW and 108 GW of negative and positive dispatchable power plants are required to balance 536 GW of solar and wind electricity.

When positive dispatchable balancing plants are already switched off, temporary net surplus electricity from solar and wind needs to be absorbed by the negative dispatchable powerplants. 175 GW of electrolyzers act as negative dispatchable power plants and produce hydrogen as a transport fuel for Fuel Cell Electric Vehicles (FCEVs) or as a source for synthetic methane to power the positive dispatchable gas turbine based powerplants [1]. Hydrogen can be stored in tanks at hydrogen fueling stations and in salt caverns for seasonal energy storage [2,3].

Positive dispatchable Open and Combined Cycle Gas Turbine (OCGT and CCGT) power plants are able to respond to the intermittent behavior of the renewables. According [1], 59 GW and 49 GW of OCGT and CCGT power capacities need to be installed, having capacity factors lower than 18 % and 3 % respectively. Avoiding low capacity factors of power plants results in lower system cost [4,5].

Could parked, temporary unused and grid connected (Vehicle-to-Grid, V2G) FCEVs and fuelled with pure hydrogen, replace positive dispatchable power plants?

Passenger cars in Germany are parked 96% of the time (capacity factor of 4%), as the average annual driven distance is 14,074 km per year at an average speed of approximately 45 km/h [6,7]. In Germany yearly 3.2 million passenger cars are sold and the total passenger car stock is 44 million [8,9]. Imagine 40% of these cars being FCEVs and having a V2G outlet of 10kW, (10% of the rated fuel cell power). This would result in an annual sold power capacity of 13 GW and a total stock capacity of 176 GW. The combination of fuel cell and battery makes it possible to deliver almost every kind of energy service [10], from balancing to emergency power back-up or primary reserve [10-12]. Hundreds of grid-connected FCEVs combined in parking lots could function as local power plants [13] and could balance entire cities [14].

FCEVs providing power to electric appliances (so called Vehicle-to-Load V2L), small grids or homes (Vehicle-to-Home V2H) [15] are developed by several FCEV manufacturers [16,17], first trials are performed with an FCEV connected to a low voltage national AC grid [18].

II. System Description

In this work a model is made to assess the usage of grid connected FCEVs in a future 100% renewable energy scenario for the following sectors; road transport, electricity, residential and services space heating and hot water, see Fig. 1. All final energy consumption is electric, electricity and hydrogen are the only energy carriers.

The model is based on the final energy consumption of electricity, space heating, domestic hot water and road transport energy of 1868 TWh in the year 2015, representing 76% of the 2015 Germany energy-related final energy consumption [19].

Considered energy sources are on- and off-shore wind, solar, hydro and biomass fueled Combined Heat and Power (CHP), all generate electricity. Electricity is consumed in industry, buildings for electrical appliances, heat pumps for space heating and domestic hot water and for charging BEV type passenger cars, vans, buses, trucks and motorcycles.

In case of a temporary surplus of electricity, electrolyzers convert surface or seawater into hydrogen. Hydrogen is produced, compressed and stored in the tanks for the cars, the hydrogen fueling stations or in salt caverns for seasonal storage. FCEV type passenger cars, vans, buses, trucks and motorcycles are fueled at the hydrogen station for driving or V2G balancing power in case there is a temporary shortage of electricity.

III. Modelling

The mathematical model is displayed in Fig. 2 and consists of an hourly and annual energy balance. First the hourly energy balance has to be met, either by converting surplus electricity into hydrogen or converting stored hydrogen into electricity. The net consumed hydrogen from the storage needs to be zero on a year basis. In case of surplus electricity, Hydrogen production, including purification, compression to 875 bar, chilling for dispensing at 700 bar, requires 49 kWh/kg H_2 in the year 2050 [1]. Conversion of 1 kg of hydrogen by a V2G connected FCEV results in 24 kWh of electricity [14,20].

A. Energy production

Renewable energy profiles are used from [21], except off-shore wind energy. Danish off-shore wind energy profiles are used from [22] instead of German off-shore wind energy profiles. The installed German off-shore wind power is still relatively low and increases during the year, therefore is not used. Renewable energy profiles from the year 2015 are scaled to the renewable energy generation mix of 2050, see Table I.

B. Electricity consumption in buildings

The so called 'classical electricity consumption', representing the consumption of electrical appliances was in 2015 510 TWh and is assumed to reduce by 25% to 375 TWh in 2050 [1].

The electricity consumption profile of heat pump systems used for space heating and domestic hot water is based on the annual heat demand taken from [1] and scaled over the year by using Heating Degree Days.

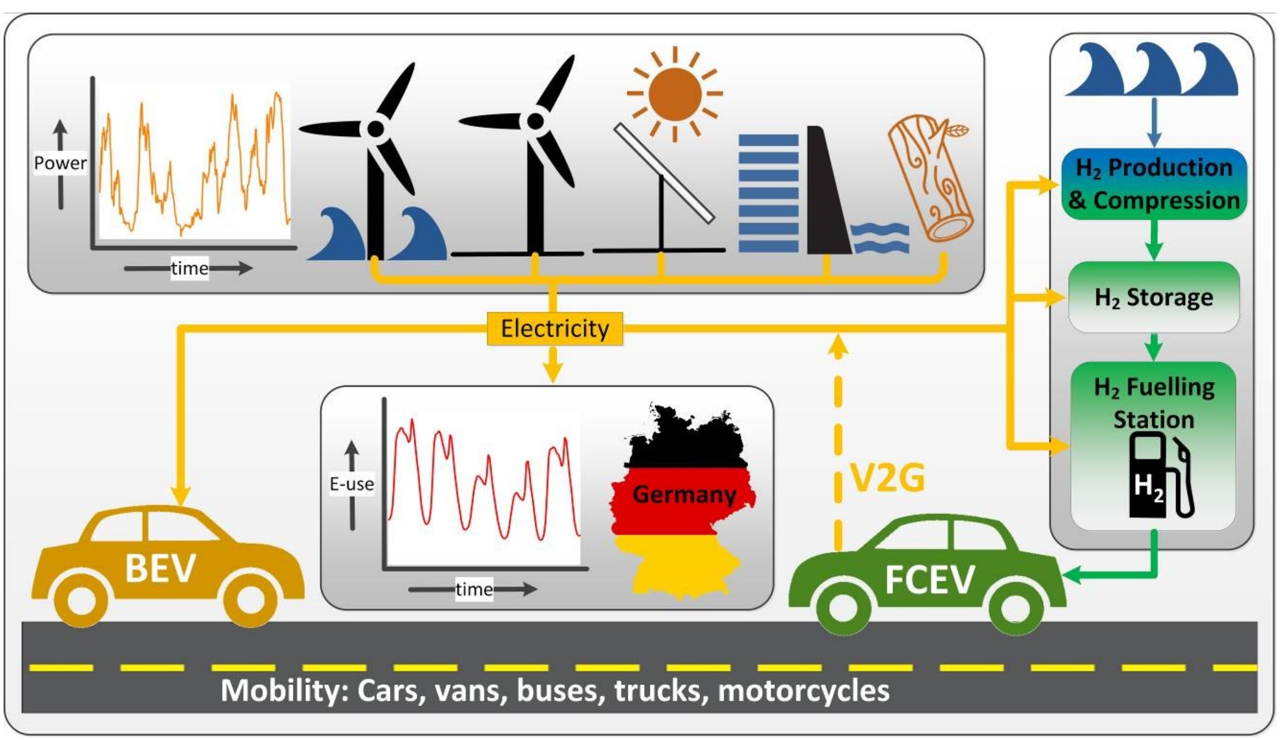

Fig. 1. System components and functioning.

Above 16°C, heating is switched off. Heat pump systems have a combined seasonal coefficient of performance (SCOP) of 3.5 [23]. This results in an annual electricity consumption of 126 TWh. The heat pumps can buffer up to one day of heat requirement in in-building hot water tanks by using temporary surplus electricity, so-called demand response heating. The 81 TWh solar thermal energy is not included in the hourly electricity balance.

C. Road transport energy consumption

Road transport energy consumption is defined using the fraction of FCEV and BEV type vehicles and their annual driven kilometers and vehicle fuel economies, see Table II and III. The fraction of FCEVs and BEVs is based on the hydrogen scenario in [1]. The annual driven kilometers are taken from [6]. Table III shows the number of vehicles in 2050, assumed to be equal as in the year 2015 [9]. 2050 Vehicle fuel economies in Table III are based on [14,20,24-26].

TABLE I. RENEWABLE ENERGY SOURCES

Energy source	***Electricity Generation Mix 2015 (%)***	***Electricity Generation Mix 2050 (%)***	***Installed Capacities 2015 (GW)***
On-shore wind	39	48	41
Off-shore wind	5	20	3.4
Solar	21	26	39
Hydro	10	2	5.6
Combined Heat & Power	25	5	7.0
Total	100	100	97

TABLE II. ANNUAL DRIVEN KILOMETERS PER VEHICLE TYPE

Vehicle Type	***Annual driven kilometers ($\times 10^3$km)***	***Fraction[a] driven km by FCEV (%)***	***Fraction[a] driven km by BEV (%)***
Passenger cars[a]	618,719,113	40	60
Vans	42,568,861	60	40
Small trucks (lorries)	16,365,863	80	20
Large trucks	18,702,129	100	0
Buses	4,378,189	70	30
Motorcycles	9,611,548	50	50

[a.] The fraction of driven kilometers per vehicle type is equal to the numbers of vehicles for each type.

TABLE III. NUMBER OF VEHICLES AND FUEL ECONOMIES

Vehicle Type	***Number of vehicles ($\times 10^6$)***	***Fuel Economy FCEV 2050 (kg H_2/100 km)***	***Fuel Economy BEV 2050 (kWh/100 km)***
Passenger cars[a]	43.962	0.6	15
Vans	2.196	0.9	21
Small trucks (lorries)	0.514	3.7	87
Large trucks	0.185	5.5	123
Buses	0.076	6.9	168
Motorcycles	4.175	0.3	6

The BEV charging profile is constant throughout the day, similar as in [23]. The charging efficiency is 95% [1]. The hydrogen fueling profile is taken from [27].

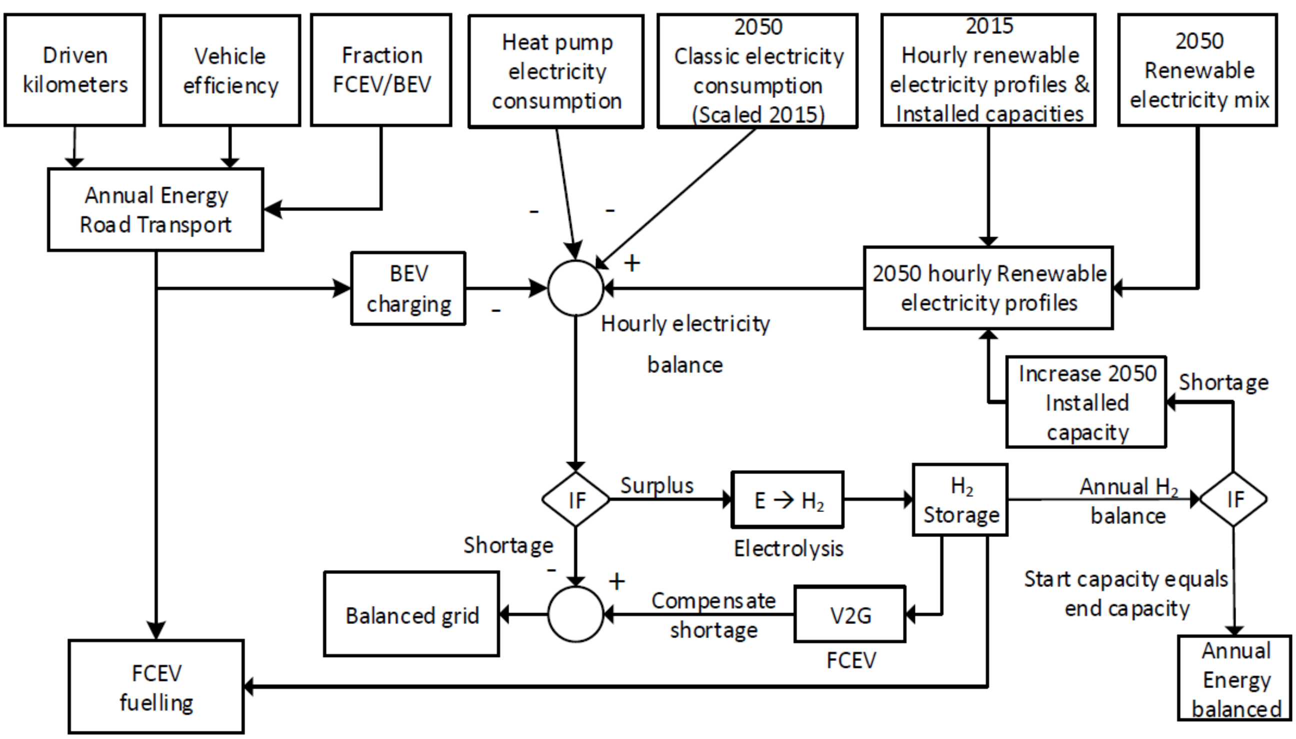

Fig. 2. Simplified representation of mathematical model.

IV. Results and Discussion

Annual energy balance

Fig 3 shows the annual energy balance. 811 TWh of renewable electricity is produced of which 63% can be consumed directly without the need of storing or converting it into hydrogen. 37% is converted via electrolysis into 245 TWh hydrogen (HHV basis). 55% of the produced hydrogen is used as transport fuel, whereas 44% is converted into 61 TWh electricity by FCEV passenger cars in V2G mode. This V2G electricity represent 11% of the total electricity consumption, consisting of the so-called classic electricity consumption, electricity for space heating and domestic hot water and BEV charging.

756 TWh electricity is produced by solar, on- and off-shore wind, 93% of all electricity produced. Solar produces 208 TWh, 26% of the total primary electricity production.

Heat pump systems convert 126 TWh of electricity into 440 TWh of heat. Solar thermal heat systems add another 81 TWh of heat resulting in a total of 521 TWh of heat for space heating and hot water.

Hourly energy balance

Fig 4 shows the electricity imbalance during the year. Highest negative imbalance occurs in the months October to February whereas the highest positive imbalance occurs during the months April to August.

In Fig 5 the electricity imbalance power is sorted from high to low, the imbalance load duration curve. The positive values represent the electrolyzers producing hydrogen (red) and the negative values representing V2G connected FCEVs converting stored hydrogen into electricity (blue).

Maximum power by grid connected FCEVs is 63 GW, producing 61 TWh balancing power. With a total available V2G power of 176 GW from FCEVs at 10 kW (10% rated fuel cell power), V2G capacity factor is only 4% and similar to the driving capacity factor of 4%. The 90% CO_2 reduction scenario from [1] predicted to need 108 GW power of positive dispatchable power plants.

Maximum electrolyzer power was 217 GW. These numbers are comparable with 175 GW electrolyzers in the 90% CO_2 reduction scenario from [1]. 308 TWh of electricity is converted into hydrogen by the electrolyzers, resulting in capacity factor of 16%. Peak electrolyzer capacity could possibly be reduced by applying smart charging of BEVs or exporting electricity to neighboring countries.

[1] Shows that for higher CO_2 reduction scenarios, higher electrolyzer and positive balancing plant power are required. Although this model did not contain the industrial heating sector, it used only renewable energy sources and has a 100% CO_2 reduction for the modeled sectors. Also any temporary electricity surplus exchange with neighboring countries was not considered, which could have a balancing effect as well.

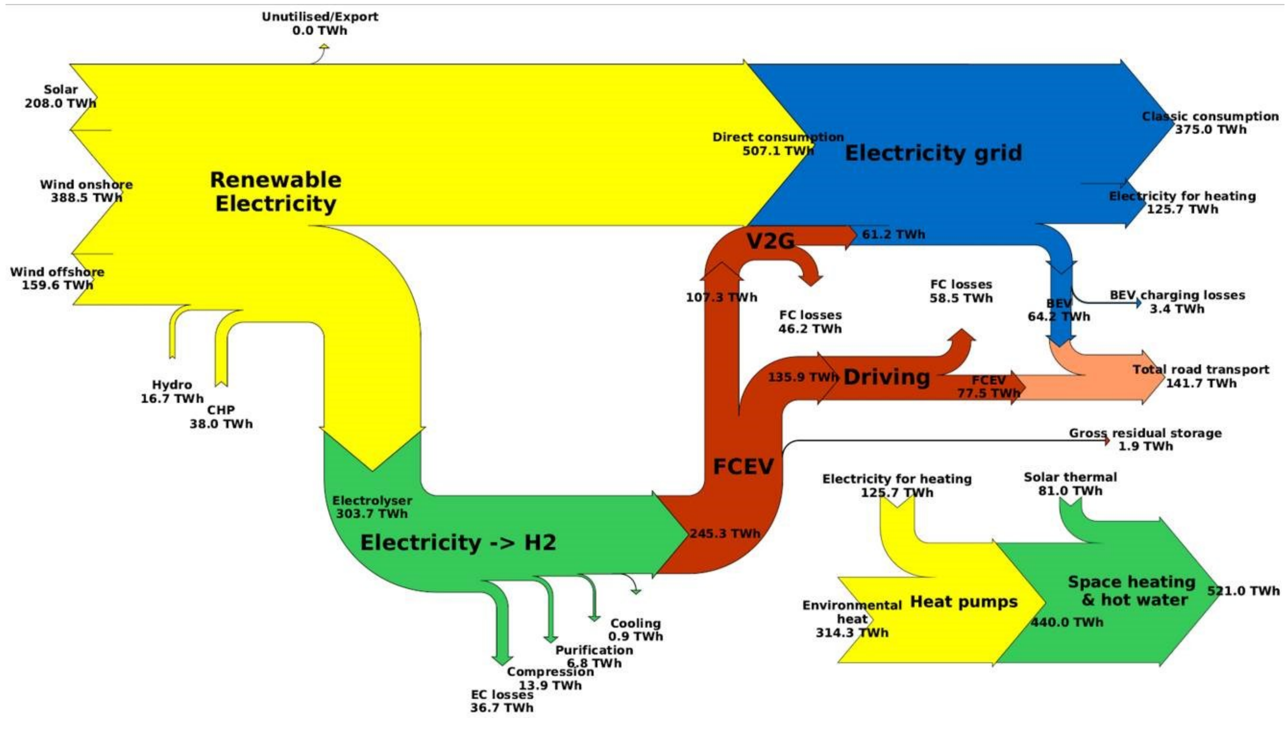

Fig. 3. Annual energy balance for a 2050 fully renewable electricity, heating and road transport system balanced with Vehicle-to-Grid Fuel Cell Electric Vehicles.

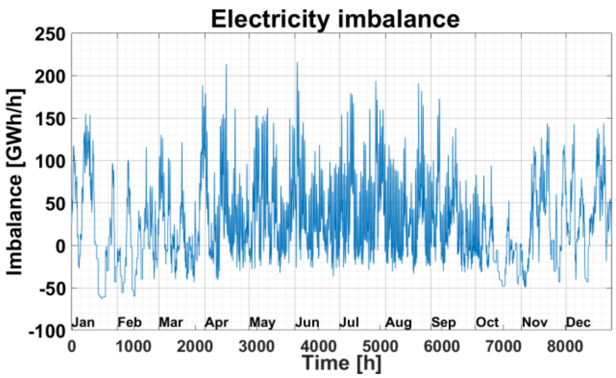

Fig. 4. Electricity imbalance during the year.

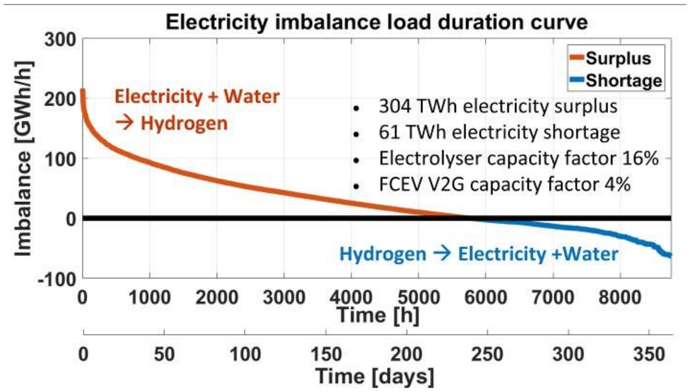

Fig. 5. Electricity imbalance load duration curve.

FCEV V2G power demand over the entire year is displayed in boxplots for every hour of the day in Fig. 6. The blue bars represent the 25-75 percentile (50%). The upper and lower whiskers represent another 44.3%. Red plusses indicate the outliers, the remaining 0.7%. Daily averages and means are displayed as black x marks and red lines in the blue bars respectively.

During daytime hours (9h-18h) next to wind, there is also a large amount of solar electricity. Clouds combined with the variability of wind energy can cause an imbalance and the need of balancing power from V2G connected FCEVs. On average less than 1% of the total passenger cars (0.5 million), are required during daylight hours (9h-18h). Although occasional peaks of up to 14% of the total passenger cars (6 million) can be seen. The modeled demand response heating contributes in reducing peak imbalance. In the evening (19h-24h) on average 2% of all passenger cars are required (0.9 million), with 21h being the peak hour. During the peak hour, 50% of the time up to 4% of all passenger cars are required (1.9 million), 99.3 % of the time 10% (4.5 million) with a maximum peak of 14% (6.3 million). From midnight to early morning (24h-8h) on average 2% of all passenger cars are required (0.9 million), with 6h being the peak hour. During the peak hour, 99.3% of the time up to 8% of all passenger cars are required (3.5 million). Largest amount of V2G power is required during the night and evening, the low and non-solar production hours. As most passenger cars are used for driving during day-light hours and less during the night, sufficient cars should be available at all times to balance the system.

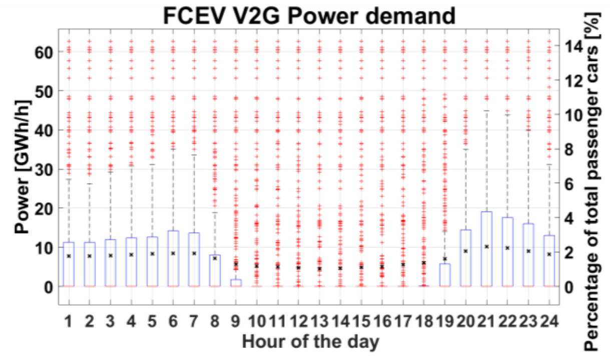

Fig. 6. FCEV V2G power demand during the year for every hour of the day.

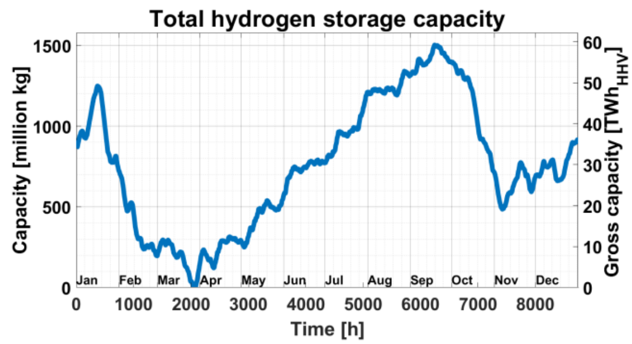

Fig. 7. Total required hydrogen storage during the year.

V2G power production is now limited at 10 kW per passenger car for FCEVs only (10% of the rated fuel cell power). Any increase, or when other vehicles such as vans are used, would result in an even lower V2G capacity factor. Using V2G connected FCEV vans, with each 10kW V2G, would add another 13 GW of available V2G power. Also BEVs could be used, but then more research is required into charging and discharging profiles with respect to driving profiles.

Fig 7. Shows the total hydrogen storage resulting from the net hydrogen production and consumption. Hydrogen can be stored in tanks at hydrogen fueling stations as well as in salt caverns [2,3]. At the beginning of the simulated year a start filling of approximately 860 million kg, 34 TWh Higher Heating Value (HHV) based is required. This increases to 49 TWh in end of January due to a high supply of wind energy. Storage level drops to 0 TWh end of March and then increases to 1500 million kg, 60 TWh in mid-September. Estimated total storage size is similar to the 101 TWh in [1] for the entire energy system and 29-90 TWh storage mentioned in [3] for Germany for seasonal storage and 60 day reserve.

V. Conclusions

In this work a fully integrated renewable energy system is made for a future 2050 scenario representing the electricity, space heating and domestic hot water and road transport energy sector of Germany. Energy consumption and production profiles of the year 2015 serve as an input to the hourly simulation. The only energy carriers are electricity and hydrogen. There is no energy exchange with neighboring countries.

The final electric energy consumption is 568 TWh and is met by the production of 811 TWh of electricity. 26% is originating from solar, 68% from wind and the remainder by hydro and biomass fueled Combined Heat and Power.

Road transport vehicles such as passenger cars, vans, buses and trucks are either Battery or Fuel Cell Electric Vehicles (BEVs or FCEVs). The passenger cars represent the largest energy consuming category, of which 40% is considered to be FCEVs and 60% BEVs.

Solar thermal energy and electric powered heat pumps provide all space heating and hot water. In case electricity consumption and BEV charging consumption is met by the intermittent renewables, temporary surplus electricity is absorbed by negative dispatchable balancing power plants. 217 GW of these plants convert electricity and water via electrolysis into hydrogen. The hydrogen is used as a transport fuel or as electricity storage for times of shortage. The hydrogen can be stored in vehicles, hydrogen fueling stations and salt caverns for seasonal storage. Combined storage of up to 1500 million kg is required, 60 TWh on a Higher Heating Value basis.

Instead of using traditional and stationary positive dispatchable power plants in times of shortage electricity, here only grid connected FCEVs are used to balance the the system. Up to 63 GW of grid connected FCEVs are required during peak shortage hours. At 10% rated fuel cell power in grid connected mode, this would represent 6 million out of total of 44 million cars (14%). Largest amount of V2G power is required during the night and evening, the low and non-solar production hours, on average 2.5 million FCEVs are required (6%). These FCEVs can be fuelled with pure hydrogen produced in times of surplus electricity and in future can fully replace all dispatchable gas turbine based power plants.

ACKNOWLEDGMENT

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