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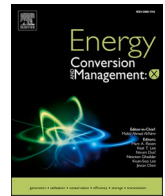
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Fuel cell electric vehicles and hydrogen balancing 100 percent renewable and integrated national transportation and energy systems

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ABSTRACT

Future national electricity, heating, cooling and transport systems need to reach zero emissions. Significant numbers of back-up power plants as well as large-scale energy storage capacity are required to guarantee the reliability of energy supply in 100 percent renewable energy systems. Electricity can be partially converted into hydrogen, which can be transported via pipelines, stored in large quantities in underground salt caverns to overcome seasonal effects and used as electricity storage or as a clean fuel for transport. The question addressed in this paper is how parked and grid-connected hydrogen-fueled Fuel Cell Electric Vehicles might balance 100 per cent renewable electricity, heating, cooling and transport systems at the national level in Denmark, Germany, Great Britain, France and Spain? Five national electricity, heating, cooling and transport systems are modeled for the year 2050 for the five countries, assuming only 50 percent of the passenger cars to be grid-connected Fuel Cell Electric Vehicles, the remaining Battery Electric Vehicles. The grid-connected Fuel Cell Electric Vehicle fleet can always balance the energy systems and their usage is low, having load factors of 2.1–5.5 percent, corresponding to an average use of 190–480 h per car, per year. At peak times, occurring only a few hours per year, 26 to 43 percent of the grid-connected Fuel Cell Electric Vehicle are required and in particular for energy systems with high shares of solar energy, such as Spain, balancing by grid-connected Fuel Cell Electric Vehicles is mainly required during the night, which matches favorably with driving usage.

1. Introduction

The future energy and transport system in Europe will and must become 100% renewable, with zero emissions [1,2]. Three major aspects dominate the transition toward this goal:

- A high share of electricity in generation but also in final energy consumption, as heating and transport shift to all-electric
- High shares of (low cost) intermittent electricity generation mainly from solar and wind
- Reliability of energy supply

Significant numbers of back-up power plants, as well as balancing and large-scale energy storage capacity are required to guarantee the reliability of energy supply in a fully renewable European energy and transport system. Additional back-up generation, energy storage and transmission requirements are driven by two key issues [3]. First, the shortage of dispatchable generation due to high shares of solar and wind

energy. Second, the surplus or deficit in overall generation. Many studies have demonstrated that the integration of high shares of renewable energy (up to 95%) into the European electricity sector is both technically feasible and affordable [4]. The literature [4,5] mentions two solutions to the above-mentioned key issues: 1) the coupling of electricity to other energy sectors, such as transport and heating, known as “sector coupling” [2]; and 2) the expansion of the power transmission network and its capacity; for example, through more and larger transnational [6] and transcontinental [7,8] power connections.

These solutions are limited to 100% renewable energy systems in a European context. In this respect, the impact of various hydrogen applications, in particular, have not been comprehensively researched in the design of 100% renewable energy systems [9,10]. However, hydrogen could play an important role in the industry and transport sectors, as well as in the provision of electricity, heat and energy storage [2,11]. Hydrogen can couple energy sectors and offer another solution in realizing 100% renewable energy systems by converting power to hydrogen, which can be used as a transport fuel and for energy storage in back-up power plants [9]. Recent research shows that in a system with

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Nomenclature

Abbreviation

BEV	battery electric vehicle
EU	european union
EUR	euro
FCEV	fuel cell electric vehicle
FCEV2G	fuel cell electric vehicle to grid
H ₂	hydrogen
h	hours
HHV	higher heating value
PEM	proton exchange membrane
PEMFC	proton exchange membrane fuel cell
USD	united states dollar
V2G	vehicle-to-grid

more than 70% intermittent renewable electricity, 10% or more needs to be converted into hydrogen [12].

Renewable hydrogen production will be cost competitive with fossil fuels in the near future, as renewable electricity and electrolyzer costs have reduced significantly [13,14]. Today, hydrogen is already being stored on a large scale in underground salt caverns [15], and this is a proven and cost-effective [16,17] storage method applicable in many countries [18–20]. Large-scale seasonal hydrogen storage also occurs in the form of ammonia, liquid hydrogen, Liquid Organic Hydrogen Carriers (LOHC) [21], or in depleted gas fields.

Present research on highly renewable European energy scenarios for 2050 use open cycle gas turbines (OCGTs) to balance the electricity grid [22,23], fueled by synthetic methane [4,24], bio-methane [25] or hydrogen [9,11]. These large, central and stationary power plants have low capacity factors of approximately 3.5% [24,25], thus contributing to higher total system costs [26,27]. The quick refueling of hydrogen, taking less than 5 min [28], makes FCEVs dispatchable generators similar to hydrogen-fueled OCGTs. An FCEV powertrain consists of a hydrogen-fueled Proton Exchange Membrane (PEM) fuel cell system and a traction battery. This combination makes it possible to outperform an OCGT (hydrogen fueled) on several parameters, such as maximum upward and downward ramp rate; hot, warm and cold start-up times [29–31]; and electrical efficiency, especially in part load [29].

Interest in the field of 100% renewable energy systems is growing [32], and no integrated transportation and energy systems are the same. Blanco et al. [33] reviewed more than 60 renewable energy system studies and made a clear distinction between “transition energy systems” (30–90% renewable energy) and “100% renewable energy system” studies. Current research agrees that the need for storage and balancing will increase significantly, with higher shares of variable renewable power sources (e.g., >80%) [22]. Increasing the share of variable renewable power sources beyond 90% will result in a sharp increase in balancing requirements [33–35]. Few studies have focused specifically on power to gas (P2G) or power to hydrogen (P2H) from an energy modeling perspective [33], and even fewer specifically look into V2G from a large system point of view. Most of the studies to date have included P2H [22,35], P2G [2,33,36,37] and/or V2G with BEVs [4,38,39] as one of the balancing or storage options, but they primarily focus on the energy system as a whole (or part), its transition pathways or overall system cost optimization.

Research by Oldenbroek et al. [29] has demonstrated that a hydrogen Fuel Cell Electric Vehicle (FCEV), the Hyundai ix35 FCEV [40], can be modified and connected to the electricity grid, so-called Vehicle-to-Grid (V2G). The same set-up also has been used to power a single house [41]. In this way, an FCEV can function as a rapid-reacting balancing and back-up power plant, known as a Fuel Cell Electric Vehicle to Grid (FCEV2G). As one car could power several houses [41],

thousands could be grouped together to power entire cities [42,43] and act as Virtual Power Plants (VPP) [44]. Millions of cars could likely replace large stationary balancing power plants in countries.

Mass production of automotive fuel cell systems will reduce costs to 40–60 USD/kW [45]. This is approximately ten times lower than the OCGT 2050 installed capital costs of 400 [4] to 600 [25] EUR/kW, with economic lifetimes of 25 [23,25,46] to 30 [4,5] years. With ultimate durability targets of 8000 h of automotive fuel cells [47], the economic lifetimes of these VPPs could also be over 20 years (400 operational hours per year).

The power capacity sold in passenger cars is enormous, with approximately 15 million passenger cars sold annually in Europe [48,49]. Imagine 50% of these cars being FCEVs and having only a V2G outlet power of 10 kW (10% of the rated fuel cell system power of an average FCEV). This would be the equivalent of an annual sold power capacity of 75 GW, much more than the total currently installed capacity of gas turbine power plants in Europe (approximately 15 GW [50]). Large fleets of future FCEV passenger cars with V2G outlet power have the potential to fully replace gas turbine power plants, especially because passenger cars in Europe are parked on average 97% of the time. In other words, they are used for driving only 3% of the time which, based on an estimate of the average annual driven distance of 12,000 km per year at an average speed of approximately 45 km/h [51], is less than 300 h per year.

Inspired by the concept of a green hydrogen economy [52–55], the question addressed in this paper is:

How might parked and grid-connected (Vehicle-to-Grid, V2G) hydrogen-fueled FCEVs balance 100% renewable electricity, heating, cooling and transport systems at the national level in Denmark, Germany, Great Britain, France and Spain?

To find an answer to this question for each of the five countries, this study designed integrated national electricity, road transport and heating systems based on renewable electricity production and hydrogen as an intermediate energy carrier. The energy balances were calculated for each of these countries. Both hydrogen fuel cell and battery electric vehicles were considered to be in use for road transport. In the energy systems designed, only fuel cell electric vehicle to grid (FCEV2G), electrolyzers and hydrogen storage were used for balancing.

In this article, first the methods and data used will be explained (Section 2), then the results and energy balances will be presented (Section 3). Subsequently, the results will be discussed (Section 4) and then the conclusions are drawn (Section 5).

2. Materials and methods

To analyze how grid-connected (Vehicle-to-Grid, V2G) hydrogen-fueled FCEVs could balance 100% renewable national electricity, space heating and road transport systems, energy systems are designed for several European countries that would be fully self-sufficient and 100% renewable. The systems are hypothetical in the sense that energy exchange with other countries is excluded, and to balance the energy systems, only fuel cell electric vehicle to grid is used, electrolyzers and hydrogen storage. First, several countries were selected and an analysis and synthesis of their existing energy scenarios for 2050 was undertaken. Data and insights gathered served as input for the adapted system design and the simulations; for example, any partial renewable energy mix in the existing energy scenarios was converted to a 100% renewable energy mix.

The adapted system designs consist of the electricity, heating and road transport sectors, with the road transport sector only consisting of battery and fuel cell electric vehicles, the heating sector relying on heat pump electric and solar thermal heating, and with all energy storage in the form of hydrogen. To address inter-annual variability effects of renewable energy production on seasonal hydrogen storage and balancing using FCEV2G, several years were simulated, as recommended by [56].

Table 1

Key figures for the selected countries 2015.

	DK	DE	GB	FR	ES	EU-28 total
Population (million) [76]	5.66	81.52	65.84 ¹	66.81	46.53	508.52
Final energy consumption (TWh) [77]	157	2568	1429	1824	912	13,042
Passenger cars (million) [49,78–82]	2.27	43.96	30.25 ¹	31.90	16.93	251.92
Number of petrol fueling stations [83]	2007	14,531	8494	11,269	10,947	109,041

¹ Figure for the entire United Kingdom (UK).

The design and analysis were performed in four steps:

- 1) Selection of countries, analysis and synthesis of their existing energy scenarios for 2050 (Section 2.1).
- 2) Adapted system design for a 100% renewable national electricity, heating and road transport system (Section 2.2).
- 3) Selection of the system components and technological characterization in a mid-century scenario ~2050 (Section 2.3).
- 4) Hourly simulation of all energy flows for multiple years for the selected European countries and sizing of the system components (Section 2.4).

2.1. Selection of countries

To verify the applicability of this concept to Europe, the analysis was applied to five European countries: Denmark (DK), Germany (DE), Great Britain (GB), France (FR) and Spain (ES). These countries already have

power-to-hydrogen sites in operation [12]; they have large-scale underground natural gas storage facilities [57]; and they have significant technical potential for hydrogen storage in salt caverns [20]. All five countries have energy scenarios for 2050 [37,58–64], and the required input data and the current hourly renewable electricity generation profiles were readily available [65–75].

Table 1 presents key figures for the five selected countries. These countries combined represent approximately 52% of the EU-28 population in 2015, 53% of the final energy consumption, 50% of passenger cars and 64% of petrol stations.

In this research, only the future energy demand is considered of the electricity, road transport, residential and commercial heating sectors. Which today represent approximately 75% of final energy consumption in the five countries [77]. Road transport in these countries represents, on average, 27%, residential and commercial heating 26%, and the electricity sector 22% [77]. Sectors such as industry and agriculture were not included, due to a lack of detailed information about energy use throughout the year, which makes it difficult to construct hourly consumption profiles.

2.2. System design

Fig. 1 presents an overview of the generic 100% renewable national electricity, heating, cooling and transport system design applied to each of the five countries modeled. In summary, in each system:

- Power is generated by renewable sources alone, the electricity generation mix is country specific but may consist of onshore and offshore wind power, solar photovoltaic (PV), Concentrated Solar Power (CSP), hydropower, biomass and waste Combined Heat and Power (CHP).
- Generated electricity is either directly consumed and transmitted via the electricity grid or used to produce hydrogen (H_2) via water electrolysis.

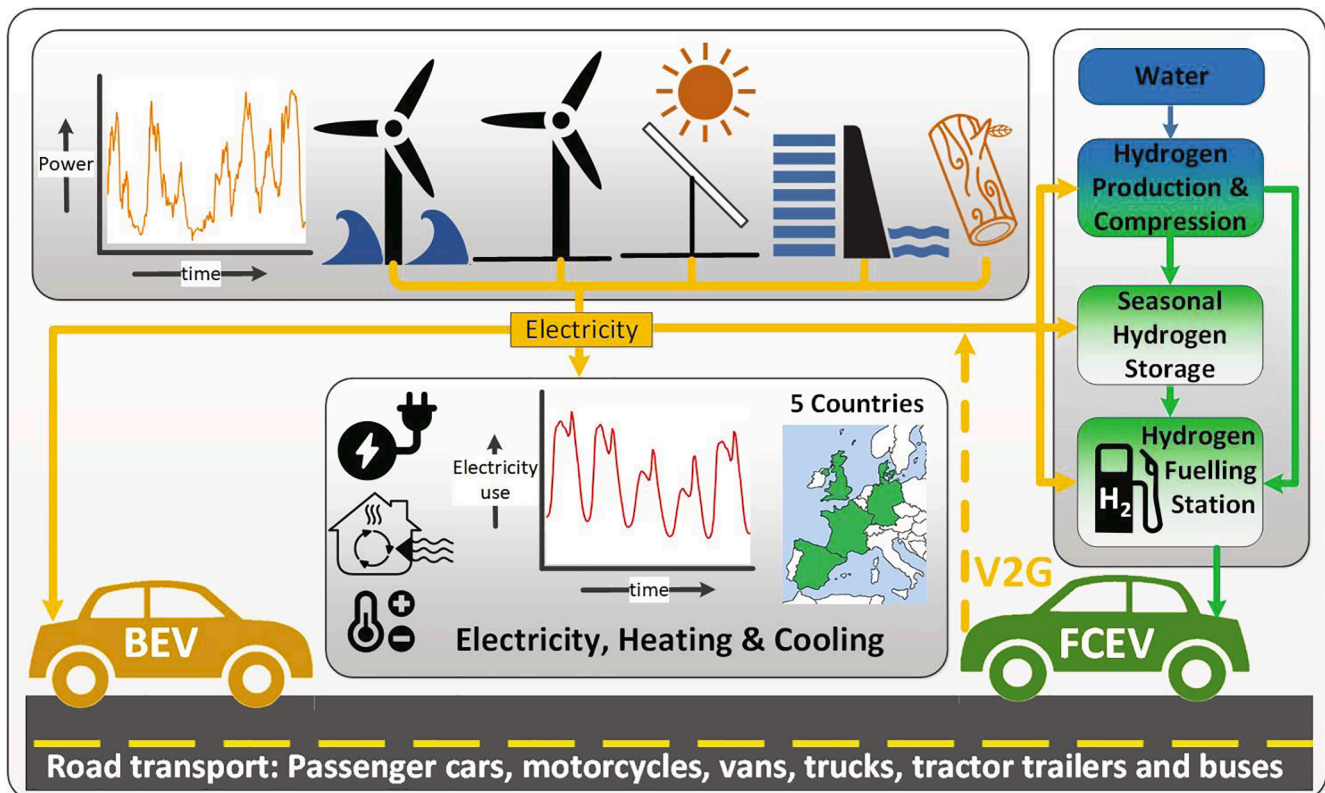


Fig. 1. Generic 100% renewable system design applied to the national electricity, heating, cooling and transport systems of Denmark, Germany, Great Britain, France and Spain. Fuel cell electric vehicle to grid (FCEV and V2G), electrolyzers and hydrogen storage provide all of the necessary balancing requirements.

Table 2

Road transport vehicle types and the share of annual distance traveled and specific energy consumption per vehicle type and technology in 2050.

	Distribution of annual distance traveled per vehicle type and technology in 2050		Estimated specific energy consumption vehicle type and technology in 2050	
	BEV	FCEV	BEV (kWh/km)	FCEV (kg H ₂ /100 km)
Passenger cars	50%	50%	0.15 [108]	0.60 [88]
Motorcycles	50%	50%	0.056 [109,110]	0.28 [88,109,110]
Vans	40%	60%	0.206 [110,111]	0.90 [88,110,112–114]
Trucks	20%	80%	0.818 [110,111]	3.70 [88,110,115]
Tractor trailers	0%	100%	–	5.50 [88,116–119]
Buses	30%	70%	1.61 [110]	6.90 [120–123]

- Road transport consists of passenger cars, motorcycles, vans, trucks, tractor trailers and buses. A combination of technologies is foreseen, including: Fuel Cell Electrical Vehicles (FCEVs) and Battery Electric Vehicles (BEVs) or Fuel Cell Hybrid Electric Vehicles (FCHEV).
- Only FCEVs connected to the grid (FCEV2G) are considered to provide balancing power to compensate electricity shortages.
- The hydrogen produced is either transported directly to the hydrogen fueling stations for road transport and re-electrification, or hydrogen is stored in seasonal hydrogen storage, such as underground salt caverns.
- From the seasonal storage, hydrogen can be transported through pipelines (converted natural gas pipelines or newly built pipelines, or via the road with tube trailer trucks).
- Heating in the residential and commercial sectors is supplied by solar thermal systems and electric heat pumps.

2.3. Technological characterization of system components

Renewable electricity is converted into hydrogen (H₂) through the electrolysis of water, which may be groundwater, surface or seawater, all demineralized through reverse osmosis. The energy use for the latter is included in the electricity consumption of the electrolyzer. Several manufacturers have designs available for large-scale alkaline electrolysis plants of up to 400 MW [84]. The electricity consumption on the basis of a produced kilogram of hydrogen for water demineralization [42,85–87], hydrogen production [88,89], drying and purification [90] at 30 bar is taken to be 47 kWh/kg H₂ and is assumed to be constant in this model. Further compression to 120 bar for either pipeline transport or underground hydrogen storage requires approximately 0.9 kWh of electricity per compressed and transported kilogram of hydrogen [91]. Further compression from the underground hydrogen storage pressure to the hydrogen fueling station storage pressure of 880 bar [91], including pre-cooling for hydrogen dispensing of 700 bar [92,93], requires about 1.4 kWh of electricity per kilogram of hydrogen. Summarizing, to produce hydrogen from water, approximately 49.3 kWh of electricity is required per kilogram of hydrogen dispensed at 700 bar. This includes the purification and demineralization of water and the production, drying, compression, storage, pre-cooling and dispensing of hydrogen. With hydrogen having an HHV of 39.41 kWh/kg [94], the estimated HHV energy efficiency in this study in 2050 of producing hydrogen from water and dispensing hydrogen at 700 bar is 80%.

Fuel cell systems in part-load have higher efficiencies than at full-load [95]. The 10 kW output per passenger car in FCEV2G mode corresponds to only a 10% load of the approximate 100 kW fuel cell system and results in high efficiency. In 2050, fuel cell system efficiencies of up to 60% on a Higher Heating Value basis (HHV) are foreseen [88]. This fuel cell system efficiency, to convert hydrogen back into electricity, results in 23.6 kWh of electricity production per kilogram of hydrogen

consumed.

Salt caverns can have geometric volumes of up to 1,000,000 m³, with operating pressures of up to 20 MPa and cushion gas ratios of approximately 30–50% [16]. For example, a salt cavern with geometric volume of 500,000 m³ has a net useable hydrogen storage of approximately 3733 ton H₂ (corresponding to 147 GWh, HHV based) [16].

There are various predictions of the vehicle technologies that will be in use in a zero or low emission 2050 road transport scenario [36–38,88,96–101]. For zero emission transport scenarios where only BEV and FCEV technologies are considered, and when reaching tens of millions of vehicles, a hydrogen fueling infrastructure demonstrates some clear advantages over a battery charging infrastructure [102]. Due to the widespread use of all vehicle types, a hydrogen fueling infrastructure is comparable to today's conventional system. Such infrastructure offers quick vehicle fueling and long refueling intervals, combined with the relatively cost-effective and high fueling capacity of hydrogen stations, which all contribute to lower infrastructure costs [102]. A hydrogen fueling infrastructure would also match well with large-scale seasonal energy storage in the form of hydrogen gas [16,20,103] and the re-use of natural gas infrastructure [9,103–107]. Robinius et al. [102] concluded that a hybrid strategy for the roll-out of both infrastructures would help to maximize energy efficiency and optimize the use of renewable energy resources, while eliminating CO₂ emissions over a broad range of purposes and transportation modes.

The distribution of annual distance traveled per vehicle type and technology in 2050 is presented in Table 2. The same distribution is used for all five countries. Table 2 also lists the estimated specific energy consumption per vehicle type and technology in 2050.

2.4. Calculation model and hourly simulation

Fig. 2 displays the simplified simulation scheme of the calculation model and consists of four major steps, executed hourly for an entire year.

1. Renewable electricity generation (grey, see description in Section 2.4.1)
2. Electricity consumption (green, see description in Section 2.4.2)
3. Road transport hydrogen and electricity demand (red, see description in Section 2.4.3)
4. Balancing electricity and hydrogen demand (blue, see description in Section 2.4.4)

As mentioned, the simulation is based on an hourly resolution performed for an entire year. The simulations were also repeated for several years to gain some insight into the annual variation of renewable electricity sources. At the time this study was conducted, four years of renewable electricity generation and electricity consumption data were

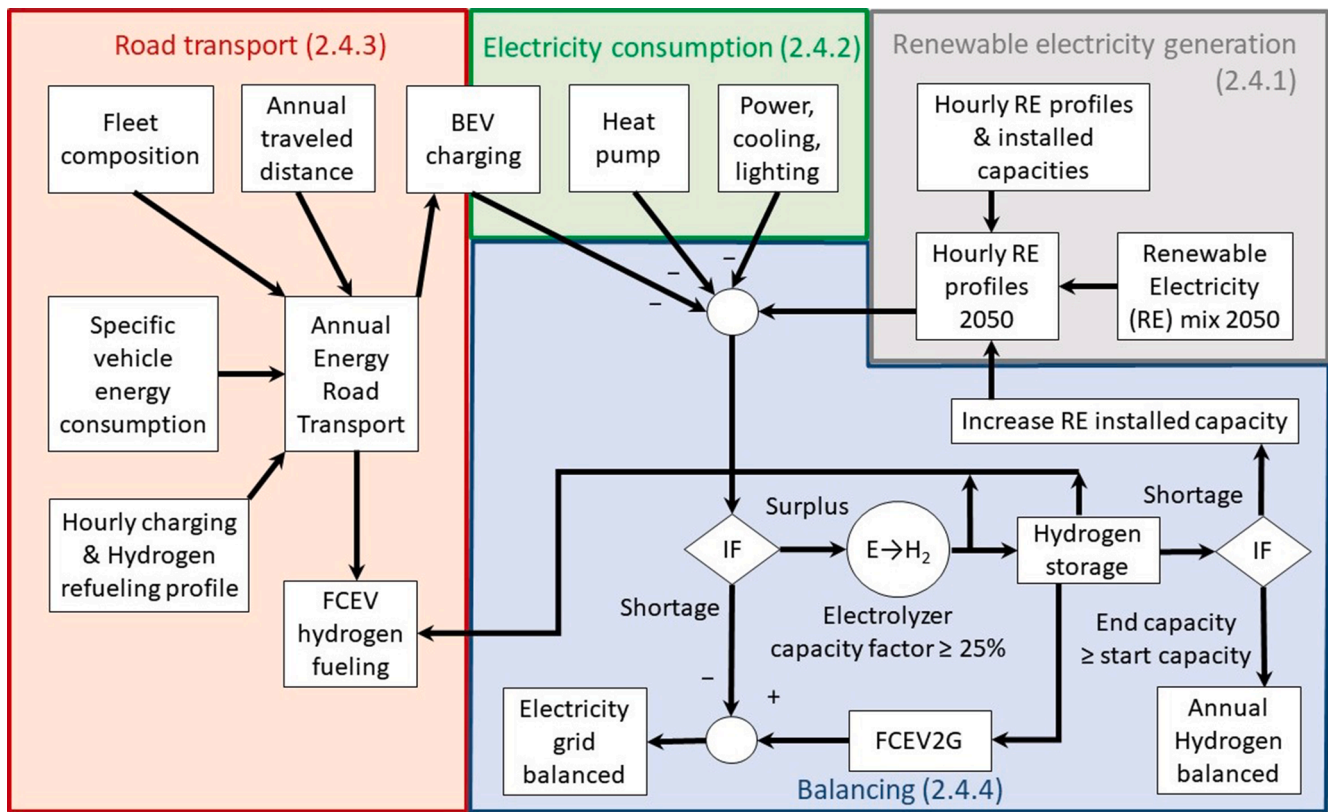


Fig. 2. Schematic and simplified overview of the model.

Table 3

Renewable electricity installed capacity mixes in 2050 for Denmark (DK), Germany (DE), Great Britain (GB), France (FR) and Spain (ES) based on existing studies [37,58–64].

	DK	DE	GB	FR	ES
Solar PV	8%	52%	42%	33%	52%
Solar CSP	0%	0%	0%	0%	6%
Onshore Wind	14%	37%	20%	50%	37%
Offshore Wind	71%	8%	28%	5%	0%
Hydropower	0%	1%	3%	12% ¹	5%
Geothermal	0%	0%	0%	0%	0%
Biomass Combined Heat and Power (CHP)	5%	2%	7%	0%	0%
Waste Combined Heat and power (CHP)	2%	0%	0%	0%	0%

5% run of the river and 7% reservoir.

available and simulated for Germany and Denmark, (2014–2017), three years for France and Great Britain (2015–2017) and two years for Spain (2016–2017). It is assumed that the road transport demand remains constant throughout the years and independent of weather influences. Both an hourly and annual hydrogen and electricity balance were calculated. The future 2050 total installed capacity of renewable energy sources was calculated in several iterations, such that both hourly and annual electricity and hydrogen balances were met (Fig. 2 in blue and Section 2.4.4).

2.4.1. Renewable electricity generation

The grey section in Fig. 2 represents the renewable energy

generation in simplified form. Table 3 shows the renewable electricity installed capacity mixes in 2050 per country. It was only in the case of Denmark that this could be taken directly from the available scenario studies [58–60]. For the other countries, a 100% renewable energy mix was constructed by omitting the fossil-fuel powered electricity generation capacity from low carbon energy scenarios and replacing this amount of electricity with an increase of renewable energy generation by wind and solar energy, according to the shares in the projected remaining electricity mix [37,61–64,124]. The hourly electricity generation profiles for every renewable energy source were collected from the Transmission System Operators (TSOs) and affiliated organizations and normalized with the installed capacity for each respective year [65–75]. These normalized hourly electricity generation profiles of solar PV, CSP, and onshore and offshore wind were then scaled with the installed capacity required. The installed capacity of hydropower, geothermal and biomass and waste-fired Combined Heat Power (CHP) should not exceed the values from the country scenario studies, as these energy sources are limited. In several iteration steps, the required installed capacity is the result of the annual energy balance calculation (see Fig. 2 and Section 2.4.4).

2.4.2. Electricity consumption

The green sections in Fig. 2 display the electricity consumption in simplified form, consisting of “classic electricity consumption,” heat pump electric heating and BEV charging.

The country-specific electricity consumption data, as provided by the TSOs and affiliated organizations, is the “classic” electricity consumption. This consists of aggregated electricity consumption data from

Table 4

Assumed road transport vehicle use in 2050.

	Annual distance traveled per vehicle type (millions of km)				
	DK	DE	GB	FR	ES
Passenger cars	38,489	618,719	398,600	414,600	212,203
Motorcycles	457	9,612	4,500	16,394	7,428
Vans	7,221	42,569	75,000	97,455	121,154
Trucks	977	16,366	12,060	7,960	59,378
Tractor trailers	1,068	18,702	14,740	8,976	
Buses	612	4,378	4,300	3,420	6,132

various sectors; for example, the services and residential building sectors (lighting, appliances, space heating and cooling and hot water), industry, rail, agriculture, public lighting and other sectors. In the case of France, the classic electric consumption profile [67] was corrected [124] for the share of about 18% of electric space heating [66,77]. It was assumed that there will be no net increase or reduction of classic electricity consumption in 2050 compared to today. Despite efficiency increases in lighting and electrical appliances, the increased number and use of these would not result in a reduction of total electricity consumption.

Currently, hot water and space heating demand in most countries still heavily relies on fossil fuels. To decarbonize this demand, most future 2050 scenarios envisage a large increase in electric heat pumps and solar thermal collectors, either per household or coupled to a district heating network [125]. These district heating networks could also facilitate the use of geothermal power, community solar thermal, and waste or biomass-fired CHPs [126–129]. Alternatively, existing natural gas distribution networks could also be used for the transport of hydrogen [55,130–134] and use in hydrogen boilers [134–136] or CHP fuel cell systems [11,137]. In the scenario studies by other institutions used in this work [37,58–64], heat supply from electric heat pumps predominates, and therefore it was used in the generic model here.

For each country, the annual total heating demand for space heating (sh) and hot water (hw), ($E_{shhw,total}$), [37,58–64,124], which cannot be met by solar thermal ($E_{shhw,solar}$) or geothermal energy ($E_{shhw,geo}$), is provided by electric heat pumps (ehp), $E_{shhw,ehp,h}$ in equation (2.1).

$$E_{shhw,ehp,h} = E_{shhw,total} - E_{shhw,solar} - E_{shhw,geo} \quad (2.1)$$

The electricity required by the electric heat pumps ($E_{shhw,ehp,el}$) is calculated in Eq. (2.2) by dividing the remaining heating demand with a seasonal coefficient of performance (SCOP) of 3.5, based on [138–141].

$$E_{shhw,ehp,el} = \frac{E_{shhw,ehp,h}}{SCOP} \quad (2.2)$$

The fraction of electricity for heating demand for domestic hot water (f_{hw}), compared to the total electricity for heating demand, if not specified in the scenario studies used, was calculated with historical data from the Odyssee database [66,142], see Eq. (2.3).

$$E_{hw,ehp,el} = E_{shhw,ehp,el} \times f_{hw} \quad (2.3)$$

The fractions for domestic hot water use are 15.3% for Denmark, 14.9% for Germany, 22.2% for Great Britain, 12.0% for France and 13.0% for Spain. The aggregated electricity demand for hot water is assumed to be constant for every hour of the year, similar to [4].

The aggregated hourly heat pump electricity profile for space heating electricity demand is dependent on the outside temperature and estimated with the use of Heating Degree Days (HDD). The daily (d) HDDs are calculated using Eq. (2.4). Where the daily mean temperature (T_{mean}) data of the five countries [124,143] serves as an input. With increased insulation in 2050, a reference temperature (T_{ref}) of 16 °C was used [144].

$$HDD(d) = \begin{cases} 0 & T_{mean}(d) > T_{ref} \\ T_{ref} - T_{mean}(d) & T_{mean}(d) < T_{ref} \end{cases} \quad (2.4)$$

The daily heat pump electricity demand for space heating, $E_{sh,ehp,el}(d)$, was assumed to be constant over a day. In Eq. (2.5), the heat pump electricity demand per day profile throughout the year is calculated by multiplying the normalized daily HDD profile over a year with the annual heat pump electricity demand for space heating and hot water ($E_{shhw,ehp,el}$, Eq. (2.2)) and the fraction of the electricity for space heating ($1 - f_{hw}$).

$$E_{sh,ehp,el}(d) = \frac{HDD(d)}{\sum_{d=1}^{365} HDD(d)} \times E_{shhw,ehp,el} \times (1 - f_{hw}) \quad (2.5)$$

2.4.3. Road transport electricity and hydrogen demand

The red section in Fig. 2 displays the road transport energy consumption in simplified form, consisting of the FCEVs and BEVs.

No increase in annual kilometers driven in 2050 was assumed in calculating the road transport energy demand. Some studies predict a growth in kilometers driven due to increasing population; other studies expect a decrease in vehicle kilometers driven due to car-sharing or increased use of public transport [98,145,146].

Total annual road transport electricity and hydrogen demand was calculated using the distribution of annual distance traveled per vehicle

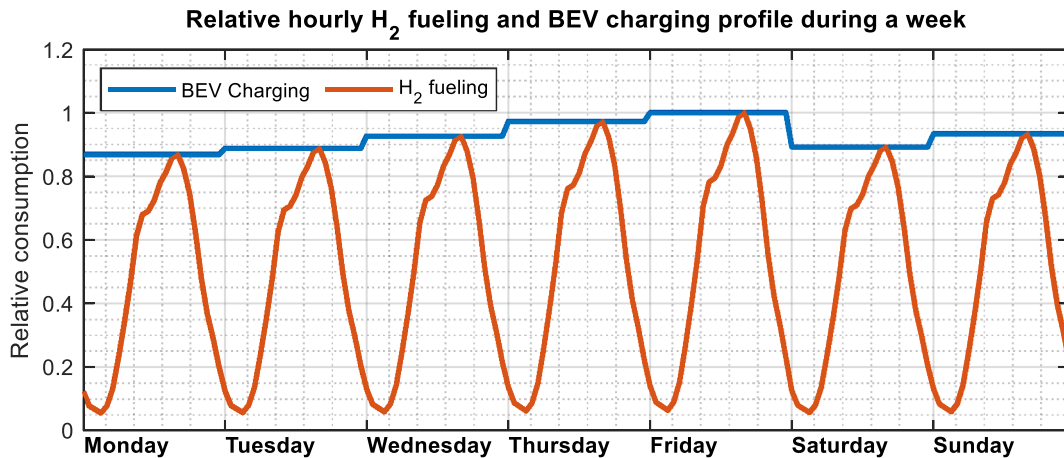


Fig. 3. Relative hourly hydrogen fueling (orang) and BEV charging (blue) profile during a week based on [58,147]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5

Key energy balancing parameters for the energy system, FCEV2G and electrolyzer usage for all five countries.

Country	Denmark	Germany	Great Britain	France	Spain
Years of electricity production data	2014–2017	2014–2017	2015–2017	2014–2017	2016–2017
<i>Energy system</i>					
Annual renewable electricity production (TWh)	61	822	541	619	471
Final annual electricity consumption incl. road transport (TWh)	47.5	637	428	503	348
Peak power “classic electricity consumption” (GW)	5.5	62.3	42.5	54.9	30.3
Peak power “classic”, heating and BEV charging electricity consumption (GW)	10.6	170	107	112	62.9
Pearson’s correlation coefficient total production vs. total demand	0.39	0.40	0.42	0.43	0.52
Installed renewable electricity capacity (GW)	17.5	569	281	391	249
Share of solar electricity generation (%) (PV and CSP ¹)	2%	34%	22%	25%	54%
Share of wind electricity generation (%) (onshore/offshore)	87%	61%	76%	64%	39%
<i>FCEV2G</i>					
Annual FCEV2G electricity production (TWh)	5.4	63.9	30.7	36.4	15.7
Peak capacity FCEV2G (GW)	4.8	79.8	44.4	41.9	25.0
FCEV2G electricity production relative to total annual electricity consumption (%)	13.2%	11.6%	8.5%	8.2%	6.2%
Peak FCEV2G fleet percentage (%)	42%	36%	29%	26%	30%
Capacity factor FCEV2G fleet (%)	5.5%	3.3%	2.3%	2.6%	2.1%
Average FCEV2G hours per car (hours/year/car at 10 kW V2G) (“full-load hours”)	480	290	200	230	190
<i>Electrolyzer</i>					
Electrolyzer installed capacity (GW)	11.1	154	92.2	93.8	97.4
Electrolyzer load factor (%)	28%	25%	27%	26%	27%

¹ Only Spain uses solar CSP electricity generation: 7% of the 54% solar electricity generation originated from solar CSP, 47% from solar PV.

type and technology (Table 2), the estimated specific energy consumption vehicle type and technology (Table 2), a charging efficiency for BEVs of 95% [37], 49.3 kWh of electricity required per kilogram of hydrogen produced and dispensed at 700 bar (Section 2.3), and the annual distance traveled per vehicle type (Table 4).

The annual amount of hydrogen dispensed for both driving and FCEV2G electricity consumption was based on the relative hourly profile for one week (orange line in Fig. 3) and was repeated and normalized for an entire year. The relative weekly profile was based on the pattern used by the US DoE in their simulations [147]. The BEV charging profile, Fig. 3, remains constant throughout the day, similar to the scenario by the Danish Energy Agency [58]. According to Ekman [148], simple day and night charging schemes do not significantly contribute to balancing,

and smart charging requires more insight into usage and charging of BEVs, and therefore they were not applied here.

2.4.4. Balancing electricity and hydrogen

The blue section in Fig. 2 displays the hourly electricity balance and hourly and annual hydrogen balance calculations in simplified form.

In the system proposed, the hourly (h) electricity balance (E_{Balance} , Eq. (2.6)) always has to be zero: a perfectly balanced electricity grid, subtracting total electricity consumption ($E_{\text{consumption}}$) from renewable electricity production ($E_{\text{production}}$). Deficits are compensated for with passenger FCEVs in V2G mode that convert the hydrogen produced earlier into electricity (E_{FCEV2G}). Surplus electricity is converted into hydrogen, the electrolyzer electricity consumption ($E_{\text{electrolyzer}}$), for both

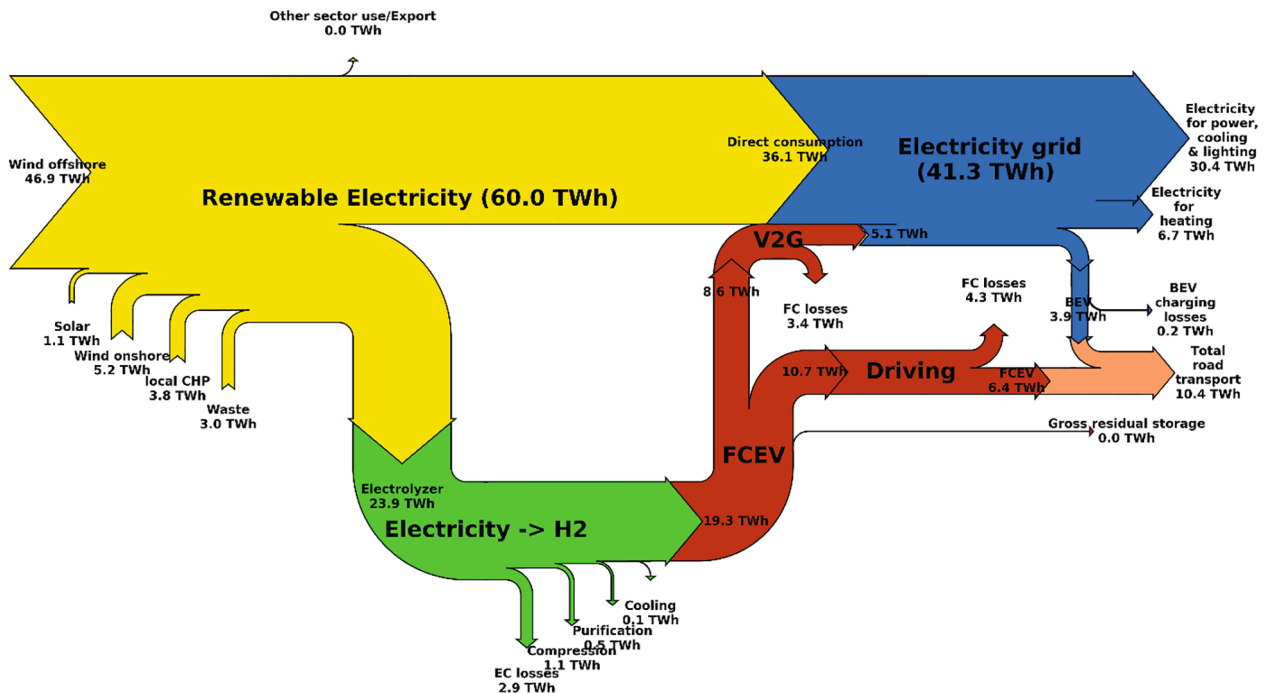


Fig. 4. Annual energy balance (TWh/year) for Denmark in 2050 based on 2017 renewable energy data.

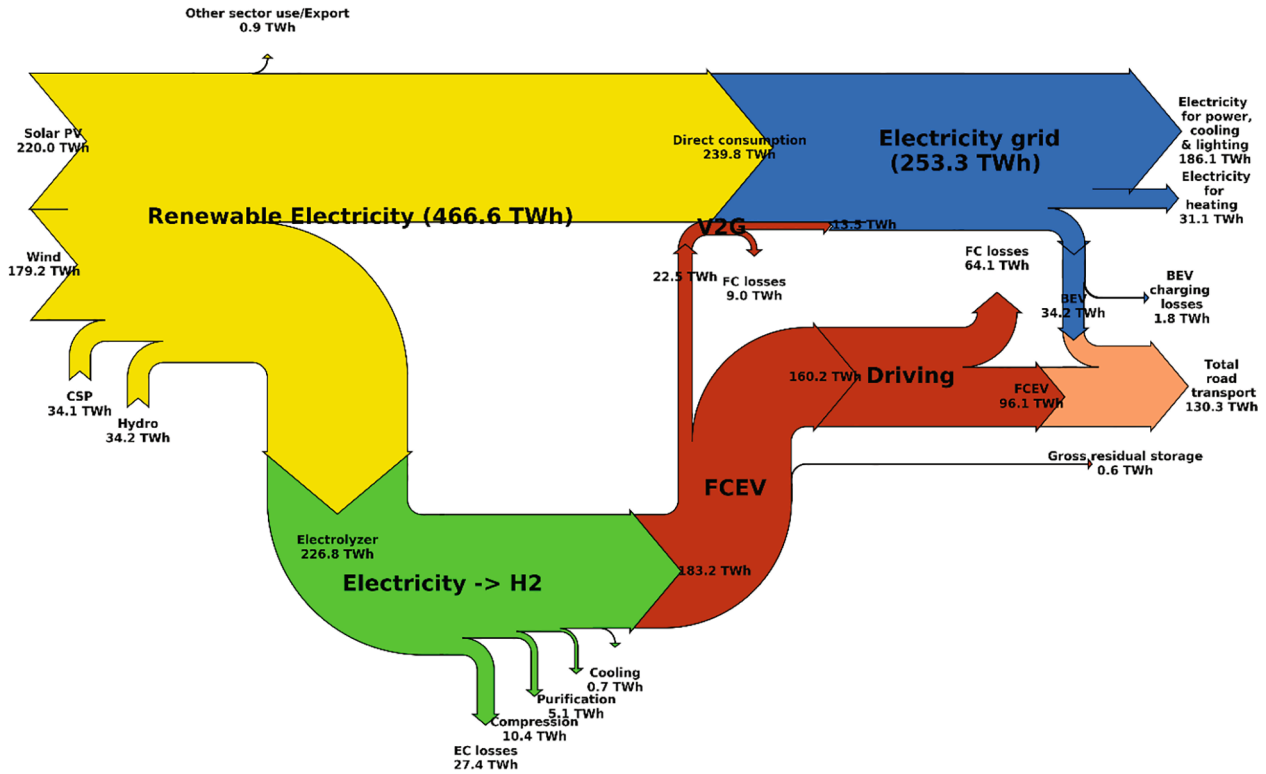


Fig. 5. Annual energy balance (TWh/year) for Spain in 2050 based on 2017 renewable energy data.

transport FCEV fueling and FCEV2G. The hydrogen produced is either used directly or stored seasonally. The total aggregated installed electrolyzer capacity is such that it operates with a minimum capacity factor of 25%. A lower capacity factor would result in higher hydrogen costs [149]. Remaining electricity production is utilized in sectors other than those dealt with in this article or it is curtailed.

$$\begin{aligned} E_{\text{balance}}[\text{MWh}](h) &= E_{\text{production}}[\text{MWh}](h) + E_{\text{FCEV2G}}[\text{MWh}](h) \dots \\ &- E_{\text{consumption}}[\text{MWh}](h) - E_{\text{electrolyser}}[\text{MWh}](h) = 0 \end{aligned} \quad (2.6)$$

The hourly electricity production ($E_{\text{production}}$, Eq. (2.7)) is the product of the estimated required installed renewable electricity capacity ($P_{\text{estimated}}$) for each hour.

$$E_{\text{production}}[\text{MWh}](h) = P_{\text{estimated}}[\text{MWh/h}] \times t[1h] \quad (2.7)$$

Here, FCEV2G electricity production (E_{FCEV2G} , Eq. (2.8)) is the product of the hydrogen fueling for FCEV2G ($H_{\text{fueling,FCEV2G}}$), the fuel cell system FCEV2G efficiency (η_{FCEV2G}) of 60% (Section 2.3) and the HHV of hydrogen (Section 2.3).

$$E_{\text{FCEV2G}} \left[\frac{\text{MWh}}{\text{h}} \right] (\text{h}) = \eta_{\text{FCEV2G}} [\%] \times H_{\text{fueling,FCEV2G}} [\text{kg H}_2] \times \text{HHV}_{\text{Hydrogen}} \left[\frac{\text{kWh}}{\text{kg H}_2} \right] \times \frac{1}{1000} \left[\frac{\text{MWh}}{\text{kWh}} \right] \quad (2.8)$$

The hourly hydrogen storage capacity (H_{storage}) at hour h , is determined in Eq. (2.9), where hydrogen production ($H_{\text{production}}$), is added and hydrogen fueling (H_{fueling}), is subtracted from the hydrogen storage capacity (H_{storage}) of the previous hour ($h-1$). Hydrogen fueling consists of both hydrogen for transportation and FCEV2G electricity production.

$$H_{\text{storage}}[\text{kg H}_2](h) = H_{\text{storage}}[\text{kg H}_2](h-1) + H_{\text{production}}[\text{kg H}_2](h) - H_{\text{fueling}}[\text{kg H}_2](h) \quad (2.9)$$

Hydrogen production ($H_{\text{production}}$, Eq. (3.0)) results from the absorbed power by the hydrogen production equipment ($E_{H_2 \text{ production}}$) multiplied by the hydrogen production efficiency ($\eta_{\text{electrolyzer}}$, Section 2.3) and the HHV of hydrogen (Section 2.3)..

$$H_{\text{production}}[\text{kg H}_2](\text{h}) = \frac{\eta_{\text{H}_2 \text{ Production}}[\%] \times E_{\text{H}_2 \text{ Production}}[\text{MWh}](\text{h})}{HHV_{\text{Hydrogen}} \left[\frac{\text{kWh}}{\text{kg H}_2} \right] \times \frac{1}{1000} \left[\frac{\text{MWh}}{\text{kWh}} \right]} \quad (3.0)$$

The seasonal storage of hydrogen must also be balanced over the course of a year, see Eq. (3.1). If the storage capacity at the end of the year is lower than at the start of the year, the estimated installed capacity in the generation mix is increased in a subsequent iteration step, until the hydrogen storage capacity is equal to or higher than at the beginning of the year (8760 h). In some case studies, the installed capacity of some renewable energy sources is limited (e.g., due to land space or hydropower). If the limit is reached, the installed capacity of the constrained energy source will increase no further, and only the installed capacities of the other sources increase.

$$\text{if} \left(\begin{array}{l} \text{H}_{\text{storage}}[\text{kg H}_2](h = 8760) \geq \text{H}_{\text{storage}}[\text{kg H}_2](h = 1) \Rightarrow \text{simulation end} \\ \text{H}_{\text{storage}}[\text{kg H}_2](h = 8760) < \text{H}_{\text{storage}}[\text{kg H}_2](h = 1) \Rightarrow \text{increase } P_{\text{estimated}} \end{array} \right) \quad (3.1)$$

3. Energy balance results

Section 3.1 presents the annual energy balance results and the key energy balancing parameters and energy flows. Balancing on an hourly

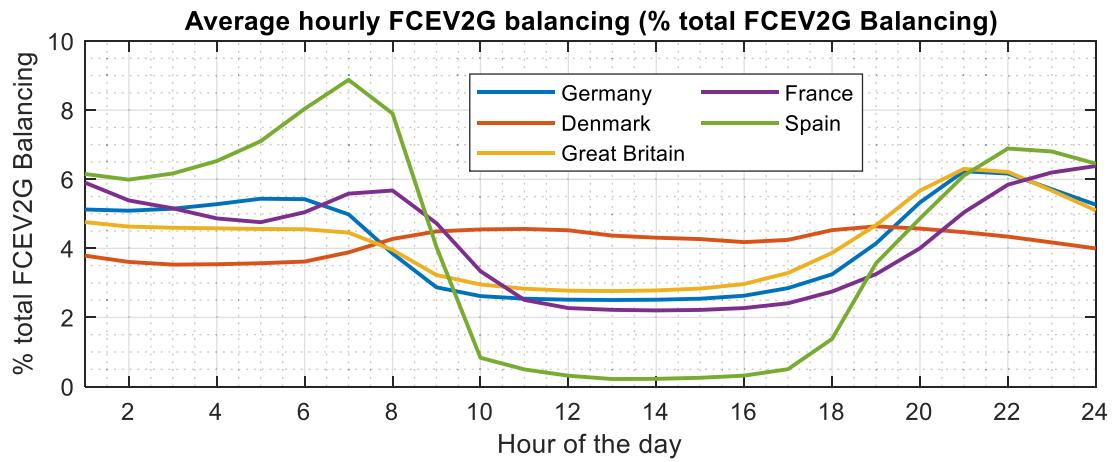


Fig. 6. Average annual hourly FCEV2G balancing expressed as a percentage of the total annual FCEV2G balancing in each country.

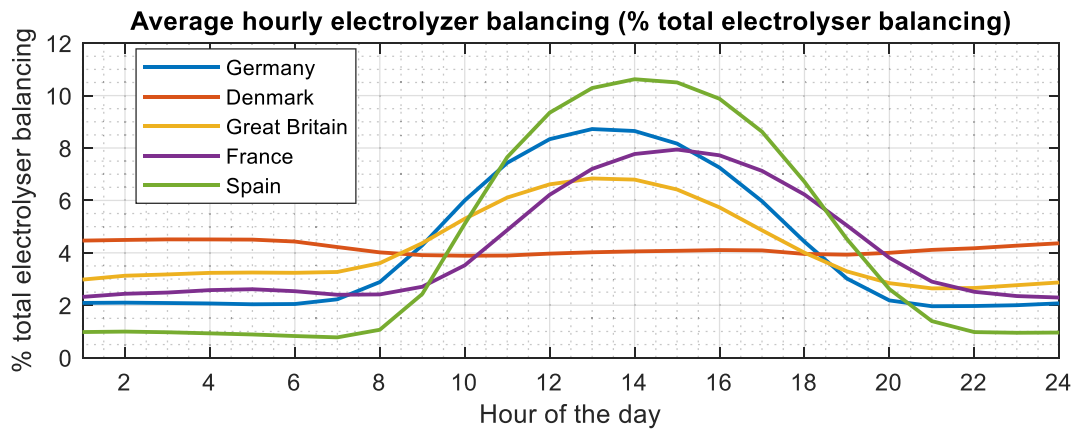


Fig. 7. Average annual hourly electrolyzer balancing as a percentage of the total annual electrolyzer balancing in each country.

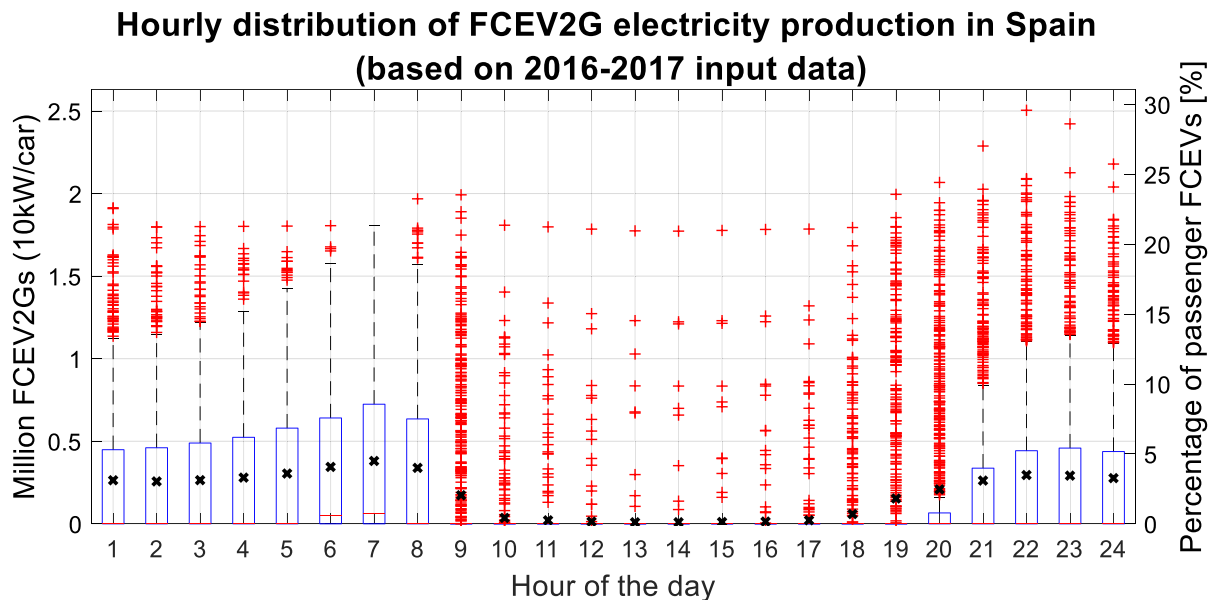


Fig. 8. Boxplot showing the hourly distribution of FCEV2G electricity production in Spain (million vehicles, left y-axis; % of all FCEV passenger cars, right y-axis) throughout the day (based on 2016–2017 input data). The black crosses represent the mean values, the medians are indicated by the red horizontal lines in the blue bars. The blue bars represent the range of 50% of the data points. The whiskers represent approximately 49% of the data points. The red pluses indicate the outliers, outside the above-mentioned ranges, and represent less than 1%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

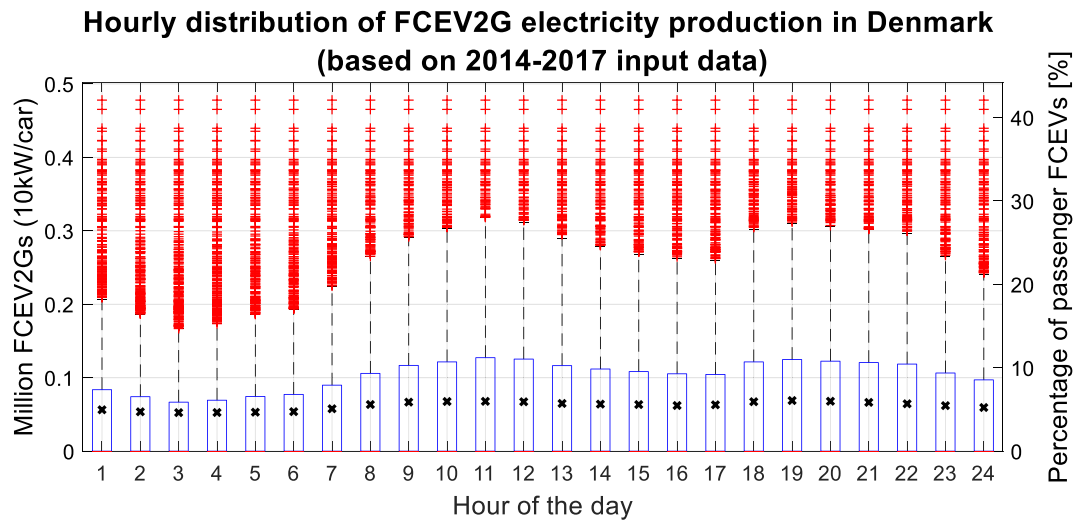


Fig. 9. Boxplot showing the hourly distribution of FCEV2Gs needed for producing V2G electricity in Denmark (million vehicles, left y-axis; % of all FCEV passenger cars, right y-axis) throughout the day (based on 2016–2017 input data). The black crosses represent the mean values, the medians are indicated by the red horizontal lines in the blue bars. The blue bars represent the range of 50% of the data points. The whiskers represent approximately 49% of the data points. The red pluses indicate the outliers, outside the above-mentioned ranges, and represent less than 1%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

resolution is done by the FCEV2Gs and electrolyzers and the hydrogen storage. These results are presented in [Section 3.2](#) and [Section 3.3](#).

3.1. Annual energy balance results

No energy balancing would be needed if renewable electricity generation always exactly matched electricity consumption; however, this is not the case. [Table 5](#) summarizes the key energy balancing parameters for the energy system, FCEV2G and electrolyzer usage for all five countries based on several years of energy data. [Appendix A1](#) shows hourly electricity consumption versus electricity generation for all five countries for an entire year. The annual energy balances (Sankey diagrams) for Denmark and Spain are shown in [Figs. 4 and 5](#), respectively. The annual energy balances (Sankey diagrams) for Germany, Great Britain and France are shown in [Appendix A2](#).

- For all five countries, more than 88% of primary electricity generation originates from solar and wind. Spain has the highest share of solar

electricity generation (54%, 46% solar PV and 8% solar CSP) and Denmark has the highest share of wind electricity generation (87%, 78% wind offshore and 9% onshore).

- In all five countries, more than 87% of electricity consumption can be directly met with renewable electricity generation. FCEV2G generates the remaining electricity, where the highest values are seen in Denmark, at 13%. Spain has the lowest share of FCEV2G electricity production relative to annual electricity consumption, at 6%.
- There is a significant share of unused FCEV2G capacity, up to 74%. At peak times, occurring only a few hours per year, 26% (France) to 43% (Denmark) of the FCEV2Gs are required (the FCEV2Gs only make up 50% of all passenger cars).
- FCEV2G fleet usage is low, with load factors of 2.1–5.5%. Denmark has the highest FCEV2G fleet capacity factor of 5.5%, corresponding to an average of 480 FCEV2G hours per car, per year. Spain has the lowest, at 2.1%, corresponding to an average of 190 FCEV2G hours per car, per year. The range of 190–480 FCEV2G hours per car has the same order of magnitude as average driving hours per year of

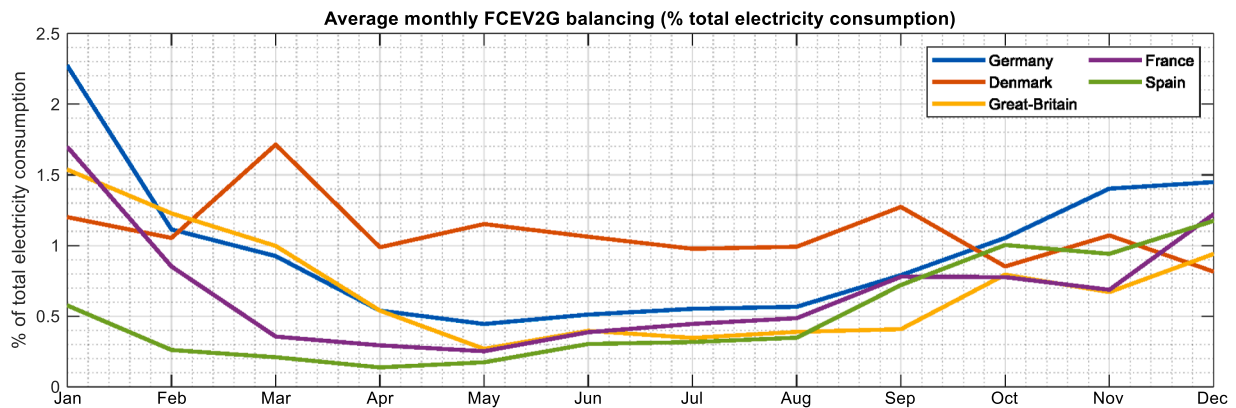


Fig. 10. Average monthly FCEV2G balancing as a percentage of total FCEV2G balancing in each country.

Table 6

Seasonal Hydrogen Storage key parameters for the five countries analyzed.

Seasonal Hydrogen Storage	DK	DE	GB	FR	ES
Peak hydrogen storage (million kg H ₂)	157	2668	1162	1564	1226
Average annual hydrogen production (million kg H ₂)	504	6632	4287	4234	4741
Peak hydrogen storage relative to average annual hydrogen production (%)	31%	40%	27%	37%	26%
Peak hydrogen storage (TWh _{HHV})	6.2	105	46	62	48
Maximum hydrogen storage relative to annual electricity production (%)	10.3%	12.8%	8.5%	10.0%	10.3%
<i>Natural gas storage</i>					
Operational, under construction and planned underground natural gas storage (TWh) [57]	10.4	270	60.4	137	32.0

approximately 300 h per car, per year (see Section 1, Introduction). Section 3.3 will shed more light on FCEV2G use during the day.

3.2. Fuel cell electric vehicle to grid and electrolyzer balancing results

Large differences in the FCEV2G fleet load factors in Spain and Denmark were observed on an annual basis and an hourly basis. Also here the large differences in wind and solar electricity generation shares are contributing to this difference in FCEV2G fleet load factors.

Fig. 6 shows average annual hourly FCEV2G balancing, expressed as a percentage of total annual FCEV2G balancing in the respective countries. All countries except Denmark show a lower percentage of FCEV2G balancing between 10:00–18:00 compared to 18:00–10:00. This effect is also often referred as the “duck curve” [150]. In other words, during daylight hours, less FCEV2G balancing is required. This would match favorably with the usage of passenger cars, as they are mostly driven during the day. In particular for Spain, on average, almost no FCEV2G balancing is needed between 12:00–16:00. However, at the same time, Spain has peaks of 8.9% and 6.9% around 07:00 and 22:00, although

there is still sufficient capacity that can easily follow the power ramps [29]. In Denmark, on average, FCEV2G balancing is almost constant throughout the entire 24 h, at 3.5% to 4.7%.

Opposite patterns to the duck curve can be seen in Fig. 7, which presents average annual hourly electrolyzer use as a percentage of total annual electrolyzer use in the respective countries. In Denmark, average hourly electrolyzer balancing is relatively constant throughout the day, at 3.9–4.5%. In contrast, in Spain, a clear pattern can be seen of approximately 1% between 22:00–08:00 and a clear peak of 10.6% at 14:00. The pattern for Spain, resulting from the large share of solar electricity generation, is very similar to other studies with high solar electricity generation [151–153]. The other countries in this study, having lower shares of solar electricity generation, show a similar but milder pattern than the Spanish one. Currently, the average hourly BEV charging pattern is assumed to be fixed throughout the 24 h (see Fig. 3). Charging more BEVs during the solar/daylight hours, except for Denmark, would reduce the electrolyzer balancing peak [154,155], provided BEVs are available for charging during the day.

The boxplots in Figs. 8 and 9 provide more insight into the hourly distribution of FCEV2G electricity production in Spain and Denmark over the course of the simulated years (million vehicles, left y-axis; % of all FCEV passenger cars, right y-axis). The black crosses represent the mean values. Based on a normal distribution, the blue bars represent the interquartile range (IQR), the difference between the first and third quartiles (Q1 and Q3), at approximately 50%. The upper and lower whiskers represent the data points within the ranges $[Q1 - (Q1 - 1.5 \times IQR)]$ and $[Q3 + (Q3 + 1.5 \times IQR)]$, at approximately 49%. The red pluses indicate the outliers, which are outside the above-mentioned ranges, and represent less than 1%. Appendix A3 also contains the boxplots for Germany, France and Great Britain.

Fig. 8 also confirms the strong solar effect for Spain. During the daytime, only some outliers higher than zero occur (red pluses, approximately 1% of the time). These outliers could originate from temporal low solar [156–164] or wind generation [165–167], a combination of both [168–171], called “dark doldrums” [172–175], or peak loads [165,166,176,177]. Most of the FCEV2Gs are required between 18:00–09:00, with averages ranging between 0.7% and 4.5% of the FCEVs (0.6–3.8 GW). The two-year peak in Spain of 29.6% of the FCEVs

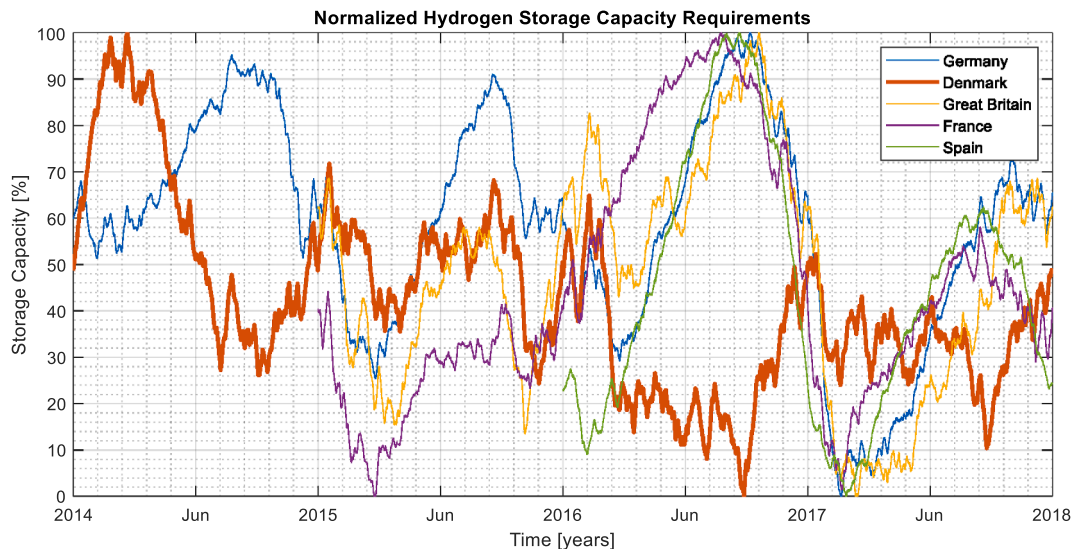


Fig. 11. Normalized hydrogen storage capacity requirements for all five countries, based on varying years of input data ranging from 2015 to 2018.

(25 GW, red plus) occurs at 22:00 (during the simulation with 2017 input data). The peak among the hourly averages (black cross) occurs at 07:00, at 4.5% of the FCEVs (3.8 GW).

The boxplot in Fig. 9 shows the hourly distribution of FCEV2G electricity production in Denmark throughout the day. The hourly average over the modeled years (black crosses) is relatively constant and ranges between 4.6% and 6.1% of the FCEV2Gs (0.05–0.07 million FCEV2Gs, 0.5–0.7 GW). A clear night (01:00–07:00) and day plus evening (08:00–24:00) pattern can be recognized when looking at the interquartile range (blue bars representing 50% of the FCEV2G hours) and the whiskers (49% of the FCEV2G hours). Of the FCEV2G hours (blue bars plus whiskers) during the night, 99% remain below 20% of the FCEV2G fleet. For 99% of the FCEV2G hours during the day plus evening (blue bars plus whiskers), this remains below 28% of the FCEV2G fleet. The four-year peak of 42.1% occurred over a period of 24 h during a period of consecutive low wind electricity generation.

Average monthly FCEV2G balancing, expressed as a percentage of total FCEV2G balancing in each country, is displayed in Fig. 10. Once again, Denmark differs from the other countries. There is no clear seasonable pattern for Denmark; throughout the year, monthly balancing ranges between 6.2% and 13%. For Germany, France and Great Britain, and to a lesser extent Spain, there are clear peaks in January and December of up to 20%, while all are below 5% in May. In the case of Spain, there is relatively low combined electricity production and relatively higher electricity consumption for space heating during the period October–December. The seasonal solar impact on the demand side for space heating and cooling, as well as solar electricity generation, is clearly reflected in hourly/diurnal and seasonal FCEV2G balancing.

3.3. Hydrogen storage and balance results

Hydrogen could be seasonally stored in underground salt caverns or empty gas fields. Table 6 shows the Seasonal Hydrogen Storage key parameters for the five countries analyzed. Germany has relatively large hydrogen storage requirements compared to the other countries. Germany has the highest hydrogen storage relative to annual average hydrogen production, at 40%, while Spain has the lowest, at 26%. Great Britain has the lowest hydrogen storage relative to annual average electricity production, at 8.5%, while Germany again has the highest, at 12.8%. Germany has the second highest share of solar PV electricity generation (34%), with most of the solar PV electricity generation concentrated during the summer months, while consumption is highest in the winter months (see Fig. A2 in Appendix A1). The current operational, under construction and planned underground gas storage [57] is comparable to the peak hydrogen storage modeled for all countries. It is noted that the volumetric density of natural gas (primarily methane) at any pressure is approximately three times higher than that of hydrogen gas [178]. From an energy point of view, as the modeled hydrogen storage is comparable to current and planned gas storage, one must consider that this study only includes the power, transport and space heating sectors. However, there are indications that the total dedicated underground cavern technical hydrogen storage potential, onshore and offshore, is several magnitudes higher [20].

Fig. 11 clearly shows strong fluctuations in the total hydrogen storage capacity requirements for Germany (blue) based on four years of meteorological input data from 2014 to 2018. Germany (blue), Great Britain (yellow), France (purple) and Spain (green) show similar trends for most of the simulated years. A low storage content is observed

between February and May and a high storage content is seen around September–October. During the summer period, energy consumption is relatively low and solar electricity contribution is high. This allows surpluses to be converted to hydrogen and stored for the winter period, during which the opposite occurs: high energy consumption and low solar energy contribution. For Denmark (orange, thicker line), no distinct seasonal pattern can be recognized in the storage content. Due to the large share of wind, mostly offshore, there is a better seasonal match between electricity generation and consumption. Both onshore and offshore wind generate more electricity during the winter period, which favorably matches the higher winter energy consumption.

4. Discussion

The focus of this study was on the role of balancing national 100% renewable energy systems with V2G using hydrogen-fueled FCEVs. Having this specific hydrogen focus, seasonal hydrogen storage and hydrogen production using downward balancing with electrolyzers were a logical and natural choice from an energy system modeling point of view. In a techno-economic energy system optimization study, Brown et al. [4] considered hydrogen for seasonal energy, but concluded that its role is limited. However, this was due to the fact that they assumed costly above-ground hydrogen storage, whereas underground hydrogen storage in depleted salt caverns may be 10–30 times cheaper [4,179–182].

The above example shows there is a trade-off between a number of balancing and storage options, various dimensions (e.g., time, cost), model complexity (regions, interconnections, integration, energy vectors, networks and their capacity constraints) and the ability to isolate and explore the maximum technical potential [20,183] of a specific technology within large energy systems. In this study, model complexity was relatively low. By not including the capacity of the electricity network or gas network, being “unlimited” or “copperplate,” and with no international connections or other balancing options, the required balancing and storage might be overestimated, as other studies [33,184] have also indicated. The focus of this study was an exploration of the technical potential of V2G with FCEVs (at 50% of passenger cars) and to highlight any potential operational restrictions or overcapacity. Both FCEV2G capacity as well as underground hydrogen storage potential are significantly greater than what is required, according to this study, even if this study overestimates the requirements.

The results show that it is technically possible to undertake all hourly and seasonal balancing with FCEV2G, electrolyzers and hydrogen storage in a 100% renewable electricity, heating, cooling and transport system. As no integrated transportation and energy systems are the same, it is not possible to straightforwardly compare results. Many studies look to Europe as a whole, or parts of Europe [2,4,22,35,185], with some focusing on the same countries analyzed in this study. As the systems developed are sometimes difficult to compare, the comparison here is limited to balancing and long-term storage. The majority of the 100% renewable energy systems analyzed in [33] include the power sector, and some include heating and mobility. The storage size expressed as a percentage of annual demand ranges between 1.5% and 5%, with some studies reporting 14% [33].

In this study, the analysis is made for Denmark, Germany, Great Britain, France and Spain, with results for the countries varying; however, the hydrogen storage relative to annual hydrogen and electricity consumption ranges between 9% and 13% for all countries. Compared to

[33], it could be concluded that the results might overestimate the storage required, due to the fact that not all possible flexibility options are included in the model. Moreover, in this study, FCEV2Gs were used for upward balancing in cases where there is a shortage of electricity and downward balancing with electrolyzers when electricity consumption is met. Below, the findings here are compared with other studies for each country separately.

Case studies of Germany [37–39] have found that its upward and downward balancing capacities range between 40 and 103 GW and 23–274 GW, excluding interconnections to other countries. In this study, respectively 80 GW and 154 GW is found for Germany for upward balancing with FCEV2G and downward balancing with electrolyzers. In relation to long-term large-scale storage, other studies found 24–154 TWh [37–39] compared to 105 TWh in this study.

Case studies of Denmark [36,59,186] have found that upward and downward balancing ranges between 4.6 and 6.0 GW and 7.2–9.0 GW, while this study found 4.8 GW and 11.1 GW, respectively. Seasonal long-term storage was not further specified in the other studies of Denmark [36,59,186], despite synthetic natural gas (SNG) and hydrogen production and consumption being part of the applied technologies. These studies [36,59,186] on the case of Denmark used approximately 60 TWh of biomass for primary energy use and included the industrial, aviation and shipping sectors. In this study, the electricity generation from CHPs and waste was fixed at 6.8 TWh and required 6.2 TWh of hydrogen storage capacity.

Case studies of the UK have concluded that there is not yet consensus across the industry about the necessary level of hydrogen storage, nor the preferred solutions [187]. One study found that the necessary upward balancing would be 73 GW [187], with 47 GW from natural gas turbine power plants with carbon capture, use and storage (CCUS). This study found 44 GW for FCEV2G balancing.

In the case of France [38,39,62], 28–57 GW of upward and 23–177 GW of downward balancing were found, excluding interconnections to other countries. In comparison, this study found 42 GW of FCEV2G and 94 GW of electrolyzer capacity. Furthermore, while 3–92 TWh of hydrogen and/or SNG storage was reported by the other case studies of France [38,39,62], this study found 62 TWh.

Finally, case studies of Spain [38,39] have reported 14–23 GW for upward and 12–117 GW for downward balancing. In comparison, this study found 25 GW FCEV2G and 97 GW electrolyzer capacity. The two studies of Spain [38,39] also reported a range of 3–92 TWh of storage. In comparison this study found 32 TWh hydrogen storage.

In summary, the results of this study are of similar magnitude to other studies. The large range in the findings across studies is the result of a multitude of different modeling and technology choices. These range from the level of renewable energy sources and fossil energy resources used, interconnections, import of energy, energy mix, parallel use of balancing and storage technologies and the number of sectors included, which all make it difficult to draw detailed comparisons.

This study assumed a “copperplate” electric grid within each country: an electric grid with unlimited capacity, with all renewable electricity sources, FCEV2Gs and electrolyzers coupled to the electric grid. In reality the electric grid has a limited capacity, locations have to be selected carefully according to the local grid capacity. The usage of a gas (hydrogen) pipeline grid for energy or hydrogen transportation was not considered, nor any synergies between the electric grid and gas grid.

The designed country systems are hypothetical in the sense that energy exchange with other countries is excluded. Currently European countries are connected to each other via electric cables and gas pipelines. Renewable energy supply deficits in one country can be balanced with surpluses in other countries. The current EU interconnection

targets for 2030 aim that each country should have in place electricity cables that allow at least 15% of the electricity produced by its power plants to be transported across its borders to neighboring countries [6]. Increased interconnection will in certain times with favorable renewable electricity and consumption patterns reduce the balancing volumes and peaks by the FCEV2Gs and electrolyzers. At the same time, increased interconnection, also means that grid-connected FCEVs in one country could provide balancing for another country in case their cars would not be available. Instead of a regional or national pool of FCEV2Gs, there could be a European pool of FCEV2Gs balancing the European electricity grid and fully replace balancing power plants on a large scale.

Instead of transporting the renewable electricity via cables, also hydrogen could be produced first and transported via hydrogen pipelines. Eleven gas grid operators have recently published their plans in the “European Hydrogen Backbone” study, outlining how a dedicated hydrogen infrastructure can be created [188]. The study also highlights potential connections to North Africa for the import of green hydrogen [103]. Having such a hydrogen pipeline network in place, it would create the possibility for countries without large underground gas storage facilities, but with large renewable energy sources, to produce hydrogen and export it via pipeline to a neighboring country. The hydrogen then can be stored in underground facilities in other countries and transported back to the country of origin when needed for balancing.

Instead of domestic hydrogen production, the importation of hydrogen might also be considered [38,39,189]. In the current energy system, most energy for transport is imported. The imported hydrogen could be distributed via the gas pipeline grid for electricity generation and refueling. In this way, it could avoid energy transport via the electric grid [55,130].

FCEV2Gs could be distributed close to load centers and help to reduce peak load on electricity transmission and distribution grids. In contrast to large stationary gas turbine plants located far from load centers. Hydrogen fueling stations supply hydrogen for both driving and FCEV2G, with hydrogen for FCEV2G potentially requiring large peak capacities. A hydrogen pipeline distribution network (e.g., converted natural gas distribution network) close to demand centers would avoid large dispensing peaks at hydrogen stations due to FCEV2G. FCEV2Gs could be supplied directly with low pressure hydrogen from a hydrogen pipeline distribution network. This would also avoid emptying the on-board hydrogen tank during FCEV2G electricity generation and thus the driving range would not be affected. Smart placement and dedicated hydrogen production at renewable energy sources close to gas storage and the gas pipeline grid also have the potential to reduce the load and further capacity expansion of the electricity grid.

Looking further into FCEV2G, electrolyzer and hydrogen storage usage in this study, several methods could improve their use. For example, although the peak FCEV2G capacity required never exceeded 43% of the FCEV2G passenger car fleet, lower capacity peaks will ease operational aspects, such as scheduling, and improve the guaranteed supply of electricity, as well as potentially reduce costs (not considered in this study). Based on the findings of this study, a 100% renewable power, heating and road transport energy system is possible, but there remain various opportunities for further optimization, outlined below.

Reducing total produced FCEV2G electricity and changing the time of FCEV2G use, which could be achieved:

- By a better match of renewable electricity generation with electricity consumption. A carefully selected mix of solar PV and wind electricity generation, combined with (partially) dispatchable renewable energy sources such as hydropower, solar CSP and CHP, could more

favorably match the seasonal and daily patterns of consumption. As cars are mostly used during the day for driving, large amounts of solar energy (duck curve) could almost completely shift FCEV2G to the night hours. With some other renewable energy sources, such as wind, solar CSP and hydropower, FCEV2G balancing during the early morning and late afternoon driving peak hours could also be avoided almost completely.

- Through the demand response of electrical devices, space heating or BEV charging, such that the consumption pattern better matches electricity generation and thus impacts the time of use of FCEV2G.
- Through the importation of electricity from other countries at times of shortage; although, when relying on wind and solar energy, shortages and surpluses might occur at similar times. However, other research mentions that interconnecting large areas reduces this effect.

Reducing the number of participating FCEV2G, which could be possible:

- By reducing FCEV2G electricity generation. Several ways have been mentioned above in this section.
- By increasing the FCEV2G output per car, which is now limited to 10 kW of the 100 kW on-board capacity. Currently, the limitation is due to the cooling capacity of the fuel cell system radiator when the vehicle is parked. Increasing FCEV2G output per car would require a better understanding of the cooling capacity of the parked radiator [29].
- By increasing capacity through the use of other vehicles, such as FCEV vans, buses or trucks, in addition to passenger cars. Although these commercial vehicles might be used more during the day, at night they could also provide FCEV2G electricity.
- By using the batteries in BEVs for (short-term) storage and upward and downward balancing.

Increasing the electrolyzer capacity factor and reducing peak capacity, which could be possible:

- Through electricity consumption by other sectors not included in this study, such as industry and agriculture.
- By exporting temporary surplus electricity to other countries.
- Through the demand response of electrical devices, space heating or BEV charging, such that the consumption pattern better matches electricity generation.

Reducing the hydrogen storage capacity, which could be achieved:

- By reducing FCEV2G electricity generation and thus hydrogen consumption and storage. Several ways were mentioned above under “Reducing total produced FCEV2G electricity.”
- By (temporarily) importing or exporting low-cost renewable hydrogen from or to other regions, or only at times when storage requirements would otherwise be high. Import or export of hydrogen could involve distant or neighboring countries and use tankers or hydrogen pipelines.
- By producing hydrogen for driving with renewable energy sources that have relatively constant output during the year. This would mean that a minimal amount of hydrogen needs to be stored, as hydrogen consumption for driving has no distinct seasonal patterns.

Similar to other studies, the five country cases were analyzed here as greenfield models [184], which generate a perfect outcome from a specific foresight [190]. V2G infrastructure and the use of BEVs are increasingly expanding [191,192]. Here, V2G with FCEVs could piggyback on BEV V2G infrastructure developments and standards. The specific role of V2G and how large it will become in balancing energy systems should be addressed in future work. Questions about the

development path – for example, will it be incremental versus disruptive, distributed versus central – remain open and depend on whether or when widespread adoption of passenger car FCEVs occurs.

There is an ever-increasing interest in the role of hydrogen in renewable energy system studies, as the cost of hydrogen technology is decreasing faster than expected [193]. Therefore, thorough cost analysis should be addressed in future work. Also cost optimizations of using FCEV2G for balancing versus other upward balancing technologies, like hydrogen fuelled gas turbines, distributed or large scale fuel cell based CHP systems could be investigated to shed light on the optimal mix of technologies in relation the balancing needs. As well as the influence of several parameters and others designs such as the use of BEVs for V2G purposes, distributed and large scale stationary batteries, the distribution between the number of BEVs and FCEVs, type of renewable energy sources could be of further interest in analyzing future cost of similar type of energy systems.

5. Conclusion

The future energy and transport system in Europe will and must move to zero emissions. Significant numbers of back-up power plants, as well as balancing and large-scale energy storage capacity are required to guarantee the reliability of energy supply. Here, hydrogen can offer a solution in highly renewable systems by converting power to hydrogen to be used as a transport fuel and in energy storage for back-up power plants.

Parked and grid-connected (Vehicle-to-Grid, V2G) hydrogen-fueled FCEV passenger cars (FCEV2G) can fully balance a 100% renewable national electricity, heating and transport system. Combined with hydrogen production using electrolyzers and large-scale hydrogen storage, energy supply can be guaranteed at all times. There is more than sufficient power capacity available from FCEV passenger cars, with no more than 43% of the FCEV passenger car fleet required, even with a restricted output of 10 kW per car and with 50% of passenger cars considered to be FCEVs. This applied to all five countries modeled: Denmark, Germany, France, Great Britain and Spain.

FCEV2G fleet usage is low and matches favorably with driving usage. For example, especially in systems with larger shares of solar electricity, FCEV2G balancing is required during the night. As cars are mostly driven during the day, they will generally be parked at night when this balancing capacity is needed. Moreover, the large overcapacity, in combination with the low usage of already purchased electric power capacity in passenger cars, would make it possible to fully replace large-scale stationary balancing plants. The capacity of millions of distributed FCEV2G can be combined into Virtual Power Plants.

In the five countries modeled, 88% or more of the electricity generation originated from solar and wind, where Denmark has the highest share of wind electricity generation (87%) and the lowest share of solar electricity generation (2%) and Spain has the highest solar (54%) and lowest wind electricity generation (39%). The FCEV2G fleet capacity factor is highest in Denmark, at 5.5% (average of 480 h per car, per year) and lowest in Spain, at 2.1% (190 h per car, per year). Nevertheless, these capacity factors are both very low and comparable to driving usage (European average, 300 h per car, per year).

Spain and Denmark also showed the most contrasting patterns in daily average FCEV2G and electrolyzer balancing. In Denmark, FCEV2G and electrolyzers may be needed at any time of the day during the year. FCEV2G is needed somewhat more during daylight hours and electrolyzers slightly more during nighttime hours. In Spain, however, FCEV2G balancing, on average, is mainly required outside daylight hours (17:00–10:00) and electrolyzers during daylight hours (08:00–20:00). By producing hydrogen from solar electricity during daylight hours, the duck curve phenomenon can be reduced. Especially in summertime, hydrogen can be produced and contained in large-scale gas storage for the winter period in, for example, underground salt caverns or empty gas fields. The calculated hydrogen storage capacities ranged between 6 and

105 TWh and were not more than 76% of the existing, under construction and planned underground gas storage capacity. Other research has reported that the total dedicated underground cavern technical hydrogen storage potential onshore and offshore is several magnitudes higher.

CRediT authorship contribution statement

Vincent Oldenbroek: Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing - original draft, Writing - review & editing, Visualization. **Siebre Wijtzes:** Conceptualization, Methodology, Software, Validation, Formal analysis, Visualization. **Kornelis Blok:** Conceptualization, Methodology, Validation, Writing - review & editing, Supervision. **Ad J.M. Wijk:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

A1. Hourly electricity generation and consumption figures

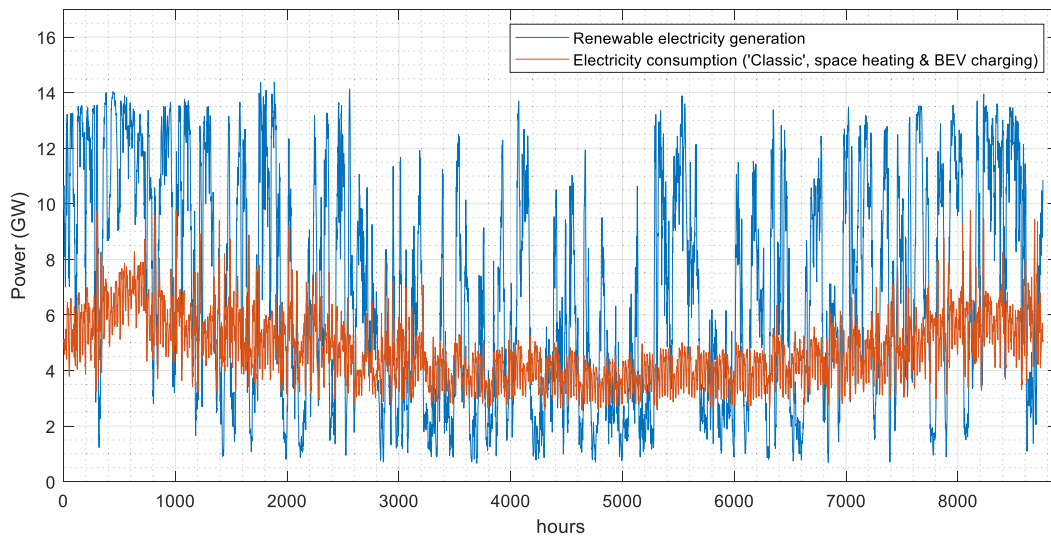


Fig. A1. Hourly electricity consumption (orange) versus the renewable electricity generation (blue) for Denmark.

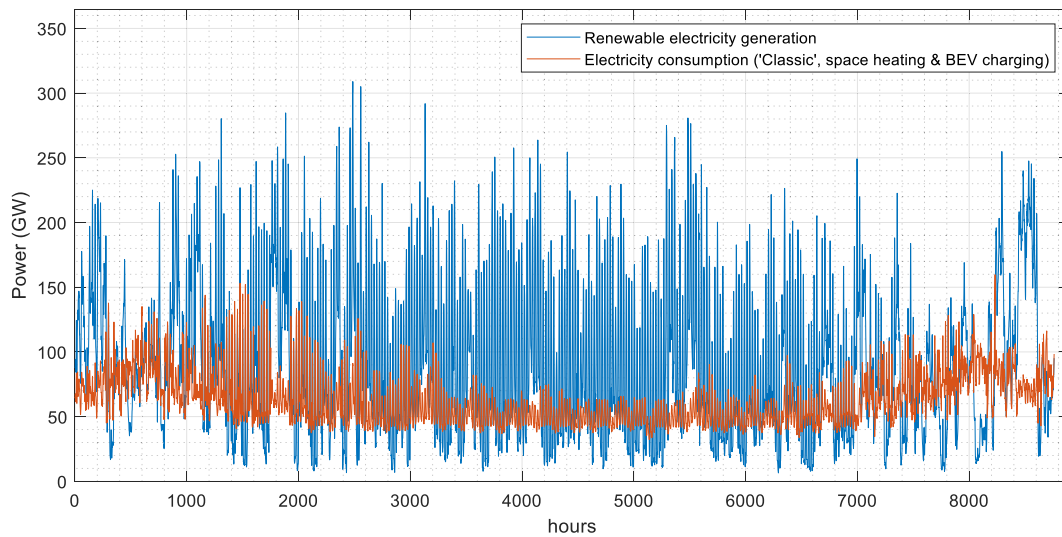


Fig. A2. Hourly electricity consumption (orange) versus the renewable electricity generation (blue) for Germany.

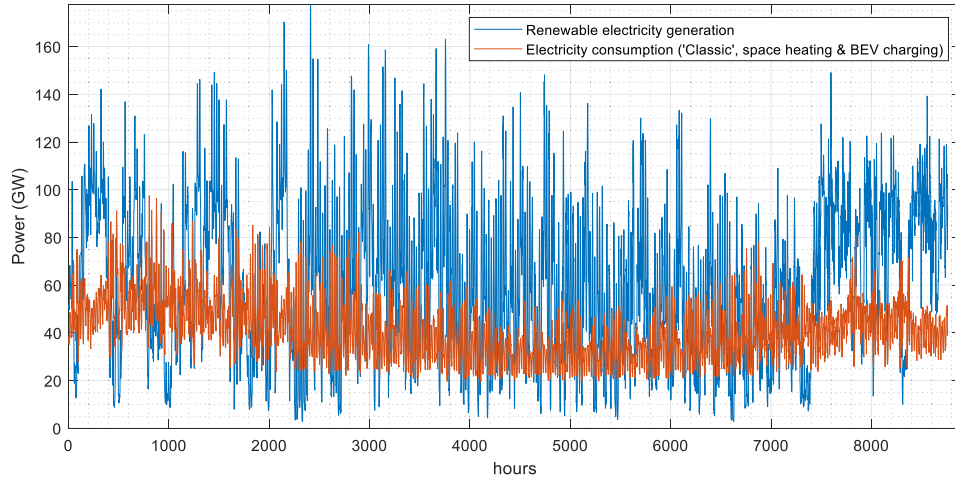


Fig. A3. Hourly electricity consumption (orange) versus the renewable electricity generation (blue) for Great Britain.

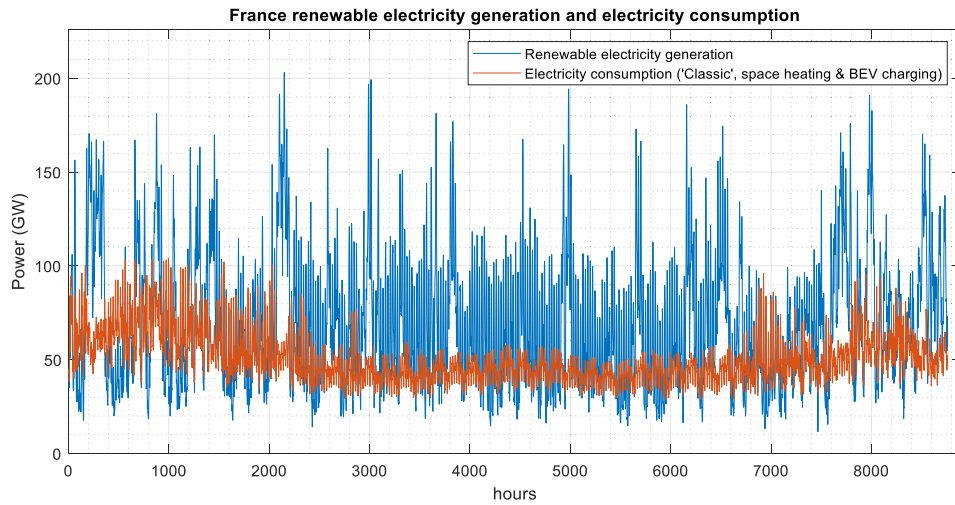


Fig. A4. Hourly electricity consumption (orange) versus the renewable electricity generation (blue) for France.

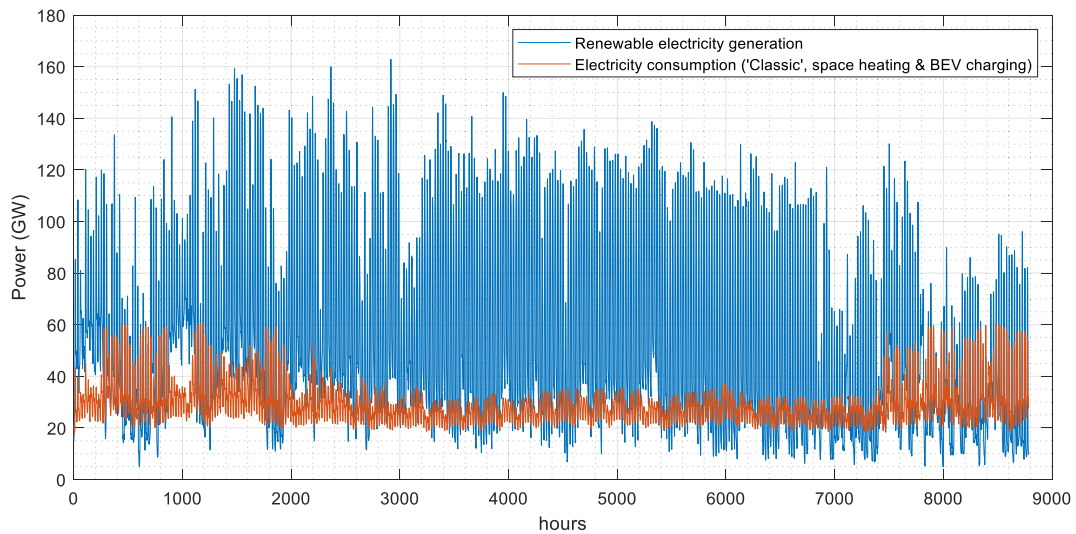


Fig. A5. Hourly electricity consumption (orange) versus the renewable electricity generation (blue) for Spain.

A2. Annual energy balance figures

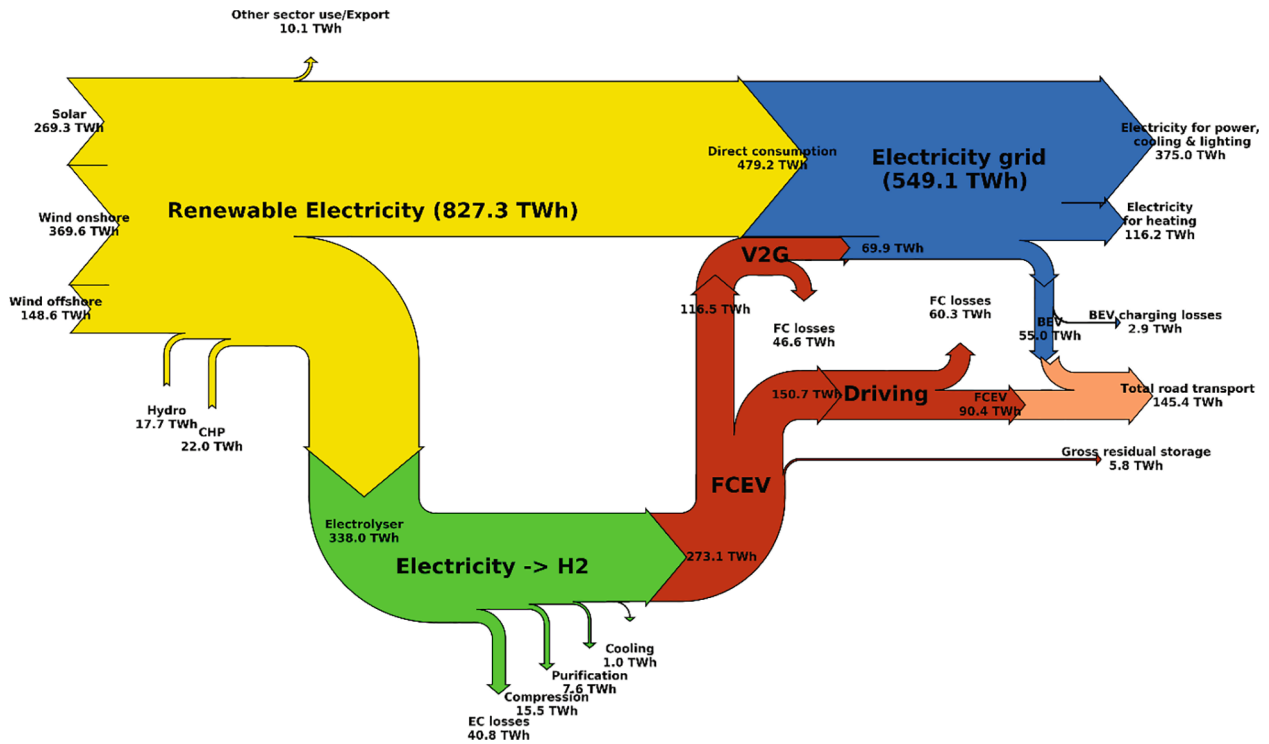


Fig. A6. Annual energy balance (TWh/year) for Germany in 2050 based on 2017 renewable energy data.

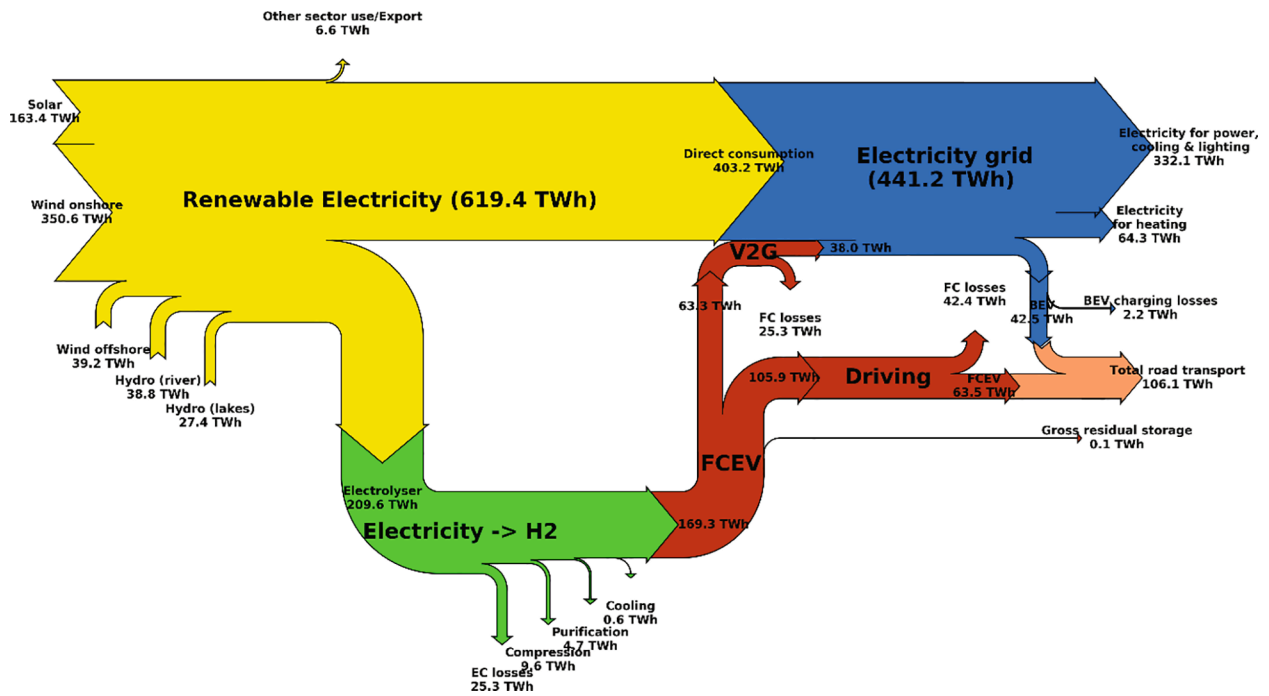


Fig. A7. Annual energy balance (TWh/year) for France in 2050 based on 2017 renewable energy data.

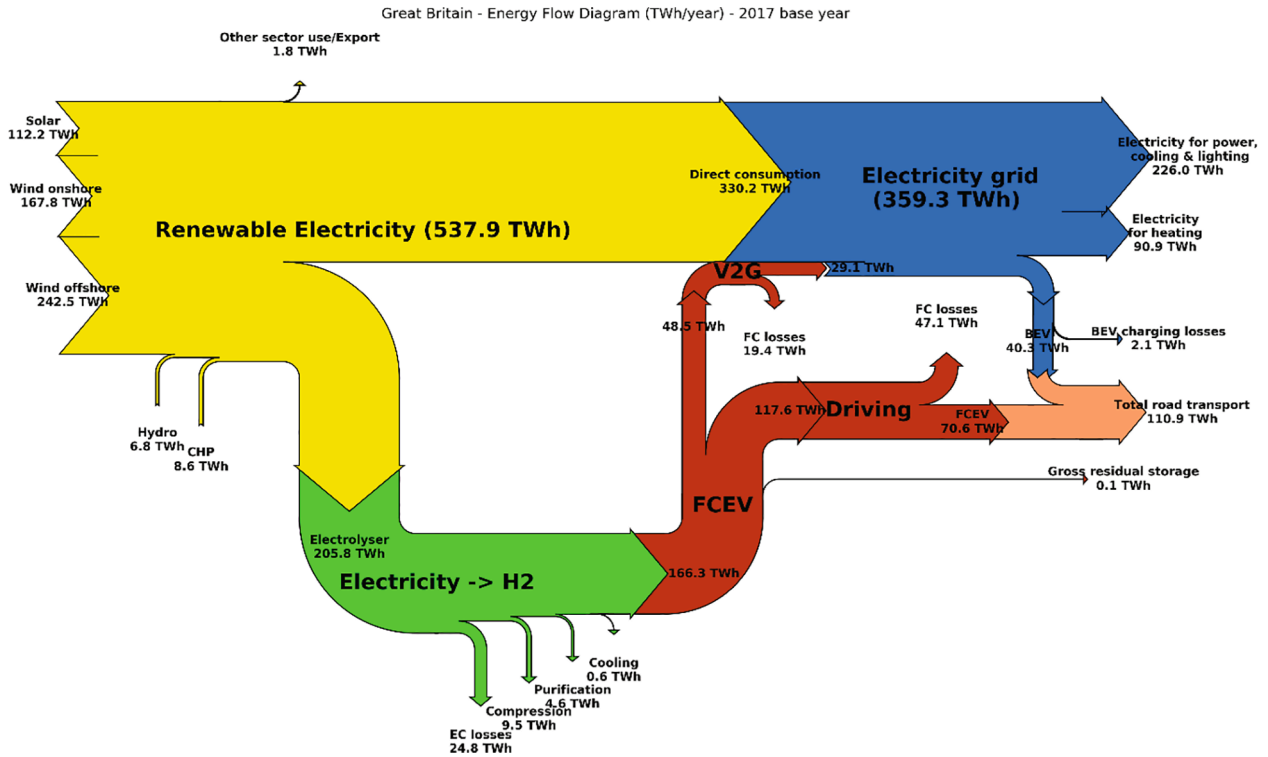


Fig. A8. Annual energy balance (TWh/year) for Great Britain in 2050 based on 2017 renewable energy data.

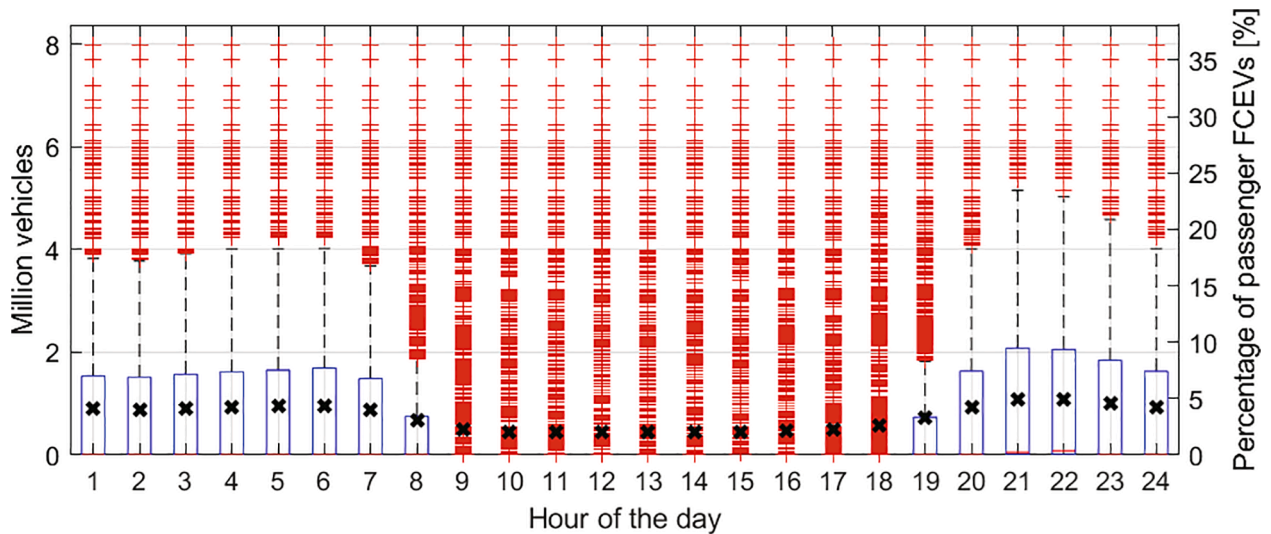


Fig. A9. Boxplot showing the hourly distribution of FCEV2G electricity production in Germany (million vehicles left y-axis, % of all FCEV passenger cars right y-axis) throughout the day (based on 2014–2017 input data). The black crosses represent the mean values, the medians are indicated by the red horizontal lines in the blue bars. The blue bars represent the range of 50% of the data points. The whiskers represent approximately 49% of the data points. The red pluses indicate the outliers, outside the above-mentioned ranges, and represent less than 1%.

A3. Hourly distribution of Fuel Cell Electric Vehicle to Grid electricity production figures

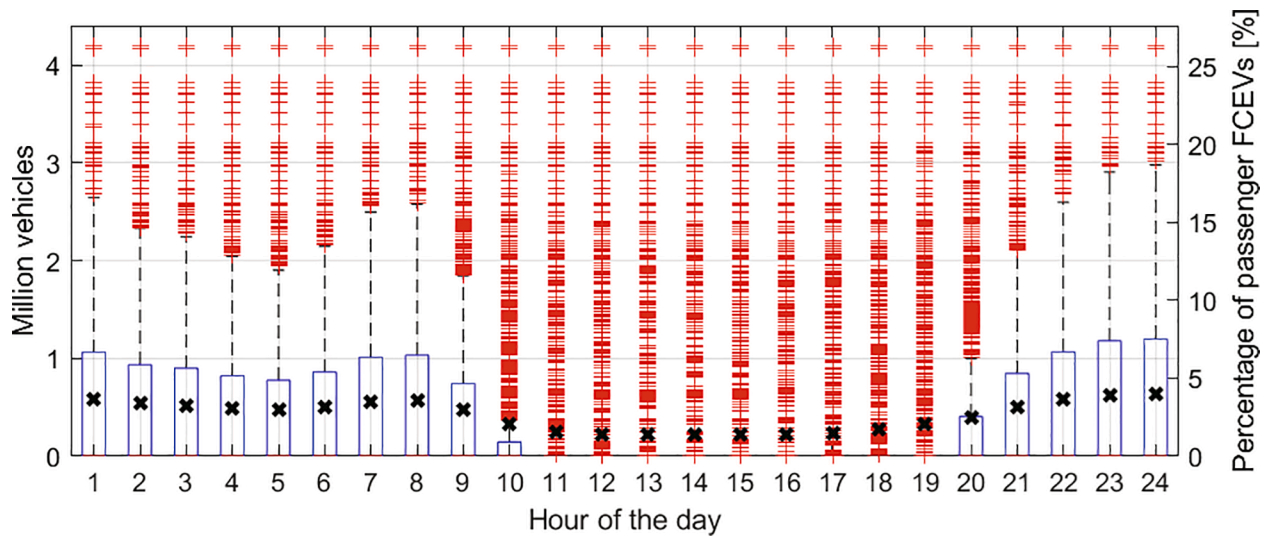


Fig. A10. Boxplot showing the hourly distribution of FCEV2G electricity production in France (million vehicles left y-axis, % of all FCEV passenger cars right y-axis) throughout the day (based on 2014–2017 input data). The black crosses represent the mean values, the medians are indicated by the red horizontal lines in the blue bars. The blue bars represent the range of 50% of the data points. The whiskers represent approximately 49% of the data points. The red pluses indicate the outliers, outside the above-mentioned ranges, and represent less than 1%.

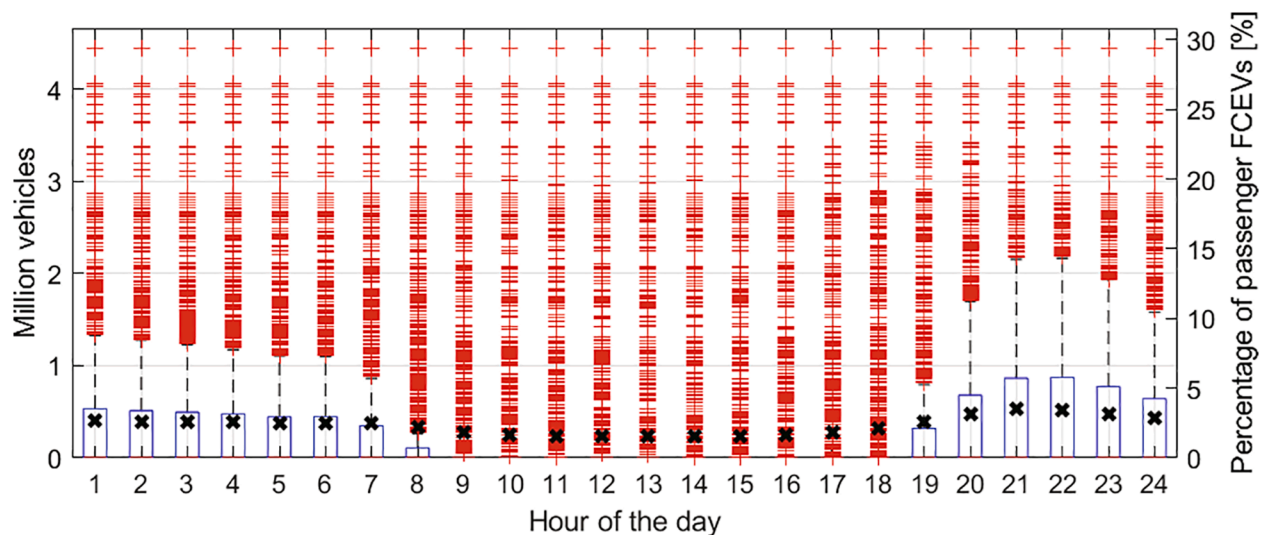


Fig. A11. Boxplot showing the hourly distribution of FCEV2G electricity production in Great Britain (million vehicles left y-axis, % of all FCEV passenger cars right y-axis) throughout the day (based on 2015–2017 input data). The black crosses represent the mean values, the medians are indicated by the red horizontal lines in the blue bars. The blue bars represent the range of 50% of the data points. The whiskers represent approximately 49% of the data points. The red pluses indicate the outliers, outside the above-mentioned ranges, and represent less than 1%.

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