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Energy System Analysis of the Power Sector Flexibility via Hydrogen Utilisation

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Abstract:
According to regulations from the EU Commission, investments in nuclear energy and fossil gas are considered sustainable. These new EU taxonomies, which are intended to provide financial markets with guidance on climate and environmentally friendly investments, actually exclude conventional fossil power- and heat plants. However, the reinterpretation of natural gas as a transitional energy until 2035 allows the construction of new gas-fired power plants. As a limiting factor, an increasing share of low-emission gases have to be used, primarily green hydrogen. In the future, fuel cell power plants could serve as an alternative to such new H_2-ready gas power plants. High-temperature solid oxide fuel cells can not only use fossil methane-containing natural gas and/or hydrogen efficiently, but can also be used reversibly for electrolysis and thus provides flexibility to the power grid. This study uses energy system optimization to analyse the behaviour of both technologies, H_2-ready gas turbines and fuel cell power plants. Across three scenarios, fuel cells are used to provide baseload and flexibility especially in periods of low wind and solar irradiation, whereas hydrogen gas turbines appear last in the order of operation. However, short-term flexibility is provided by battery storage, e.g. by using existing battery capacities from electric vehicles. As Germany has a lower potential for local hydrogen production in an international comparison, significant quantities of hydrogen will only be produced in Germany if import possibilities are strongly limited and technology costs decrease at the same time.

Keywords:
Energy system simulation, Hydrogen, rSOC, sector coupling.

1. Introduction

The decision to make the European energy system, or rather the entire European economic area, climate-neutral by 2050 at the latest is associated with high costs, especially in a short-term period. These costs can lead to a competitive disadvantage for the involved economies. In order to partially compensate for this, the European Commission has introduced regulations, e.g. the European Union (EU) taxonomy. The aim of the taxonomy is a clear definition or classification of sustainable ("green") economic activities. In this context, the European Commission has agreed that the energy transition to a fully defossilised system can only succeed over a transition period in which fossil feedstocks continue to be used. These transitional technologies, in particular conventional natural gas (NG) and nuclear power plants, are initially intended to replace plants with higher specific emissions such as coal-fired power plants. Later on, these power plants are converted to be emission-free. [1]

Focusing on the German energy system, due to the nuclear phase-out, only NG power plants are affected. In recent system studies, it is usually assumed that centralised large-scale power plants will play an important role in energy supply both during the energy transition and in the long-term [2]. Thus, it is assumed that NG-fired power plants will initially replace coal and nuclear power plants in terms of supply security and flexibility. Subsequently, a fuel switch is expected beginning in 2040, whereby both hydrogen-fuelled gas turbines and synthetic natural gas (SNG) are mentioned. However, while these studies assume that the corresponding technology will be available at the respective time, hydrogen gas turbines are not yet state of the art. For this reason, the technical association of energy plant operators (vgbe energy e.V.) has published a position paper and a fact sheet [3] on the topic of *H_2-Readiness* of gas turbines. This includes the definition that *H_2-Readiness* only applies if a gas turbine can be used with 100 % hydrogen or can be upgraded to this in the future. Finally, it is stated that the necessary regulations are still missing at EU level. Thus, it can be concluded that the final boundary conditions for hydrogen utilisation have not yet been finalised. As policy makers often use energy system studies as part of the decision process, extensive research regarding hydrogen and other synthetic energy carrier utilisation is needed [4]. Reviewing existing literature, Yue et al. conclude the not cost-competitiveness is one of the major reasons for the slow increase in hydrogen utilisation worldwide [5].

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They also note that a lack of system integration, e.g. as a planning model, could be a reason why policy makers hesitate to further promote the development of a hydrogen economy. Looking more detailed into existing literature, Ball et al., e.g., modelled the German energy system including a high spatial resolution to discuss the possibility of a German hydrogen economy, focusing on the infrastructure demand and impact on greenhouse gas emissions [6]. Here, hydrogen is not only seen as an alternative to fossil fuels, but also as a storage and flexibility option in fully renewable energy systems. However, the expected hydrogen demands and feedstock costs are outdated due to developments in the energy market in recent years. Robinius et al. discuss the possibilities of power-to-gas as a network expansion alternative [7]. It is shown that there are scenarios in which the use of electrolysers is more reasonable than the expansion of the power grid. Especially when considering both the possibility of selling hydrogen and the saved costs for laying new transmission lines. Li and Mulder evaluated the impact of hydrogen on the electricity and hydrogen market from an more economic point of view [8]. They show that especially in combination with the volatility of renewable power generation power-to-hydrogen brings huge economic advantages. However, they also state the importance of greenhouse gas emission reduction targets, as steam methane reforming still is the cheapest way to produce hydrogen. He et al. published a more detailed study of the complex interactions of sector-coupled systems considering hydrogen as a decarbonisation option on a northern american example [9]. In summary, the concept of sector coupling itself reduces total system costs. For example, since the round-trip efficiency of electricity-to-hydrogen-to-electricity is still low, using hydrogen in other sectors such as transportation reduces losses. They were also able to show that as the demand for hydrogen increases, the specific cost of flexibility decreases. However, the assessment lacks the inclusion of industrial and heating demand. In an extensive review on sector coupling Ramsebner et al. conclude, that there will always be the competition between the higher efficiency of direct electrification versus long-term storage capabilities of power-to-gas applications [10]. As there are many different system-wide effects, no specific predictions can be made. Especially since regional climate goals and policies can strongly influence the final technology deployment. Nevertheless, as some applications are not able to be electrified, there will be a non-neglectable share of hydrogen-based applications.

The use of hydrogen as a flexibility and storage option for the power sector has not been consensually agreed on. It strongly depends on the chosen scenario and assumptions regarding technological and economic parameters. The invention of innovative technologies, such as solid oxide cells (SOCs) with their ability to be operated reversibly for both hydrogen and electricity generation, adds further degrees of freedom to the decision-making process. In this study the utilisation of hydrogen as flexibility option in the electricity sector is evaluated. Therefore, both fuel cell and gas turbine based pathways are benchmarked alongside battery storage as main flexibility option (Figure 1). Due to the great influence of sector coupling on the use and the specific costs of hydrogen, a highly coupled energy system model is used. The German energy system embedded in an abstracted, interconnected European system serves as an example. The focus is on the application of the used technologies, as well as the interactions between different sectors. Therefore, different scenarios are considered and individual system parameters are evaluated. The assessment is related to the EU taxonomy rules, although the latest updates to the regulation regarding temporal and geographical correlation and additionality as defined in [11] are not considered.

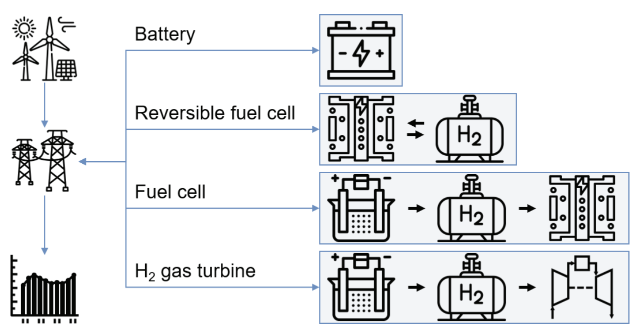

Figure 1: Overview of the considered hydrogen utilisation pathways, including separated hydrogen generation and consumption and the utilisation of reversible technologies.

2. State of the Art and Methods

2.1. Political Boundary Conditions and Current Situation

The use of hydrogen as a sustainable energy carrier is primarily based on the climate protection goals of the German government. The latest amendments to the climate protection law mandate that Germany should be climate-neutral by 2045. This necessarily includes the replacement of fossil energy carriers with sustainable ones. This cost-intensive undertaking is also supported by the EU. Here, several regulations for the member states of the EU have been adopted, which are intended to provide security in financial planning. This includes, for example, the EU taxonomy, which defines whether an investment is beneficial for climate protection and in terms of sustainability. To qualify as a sustainable investment under the new rules, several technical screening criteria must be met [1]. In the case of power generation from fossil gases, a distinction is made between two groups. Plants with life cycle emissions of 100 g_{CO2e} $kWh^{-1}{}_{el}$ or less will be considered sustainable without any further conditions. In addition, there is the possibility to also fall under the label of sustainability for plants that receive their permit to operate by 2030. To do so, a set of criteria must be met, two of which are directly related to the use of hydrogen. For example, specific emissions must initially only comply with a limit of 270 g_{CO2e} $kWh^{-1}{}_{el}$. However, it must be ensured that by 2035 the plants are capable of running entirely on low-carbon fuels. In this context, the results of a UNECE[1] study can be used, in which the life cycle emissions of several power generating technologies are calculated [12]. Here, natural gas based combined cycle power plants without carbon capture and storage have emissions of 403-513 g_{CO2e} $kWh^{-1}{}_{el}$ and with carbon capture and storage 92-220 g_{CO2e} $kWh^{-1}{}_{el}$. Considering only the stoichiometric combustion of natural gas the emissions under assumption of a combined cycle plant efficiency of 63 % are already higher than 315 g_{CO2} $kWh^{-1}{}_{el}$ (see Figure 2). Using an Aspen Plus simulation, Figure 2 also shows the correlation of the specific direct CO_2 emissions with increasing hydrogen admixture. To comply with the limit value of 270 g_{CO2e} $kWh^{-1}{}_{el}$, at least 36.1 vol.-% hydrogen would be required, and for 100 g_{CO2e} $kWh^{-1}{}_{el}$ even more than 87.7 vol.-% hydrogen.

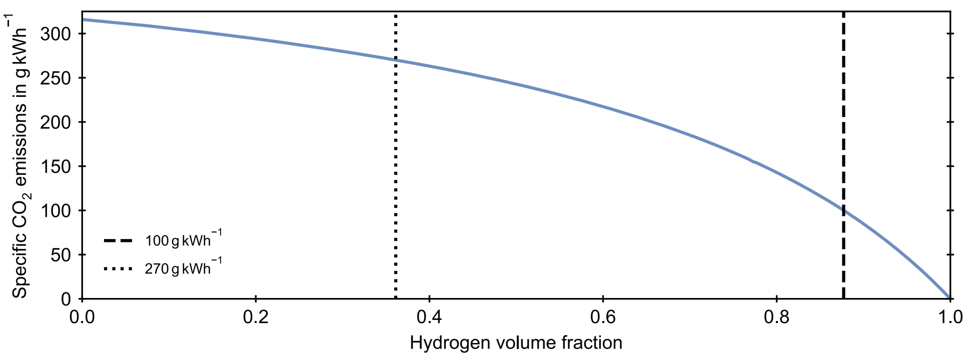

Figure 2: Specific CO_2 emissions of the stoichiometric combustion of a hydrogen-methane mixture with a varying hydrogen fraction.

2.2. Hydrogen Technologies

The aim of the study is to evaluate the flexibility supply via hydrogen in comparison to battery technologies. In the following, the technological and economic parameters of the hydrogen technologies are presented. On the side of battery technology, it is assumed that by 2045 the goals of the German government regarding the expansion of e-mobility and the large-scale application of bidirectional charging (vehicle to grid (V2G)) will have been implemented.

2.2.1. Hydrogen Supply

The supply of green hydrogen in context of this work is realised exclusively via water electrolysis. Both local production within the German energy system and import are allowed. The generation itself can take place via the three technologies alkaline electrolysis (AEL), polymer electrolyte membrane electrolysis (PEMEL) and solid oxide electrolysis (SOEL). The technological and economic parameters are based on literature values for all technologies. As several detailed studies and reviews on each of the technologies, as well as comparative work, are already available, a detailed description is not provided. For more detailed information, the authors refer to the existing literature such as [13,14]. A summary of the parameters used and the corresponding references are given in Table 1. The import of hydrogen is again divided into two segments. First, the import via sea route is possible. Based on [15,16], it is assumed that the import of hydrogen based on renewable power from Saudi Arabia will be possible for a cost of 2.4-3.1 $\$\,kg_{H2}{}^{-1}$ or 5.2 € $kg_{H2}{}^{-1}$ respectively. In addition, hydrogen pipelines can be used to import from sun-rich countries in the EU. For this purpose, the energy system model has the possibility to expand renewables in Italy or Spain in combination with electrolyser capacities to supply hydrogen to the German subsystem[2].

[1] United Nations Economic Commission for Europe

[2] For example the decision to extend the pipeline from the *H2Med* project to Germany.

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2.2.2. Techno-Economic Parameters of Hydrogen Gas Turbines and rSOC

Hydrogen Gas Turbine

When assessing the hydrogen compatibility of gas turbines (GTs), it is necessary to distinguish between two types of combustion methods. Initially, gas turbines utilised a simple diffusion mechanic to burn fuel, which is a robust process. Indeed diffusion-style are already capable of burning pure hydrogen, but comes with the downside of higher NO_x emissions and lower efficiency. To reduce emissions, gas turbine manufacturers introduced a lean-premixed combustion process in the 1980s, for which fuel and air is mixed in a lean ratio before introduced into the combustion chamber. Since then, basically all heavy-duty gas turbines incorporate some form of premixing fuel and air. While the NO_x emissions can be significantly lowered using lean-premixed combustion, the stable operational range of these gas turbines is narrow, making them susceptible for any type of disturbances, like a fuel switch from natural gas to hydrogen, which has fundamentally different combustion characteristics, especially regarding flame temperature, flame speed, volumetric heating value and quenching distance. [17, 18]

The most challenging problem during the combustion of lean-premixed gas is the occurrence of flame flashbacks. Due to the combustibility of the fuel-air mixture, flames in premixed gas turbines can shift from the combustion chamber upstream to the fuel injection nozzles, damaging the turbine hardware. Fuelling hydrogen increases the risk of flame flashback as the higher flame speed of hydrogen more often fulfills the prerequisite of the local flame speed being higher than the local fuel-mixture flow velocity. Additionally, hydrogen has a shorter autoignition delay time. The autoignition delay time corresponds to the time interval for a reactive mixture to react without an ignition source. If this time interval is shorter than the fuel–air mixing residence time in the non-combustion zone, autoignition can occur and lead to local flame holding or further flashbacks. [19]

Another concern are thermoacoustic instabilities, which describe an unwanted feedback loop of combustion fluctuations leading to an unstable heat release and thus pressure oscillations which can excite natural acoustic modes of the combustor, intensify and cause more combustion fluctuations closing the loop. Consequences can reach from affected plant efficiency to damaged hardware. While not being an inherent consequence of fuelling hydrogen, thermoacoustic instabilities are a concern when switching to hydrogen in gas turbines former designed for fuelling natural gas and may prevent an easy retrofit. [20]

Lastly, the higher flame temperature of hydrogen and the increased heat input due to the larger water content in the hot gases have higher demands on materials used for turbine parts like heat shielding or turbine blades. The increased thermal stress will lead to a degradation of parts. Also, effects like hydrogen embrittlement and hot corrosion must be considered. [21]

While there will likely be technical solutions for all of the aforementioned issues, it becomes clear that hydrogen can not simple be burned in today's gas power plants. Yet there are no reports of successfully operating a premixed heavy-duty gas turbine with pure hydrogen. However, for state-of-the-art turbines like the Ansaldo GT36 up to 70 % hydrogen by volume are available for operation. [22]

SOFC and rSOC

SOCs are solid-state electrochemical devices which can either be configured as fuel cell (solid oxide fuel cell (SOFC)) producing electricity directly from oxidizing a fuel or, if configured as electrolyser cell (SOEL), produce hydrogen through water electrolysis. The reactions in a solid oxide cell are reversible, if a solid cell is configured to work alternating as a fuel cell and a electrolyser, it is called reversible solid oxide cell (rSOC) (see Figure 3). SOCs are made of four main components: the anode and cathode (defined in fuel cell-direction), named fuel and oxygen electrode to avoid confusion when the cell operation is reversed, the solid electrolyte layer and the interconnector. [23]

SOCs recently received increased attention due to advantages over other fuel cell/electrolyser technologies. First, the efficiency in both operation modes are the highest reported with over 65 % for SOFCs and over 80 % for SOELs [14]. Second, the aforementioned reversibility, which allow for a high utilization of rSOCs. Third, SOCs can utilize different fuels, like hydrogen, methane or ammonia, making them deployable for a wide range of applications. Fourth, due to their simple layer structure, the currently favoured design, they are predestinated for mass manufacturing and are scalable to any capacity. Additionally, no rare materials like iridium are used in SOCs. While research focuses on finding improved materials, currently mostly Ni-based alloys and yttria-stabilized zirconia (YSZ) are utilised. [24]

Drawbacks of SOCs are the current high investment costs which belong to the highest among all fuel cell/electrolyzer technologies and reported degradation issues. However, the high costs are predicted to decline from todays $>2000\,€\,kW_{el}{}^{-1}$ to less than $800\,€\,kW_{el}{}^{-1}$ in 2045 due to economics of scale (see Table 1). The lifetime is being constantly improved through better material choices and operating modes, like the reversible operation. An example for the improved durability is a long-term test of an SOFC in Jülich, which was shut down after 100,000 h of operation without major power degradation. [25]

Depending on the costs of imported hydrogen, rSOC are an attractive technology to provide flexible power generation to a future energy system as they have a natural investment advantage over an alternative combination of electrolysers and hydrogen gas turbines. They are considered a viable long-term energy storage technology and could improve the integration of renewable energy sources by utilising surplus electricity production for electrolysis.

Currently, SOCs are entering an early commercial phase with several manufacturers announcing investments to scale up their production in the gigawatt range. While this developments mainly relate to SOEC production, exemplary pilot-projects for dedicated rSOC are a 140 kW_{SOEC}/50 kW_{SOFC} installation in 2016 [26] and a 80 kW_{SOEC}/15 kW_{SOFC} in 2018. [27]

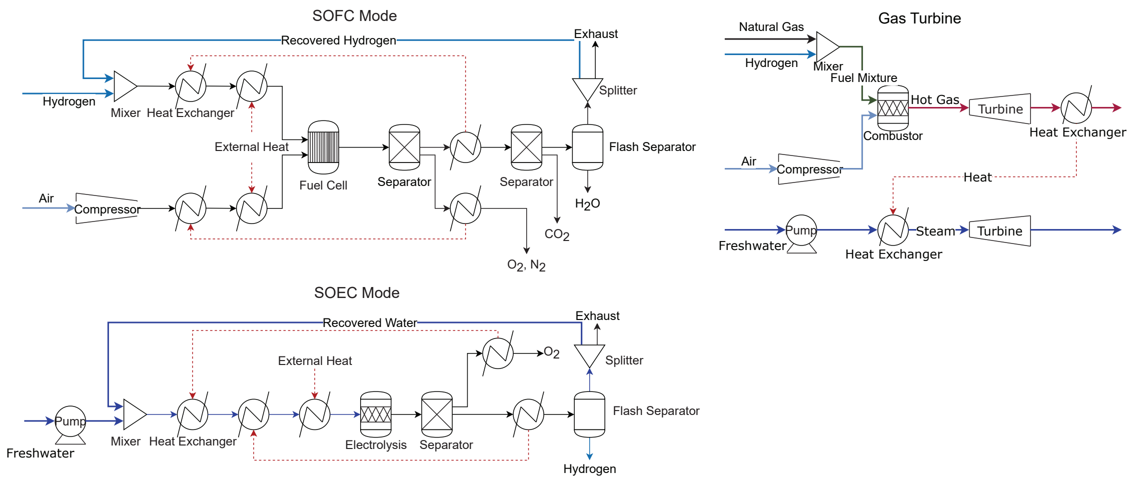

Figure 3: Process flow-sheets of SOC in fuel cell and electrolysis mode (left) and of a combined cycle gas turbine (right).

Cost estimations

Table 1 summarises the key parameters of the hydrogen technologies, where in case of H_2 gas turbines a CCGT is assumed. Included are the efficiency, expected lifetime, as well as the fixed and variable costs. Since the energy system model considers a whole year for each scenario, the costs must be scaled to the annual costs. For this purpose, the annuity method is used.

Table 1: Summary of the hydrogen technologies including technological and economic parameters.

Technology	TRL	Efficiency	Lifetime	CAPEX	OPEX	Reference
Hydrogen CCGT	6-8	0.630	45 a	920 € kW_{el}^{-1}	18 € kW_{el}^{-1} a^{-1}	o.a.[a]
SOFC	5-7	0.699	30 a	640 € kW_{el}^{-1}	51 € kW_{el}^{-1} a^{-1}	o.a.[a]
rSOC	3-6	-	30 a	704 € kW_{el}^{-1}	56 € kW_{el}^{-1} a^{-1}	o.a.[a]
SOEL	5-7	0.800	30 a	640 € kW_{H2}^{-1}	51 € kW_{H2}^{-1} a^{-1}	[13, 14, 29]
PEMEL	7-8	0.590	30 a	300 € kW_{H2}^{-1}	12 € kW_{H2}^{-1} a^{-1}	[13, 14, 29]
AEL	9	0.757	30 a	460 € kW_{H2}^{-1}	18 € kW_{H2}^{-1} a^{-1}	[13, 14, 29]

[a] Own assumption based on Aspen Plus process simulations and [13, 14, 28, 29]

2.3. Energy System Model Framework

The energy system model used is based on the framework ”OpTUMus”, which is described in detail by the authors in [30]. The energy system model is a linear optimization problem, which is solved with IBM ILOG CPLEX 22.10.0 using a barrier optimization algorithm. The temporal resolution for each optimisation problem corresponds to one year in one-hour steps. The model itself is constructed as a *nodes and edges* model. *Nodes* represent different forms of energy or energy carriers such as electricity, hydrogen or natural gas. According to Equation 1 in each time-step t energy and material balances must be conserved for all nodes n.

$$P_{demand}[n][t] + P_{out}[n][t] = P_{in}[n][t] \quad (1)$$

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Edges, on the other hand, describe all possible transformation paths and thus all technologies for energy conversion and transport. This includes the efficiency of energy transportation or transformation from node *n* to *m* in each time step *t* (Equation 2). A simplified example is shown in Figure 4a.

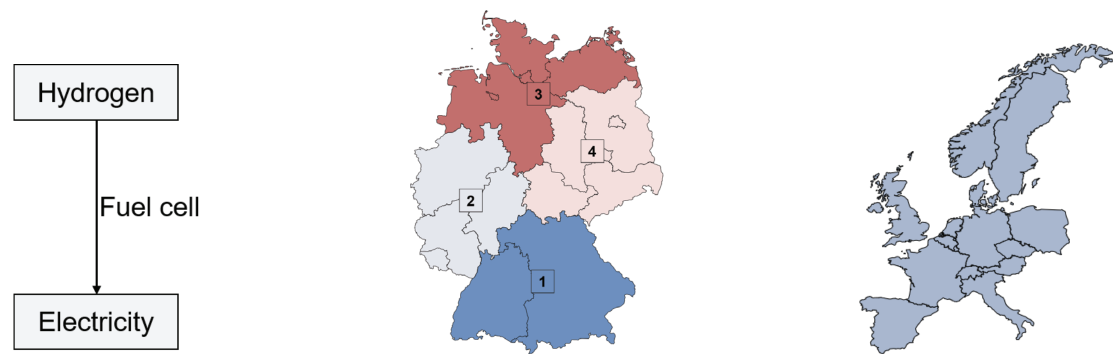
$$P_{in}[n][t] = a_{mn} \cdot P_{in}[m][t] + b_{mn} \tag{2}$$

The model contains an abstract digital twin of the German energy system. This includes the electricity and heating sector as well as the supply of mobility and the supply of energy and a selection of basic chemicals to industrial applications. The German energy system is divided into four regions (Figure 4b) in order to be able to map the local potentials of renewable energies, energy demands and transport limitations. Furthermore, the model includes Germany's direct neighbors as well as Norway, Sweden, the United Kingdom, Spain and Italy, each reduced to the electricity sector. A graphical summary of the regions considered is given in Figure 4c. In order to enable the import of synthetic energy carriers from the southern European regions, electrolysers and pipelines can be built.

On the demand side of the German energy system model, the four sectors

(1) electricity (2) heat (3) mobility (4) industry

are considered. Here, it is important to note that the electricity sector includes all power demands consisting of conventional demands as well as electricity for heating, transport and industry. Each of the demand segments is based on a separate model, which determines the hourly demand for electricity. The material demands for basic chemicals and fuels (methanol (MeOH), SNG, Fischer-Tropsch (FT)-fuels, ammonia (NH_3), hydrogen (H_2)) are also calculated specifically for the respective applications and transferred to the model as a summed demand time series. The same accounts for the heating demand both in domestic and industrial applications. The overall demands are divided into the four regions using statistical methods. Each region is optimised by itself, having the possibility to interact with all neighboring regions. Additionally, the northern and southern Germany regions are allowed to built direct connections for both power and hydrogen transportation. In the same manner, Spain and Italy are connected to the southern German region via the possibility of an hydrogen pipeline. Finally, northern Germany has the option to import hydrogen by ship. The demand side models are adopted from previously by the authors published works [31–33] and therefore are not further discussed. However, an overview of the included technologies and the respective demand side connections are summarised in the appendix in Table 5.



(a) Simplified Scheme of an *edge-node* based energy system model.

(b) Geographical resolution of the model of the German energy system.

(c) Overview of the considered Subsystems of the European energy system model.

Figure 4: Overview of the energy system model basic structure (a), the spatial resolution of the German subsystem (b) and the considered countries of the European energy system model (c).

2.4. Scenario Definition

Various scenarios are important in energy system optimisation to assess the robustness and flexibility of energy systems under different conditions, to identify potential risks and opportunities, and to inform decision-makers for long-term planning and policy development. In context of this work, a variation of hydrogen connected parameters is performed, to identify the influences of the energy system behaviour. Therefore, the parameters hydrogen demand, hydrogen import costs and the technology cost developments are chosen. In a base case scenario, most parameters of the entire model are set to the mean expected values found in literature. Two additional scenarios are defined, one with a higher hydrogen demand (H2-high) and one with a lower penetration of hydrogen and a restricted availability, e.g. reduced pipeline availability, (H2-restr.). At the same time it is assumed, that a higher hydrogen demand correlates with lower specific technology costs and vice versa. Additionally, the overall end-use energy demand stays constant over the different scenarios. Therefore, a higher hydrogen demand is connected to a lower direct electrification. A summary of the scenarios and the respective parameter variation is given in Table 2.

Table 2: Scenario definition with the respective parameter variation.

Scenario	H_2 demand[a]	H_2 import[b]	Tech. costs[c]	Comment
BC	113 TWh a^{-1}	2.4 € $kg_{H2}{}^{-1}$	-	-
H2-high	172 TWh a^{-1}	2.1 € $kg_{H2}{}^{-1}$	-15 %	Electrification ↓, H_2-tech. costs ↓
H2-restr.	113 TWh a^{-1}	5.2 € $kg_{H2}{}^{-1}$	-25 %	H_2 availability ↓, H_2-tech. costs ↓

[a] Only predefined hydrogen demand. Not included are demands for power generation and for further synthesis.
[b] Import via ship from MENA region.
[c] Own assumption; Relative cost reduction for PEMEL, AEL, SOEL, SOFC and rSOC

3. Results

The energy system is largely based on electrical energy. As expected, most of this is provided by wind turbines and photovoltaics, as summarised in Table 3. The contribution of biomass via biogas and combined heat and power is also not to be neglected, whereas plants with higher complexity as polygeneration plants are only used in the restricted scenario. In addition to battery storage or V2G, both conventional gas turbines and hydrogen-based technologies are used to cover the flexibility demand. A summary of the amount of energy provided per technology is given in Table 3. In all scenarios the biomass potential of Germany, which summarises to around 420 TWh a^{-1} for all regions, is fully utilised. Large shares are needed for the heat supply and as carbon source for synthesising chemicals and fuels. This indicates the rising demand for carbon sources in future energy systems. Since this model only allows biomass as a sustainable feedstock, potentials from the use of residues and waste materials - as required in a circular economy - are neglected. In particular, technologies such as polygeneration plants will also be used in the future to exploit residues such as plastic waste and municipal solid waste as input for the synthesis of high-value products or for the efficient supply of flexibility to the electricity and heat sectors. However, doubling the sustainable feedstock potential could reduce the total system costs by 10 %[3], by using the same boundary conditions as in the base case scenario.

Table 3: Summary of the power generation in Germany without storage technologies or grid as comparison between the scenarios BC, H2-high and H2-restr.

	Biomass[a]	GT	H2GT	Hydro	PV	WOFF	WON	SOFC	PolyGen
BC in TWh	86.7	16.0	22.0	12.5	326.8	137.0	224.0	70.5	0.0
H2-high in TWh	85.1	5.5	25.0	13.2	284.9	91.0	225.3	128.0	0.0
H2-restr. in TWh	84.8	35.2	8.2	13.1	415.9	136.6	224.9	7.0	0.9

[a] Sum of all biomass based power plants and CHPs.

As can be seen in Table 4, in the base case scenario hydrogen is exclusively imported. As electricity prices are most of the time (90 %) higher than the import costs of hydrogen, hydrogen production in Germany is not viable under the given boundary conditions. The electricity and hydrogen prices are calculated as shadow prices, which is not directly comparable to the pricing on the stock exchange. In this case, they can rather be interpreted as the hourly system costs for one additional unit of electricity or hydrogen. Summarised, the hydrogen demand is covered mainly by pipeline import from Spain (66 %) and import via ship (30 %). From a system perspective, the mean electricity supply costs 64.06 € MWh^{-1} and the mean hydrogen supply costs 44.95 € MWh^{-1} in the base case scenario. In a restricted overarching system, both electricity and hydrogen prices rise. In the H2restr. scenario, in more than 20 % of the time hydrogen production in Germany becomes more viable than import. While the average electricity costs increase only slightly, the average hydrogen supply costs increase by almost 25 %, with significantly higher extremes in times of low renewable availability. Here, in some hours of the year, even hydrogen production from biomass becomes economical.

Figure 5 gives an overview of the time-resolved utilisation of flexible power in the described energy system, aggregated for all four regions in the base case scenario. As no electrolysis is operated only battery storage

[3]The number is based on a separate optimization in which the identical system but with twice the sustainable feedstock input potential was calculated.

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Table 4: Summary of the hydrogen supply in Germany as comparison between the scenarios BC, H2-high and H2-restr.

	AEL	PEMEL	SOEL	rSOC	ES	IT	Ship
BC in TWh	0.0	0.0	0.0	0.0	176.2	9.6	80.8
H2-high in TWh	0.0	0.0	0.0	0.0	173.5	32.6	202.9
H2-restr. in TWh	0.0	0.0	77.9	0.0	18.1	16.0	36.9

via V2G is used to cover peaks in renewable power generation. Battery storage systems are particularly useful for short-term electricity generation. The available capacity of battery electric vehicles ultimately leads to a factor of 10 greater utilised power of V2G compared to SOFC and H2GT. However, the total amount of energy provided, 94.4 TWh, is comparable to the sum the power generation by fuel cells and gas turbines.

Due to the higher efficiency of the SOFC, fuell cells are used preferably to gas turbines. The load curve in Figure 5 shows that the fuel cells are used to provide the base load in both summer and winter, with a higher share in winter. Particularly during periods of low wind in winter, the fuel cells are operated at full load for several days, as shown in Figure 5 (top left and top right). The fluctuation in the utilisation is greater in summer, which, as can be seen in Figure 5 (top center), falls on the daily rhythm of PV electricity generation and thus behaves comparably to the load peaks of battery storage. Hydrogen gas turbines, in contrast, are used as the last flexibility provider. Particularly in the winter months, some periods can be identified in which gas turbines are operated at full load. However, during the rest of the year, hydrogen gas turbines are only used to cover peak loads for a few hours. The infrastructure of the hydrogen supply via ship combined with the storability of synthesis products as well as the sector coupling effect of hydrogen lead to no further[4] demand of hydrogen storage facilities.

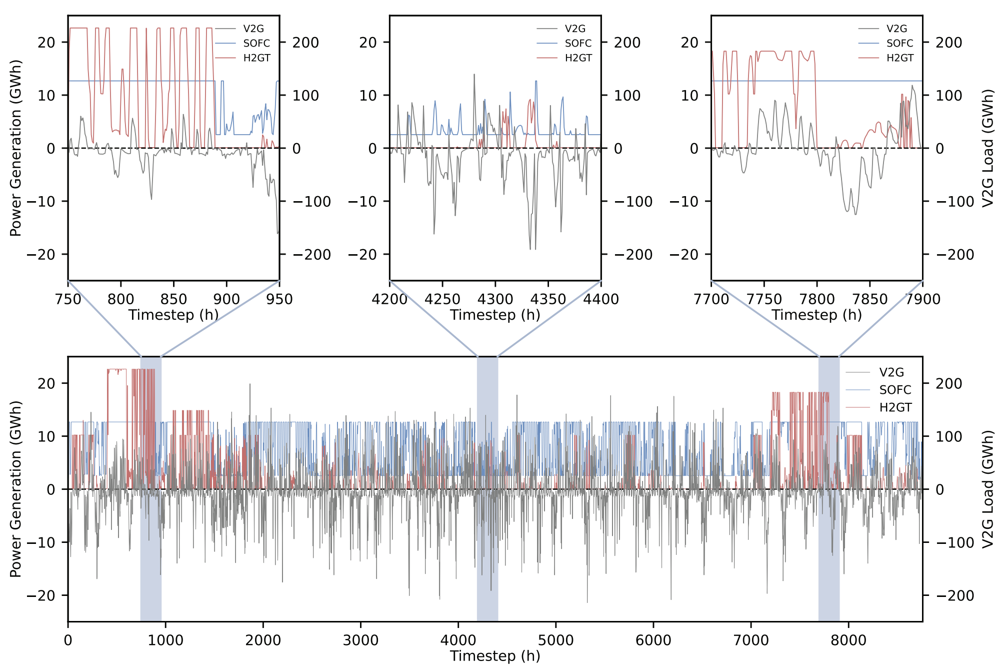

Figure 5: Timeline of the base case power generation via SOFC and hydrogen gas turbines and the utilisation of vehicle-to-grid (V2G) battery storage with additional cut outs for specific time periods.

A more detailed evaluation of the application of hydrogen as a feed-in fuel for electricity generation is shown in the residual load curves of the three scenarios in Figure 6. In the BC scenario and the case of significantly higher hydrogen penetration (Figure 6 left and centre), it can be seen that due to the significantly larger scaled hydrogen production worldwide, on-site generation in Germany is not economical. In contrast, in the restricted scenario (Figure 6 right), electrolysers are operated almost throughout the year. In the case of high residual

[4]Beyond the storage capacity of the ship discharge stations and the storage capacity of the grid.

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load, hydrogen serves to provide base load in all cases, whereby a flexible behaviour with short load cycles can be observed except for a few hours. As the residual load decreases, the demand for electricity generation from hydrogen also decreases and fuel cells and hydrogen gas turbines are only required for flexible power. In case of negative residual load, hydrogen is continuously produced in the restricted scenario, whereby high fluctuation can also be seen here.

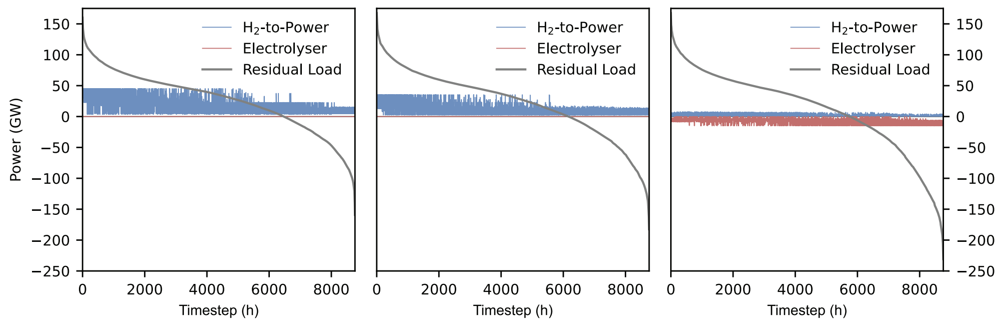

Figure 6: Residual load curve of the H2-high scenario (left), BC scenario (mid) and H2-restr. scenario (right) including the electrolysis and hydrogen based power generation.

4. Conclusion and Outlook

In this work the potential of hydrogen-fuelled gas turbines and solid oxide cells (SOCs) as solutions for providing flexibility in the future electricity grid is evaluated. The study reviews recent publications on both technologies, focusing on the engineering challenges that need to be overcome. Two simplified process simulations ware used to estimate future performance capabilities, and a cost estimation was conducted for both systems.

The analysis finds that both technologies are capable of providing flexible power output in future energy systems with high shares of renewable energy sources. While gas turbines benefit from higher technology maturity and availability, SOCs are more efficient and could act as energy storage due to their reversibility (rSOC), making them a potentially more economical option when considering the whole power-to-gas-to-power chain. However, both technologies still need to overcome significant engineering challenges, such as flashback avoidance in hydrogen gas turbines and better electrolyte and oxygen electrode materials in rSOCs. Cost-wise, gas turbines are currently favored over rSOCs, but rSOCs have the potential to decline in costs as mass manufacturing comes into play.

Energy system modeling shows that if SOCs become economically viable, they could make large scale usage of hydrogen turbines obsolete. Additionally, the results suggest that as long as the electricity supply costs stays to high, electrolysis is not cost-competitive compared to hydrogen import. However, if conservative estimates of future rSOC costs prove correct, the benefits of combining an efficient electrolyser and fuel cell in a single device could make up for the higher costs. Both gas turbines and fuel cells based on SOCs are viable options for providing flexible power output in future energy systems with high shares of renewable energy sources. The choice between these technologies will depend on their respective costs, efficiency, and performance capabilities, as well as the specific requirements of the energy system in question. Both technologies can reduce the overall system costs due to a lower demand of renewable power generation capacities.

However, further model development is needed for a broader discussion of the utilisation of hydrogen in energy systems. On the one hand, the carbon supply for the synthesis of fuels and chemicals could be identified as a limiting factor. Limiting the usability of biomass to what is currently assumed to be sustainable potential by using it to provide heat and electricity and as a carbon source leads to competitive behavior. The utilisation of residues should also be taken into account in order not to impose restrictive boundary conditions on the system. Furthermore, the largest influencing variables could not be clearly determined, which makes the use of a sensitivity analysis indispensable.

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Nomenclature

AEL	alkaline electrolysis
EU	European Union
FT	Fischer-Tropsch
GT	gas turbine
H_2	hydrogen
MeOH	methanol
NG	conventional natural gas
NH_3	ammonia
PEMEL	polymer electrolyte membrane electrolysis
rSOC	reversible solid oxide cell
SNG	synthetic natural gas
SOC	solid oxide cell
SOEL	solid oxide electrolysis
SOFC	solid oxide fuel cell
V2G	vehicle to grid
WOFF	Offshore wind turbines
WON	Onshore wind turbines

Appendix A Energy System Model Technology Portfolio

Table 5: Summary of the considered technology portfolio per region and temporal availability, as well as the associated demand and limitations.

technology	regions	time span	associated demand	limitations
power generation				
photovoltaic	DE, EU[a]	today-2045	electricity	local solar irradiation
onshore wind	DE, EU[a]	today-2045	electricity	local wind potential
offshore wind	DE, EU[a]	today-2045	electricity	local wind potential
biomass plants	DE, EU[a]	today-2045	electricity	local biomass potential
hydro power	DE, EU[a]	today-2045	electricity	today's capacities
CCGT	DE, EU[a]	today-2045	electricity	-
nuclear plant	EU[a]	today-2045	electricity	-
coal power plant	DE, EU[a]	today-2030	electricity	-
battery storage[b]	DE, EU[a]	today-2045	electricity	-
pumped hydro	DE, EU[a]	today-2045	electricity	today's capacities
power grid	DE, EU[a]	today-2045	electricity	-
building-specific heat supply				
heat pump	DE	today-2045	domestic heating	predefined demand[c]
heating rod	DE	today-2045	domestic/process heating	predefined demand[c]
biomass boiler	DE	today-2045	process heating	predefined demand[c]
gas boiler	DE	today-2045	process heating	predefined demand[c]
grid-connected heat supply				
heat pump	DE	today-2045	domestic heating	predefined demand[c]
heating rod	DE	today-2045	domestic heating	predefined demand[c]
biomass CHP	DE	today-2045	domestic heating	predefined demand[c]
gas CHP	DE	today-2045	domestic heating	predefined demand[c]
geothermal energy	DE	today-2045	domestic heating	predefined demand[c]
base chemicals and energy carriers				
electrolysis	DE, ES, IT	today-2045	H_2	-
power-to-x	DE	today-2045	MeOH, SNG, NH_3, FT-fuels	CO_2 point sources[d]
biomass-to-x	DE	today-2045	H_2, MeOH, SNG, NH_3, FT-fuels	local biomass potential
polygeneration[e]	DE	today-2045	H_2, MeOH, SNG, NH_3, FT-fuels, electricity	local biomass potential
hydrogen import	DE	today-2045	H_2	-
hydrogen pipelines	DE, ES, IT	today-2045	H_2	-

[a] If applicable in specific region.
[b] Implemented as bi-directional battery electrical vehicle storage: .
[c] The demand is calculated by an GIS based analysis in [31].
[d] If applicable to specific technology. This includes cement plants and fossil gas power plants.
[e] Polygeneration of synthetic energy carriers and electricity from biogenic feedstock.

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