Renewable and Sustainable Energy Reviews 45 (2015) 207–218

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Power to liquid and power to gas: An option for the German *Energiewende*

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ARTICLE INFO

Article history:
Received 22 June 2014
Received in revised form
27 November 2014
Accepted 9 January 2015
Available online 9 February 2015

Keywords:
Energy model
Energy transition
Sustainability
Co-electrolysis
Power to liquid
Power to gas

ABSTRACT

The large-scale deployment of renewable energy sources (RES) is an important aspect of decarbonising the energy supply, and represents a key part of the German *Energiewende*. However, significantly increasing the share of renewable power in the energy mix implies coping with the natural intermittency of RES like wind and solar. RES development also does not directly address non-electric energy needs such as fuels for transportation and industry feedstock, which are presently relying on fossil fuels. Therefore, the conversion of surplus renewable electricity (RES-E) into the more convenient form of a liquid or gas (power-to-liquid and power-to-gas) could help offset RES intermittency while providing a diverse mix of energy carriers. If recycled CO_2 is used in the fuel synthesis process, overall emissions can be greatly reduced. This paper aims to sketch the possible contribution of RES-E combined with power-to-gas (PtG) and power-to-liquid (PtL) schemes in the 2050 German energy system, by modelling an increase in installed renewable power. Different scenarios are laid out and compared, and the results are utilised in a basic economic assessment of the fuel production cost for an hypothetical power-to-liquid plant.

Contents

1. Introduction

Greenhouse gas (GHG) emissions are the major driver of man-made climate change. The emission of carbon dioxide, the largest source of GHG, has growing dramatically in the last decades, due

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http://dx.doi.org/10.1016/j.rser.2015.01.049
1364-0321/

in large part to the combustion of fossil fuels for transportation and power generation. Emissions from the transport sector have been the fastest growing, with a more than 50% increase since 1990, and now account for a quarter of all CO_2 emissions from fuel combustion [1]. With global energy demand set to double by 2050, most scenarios forecast a continued reliance on fossil hydrocarbons and their products for the decades to come, a trend that is likely to negate any effort at curbing global warming [2]. In the case of transport, economic growth in developing countries such as China and India will drive transport fuel demand up by at least 40% by 2050, a demand that under current policies will be met with a fuel mix heavily dependent on fossil fuels, resulting in a significant increase in CO_2 emissions [3].

The transition to a more sustainable energy system will therefore require a switch to low-GHG energy supply technologies such as renewable energy sources (RES). In the last years, many RES technologies have achieved significant progress in technical and economic maturity accompanied by a sizeable growth in installed capacity [4]. Further deployment of RES is a major target of many countries' long-term energy strategy. In Germany, the Integrated Energy and Climate Programme [5] aims to increase the share of renewable power in the energy supply from the current 20% to 35% in 2020 and 80% in 2050. Greater RES penetration is one of the drivers of the programme's GHG reduction targets (40% by 2020 and 80–95% by 2050) [5–14].

Yet, RES deployment at a significant scale faces a number of constraints or limiting factors. In particular, the natural intermittency of RES translates into a variable and not entirely predictable power output, thereby creating system balancing and capacity adequacy issues that may hamper the viability of an energy supply configuration relying mostly on RES. For instance, the ability of wind power to ensure availability of sufficient power generation (capacity value) ranges from 5% to 40% of the nameplate capacity [4]. Conversely, variable RES output can lead to periods when power generation far exceeds demand, thus straining the system's flexibility or resulting in an economic loss if plants are switched off. Higher shares of renewable electricity (RES-E) will therefore require appropriate system balancing measures, of which energy storage is a potential option. As mentioned in the IPCC's *Mitigation of Climate Change* report [4], "because some forms of RE are primarily used to produce electricity, the ultimate contribution of RE to overall energy supply may be dictated in part […] by using RE to produce other energy carriers".

Finally, while RES represent a promising avenue to decarbonising the energy supply, they do not directly address fossil fuels combustion in the transport sector and its related GHG emissions. In this sector, a transition to electrical vehicles – backed by renewable electricity generation – is a possible solution, but which however entails several limitations (heavy load vehicles, aviation, marine transport) as well as major infrastructure changes and related costs.

1.1. The role of synthetic fuels

In this context, synthetic fuels such as methanol (CH_3OH), dimethyl ether (DME), methane (CH_4) and other hydrocarbons are being promoted as storage media for surplus RES power that could easily substitute fossil fuels and their derived products in many sectors, including transportation. Transforming renewable energy (electricity and/or heat) into the more convenient form of liquid and gaseous energy carriers (power-to-liquid and power-to-gas) offers a way to buffer RES intermittency and thereby alleviate one of the main constraints to their large scale deployment. All synthetic fuels could moreover be directly integrated into existing infrastructure (e.g. filling stations) without incurring excessive costs, technical barriers or change in habits. This has implications for the transport sector, but also for many other sectors of application where synthetic fuels could be used as final energy carriers and raw material: industry, electricity generation, heating, chemical feedstock, fuel cells.

Additionally, the carbon input required for the fuel synthesis process could be obtained from recycled CO_2, such as CO_2 captured from large point sources like fossil-burning power plants, or, in the future, from the air itself [15–17]. Such Carbon Capture and Utilisation (CCU) schemes could transform CO_2 from a liability into an asset [18–21]. This approach builds upon the growing technological expertise on carbon capture, but, compared to Carbon Capture and Sequestration (CCS) [15,22], it avoids the technical difficulties and safety concerns associated with long-term CO_2 storage [23–25]. Consequently, the combination of renewable inputs (RES power and captured CO_2) in the synthesis process could lead to a potentially carbon neutral fuel cycle, and truly sustainable synthetic fuels [26]. Based on PtL and PtG technologies, all components of the final energy mix – electricity, liquid and gaseous fuels, feedstocks – could therefore be successfully covered whilst greatly reducing CO_2 emissions [27].

1.2. The methanol economy®

Among synthetic fuels, methanol in particular holds significant potential due to its inherent proprieties and diverse applications. These have led Nobel Laureate George A. Olah to develop and promote the concept of a "Methanol Economy®" [28,29] as a more practical alternative to, for instance, a "Hydrogen Economy". The use of hydrogen (H_2) as final energy carrier is interesting because of its clean combustion, but in practice the storage, transport and distribution of H_2 raises many technological and safety concerns (e.g. it is a highly explosive gas), while the cost of transforming the whole energy infrastructure is likely to prove economically prohibitive.

By contrast, methanol is a liquid under normal conditions, meaning its handling does not require extensive safety precautions and high pressures (or very low temperatures), and its volumetric energy density is higher than H_2. The synthesis of methanol is well known industrially [30,31], as its conversion to higher hydrocarbons required to supply specific transport sectors like kerosene for aviation [32,33]. As a fuel for internal combustion engines (ICE), methanol also provides a number of benefits pertaining to safety and engine performance (high octane rating, heat of vaporization, flame speed), and its combustion is cleaner than that of petrol [34–37]. The power train and marine vehicle companies for instance have been demonstrating growing interest in methanol and other synthetic fuels in order to curb SO_x and NO_x emissions [38]. Similarly, DME is an equally interesting alternative fuel for diesel engines [39,40].

While transportation would be the main sector of application, synthetic fuels could replace fossil-derived products in other sectors as well, such as electricity generation in conventional power plants and the chemical industry [41]. Indeed, higher (cetane and octane) fuels can also be synthetically produced, while methanol is a flexible C1 platform chemical that can be transformed into a variety of commercially relevant compounds like propylene, often using already established processes.

1.3. 2050 German energy scenario

In the last years, developments in the sector of H_2O and CO_2 reduction via electrolysis have led to significant growth in process efficiency and improvements in material durability and robustness, making PtL and PtG schemes an increasingly attractive option for future energy scenarios [42–45]. In the German case, recent reports from the German Federal Environment Agency [46–48] aim to demonstrate the technical and ecological feasibility of greatly reducing GHG emissions in 2050 by relying entirely on renewable

electricity supply and PtL/PtG conversions. The main premises include enhancements in energy efficiency measures, the complete phasing out of fossil and nuclear energy, and the absence of CCS and of biomass cultivation for energy purposes. In 2050, the primary energy supply would consist of 100% renewable energy, and all non-electric energy needs would be covered by renewably produced synthetic fuels (essentially methanol and methane). As a result, CO_2 emissions from the energy sector (including transport) would be cut down to almost 0. Unavoidable residual emissions would arise from agriculture and some industrial processes.

Based on the assumptions and framework of these scenarios, as well as the current characteristics of PtL and PtG technologies, this paper aims to sketch a preliminary evaluation of the RE installed power and sustainable synthetic fuel production in 2050 Germany. An increase in installed renewable power (mainly wind and photovoltaic) is modelled in order to determine RES-E generation and overflow ratios. The results are subsequently combined with other parameters to provide a rough cost estimate of renewable fuel production.

Except for this cost estimate, this paper does not aim to provide a comprehensive assessment of the technical challenges, costs and economic benefits of realising the proposed scenarios. Greatly increasing RES-E production, for instance, would require substantial investments in electricity grid expansion that combined with the large scale application of PtL and PtG technologies, would also imply new plants as well as modifications to the fuel distribution infrastructure. All of these aspects represent important areas of inquiry that, however, are out of the scope of this paper.

2. PtL and PtG technologies

In principle, there are four main components in the synthetic fuel production chain:

- Carbon source—e.g. CO_2 capture;
- Hydrogen and/or synthesis gas production;
- Fuel synthesis;
- Fuel purification (if required).

Utilising captured CO_2 as the carbon source in the synthesis process is an attractive option for the reasons detailed in the Introduction [49–51]. Alternatively, biomass and associated low-value wastes can also represent a suitable carbon source, and in this field, commercial applications have already been established [52,53]. However, biomass-based processes are ill-suited for large-scale synthetic fuel production due to constraints on biomass availability (quantity, location, etc.)

Synthesis gas ("syn-gas") is composed predominantly of H_2 and CO but also may contain CO_2 (depending on its source) [54]. The molar H_2/CO syn-gas ratio will be determined by production route; for methanol synthesis, the ideal ratio is 2. Conventionally, it is produced from the steam reforming of methane (SMR) or from coal gasification. The latter process produces large quantities of CO_2, while SMR requires a significant heat energy input. Both processes produce syn-gas not optimal for methanol synthesis and rely on the consumption of finite fossil reserves. Alternatively, CO_2 and H_2 can be reacted directly to produce methanol (and H_2O); meaning routes to the sustainable production of H_2 are also required.

In recent years, a number of innovative technologies for the production of sustainable synthetic fuels have emerged and currently are at different stages of industrial maturity [40,55–57]. Among these, electrolysis and Solid Oxide Electrolysis Cells (SOECs) in particular could play a central role in future renewable fuels scenarios.

2.1. Electrolysis and SOECs

Electrolysis is an electrochemical process utilising a direct current to drive an otherwise non-spontaneous reaction. Electricity can be converted into chemical energy very efficiently in an "electrolysis cell" as there are no moving parts (e.g. high Carnot efficiency). The recent market introduction of Solid Oxide Electrolysis Cells (SOEC) is of particular significance. These high temperature cells can electrochemically reduce H_2O or H_2O and CO_2 (co-electrolysis) at very high efficiencies to produce either H_2 or syn-gas for fuel synthesis [58,59]. The SOEC operates typically in the 700–1000 °C range, meaning part of the energy required for the chemical reduction can be obtained from heat—obtainable via a consequence of internal cell resistance or heat exchange from associated processes. After extensive R&D efforts, SOECs are now entering the market and are receiving serious consideration in synthetic fuel production schemes [60], with recent reports indicating final efficiency of around 70%, depending on the produced fuel [61,62].

These cells can operate in either electrolysis mode – converting surplus electricity to chemical energy – or fuel cell mode – converting chemical to electrical energy – by changing the current direction. Furthermore, the H_2 and O_2 are physically separated within the cell and of extremely high purity, reducing the need for purification steps.

In light of these characteristics, SOECs and the stated efficiency numbers are taken as the reference technology for the modelling approach in Section 3 and the economic assessment in Section 4.

2.2. Coupling electrolysis with oxy-fuel combustion

The mass balance of the gaseous materials involved in the process is an important feature of the co-electrolysis of H_2O and CO_2. When the electrolytic process is designed in order to achieve the ideal stoichiometric ratio – i.e. for methanol production $H_2/CO=2$ – the only by-product of the process is pure oxygen. From a stoichiometric point of view, for each mole of produced methanol the co-electrolysis process releases as a by-product 1.5 mol of O_2, which could potentially hold a commercial value of their own.

Indeed, in a scenario featuring widespread application of co-electrolysis for PtL and PtG conversions, the resulting massive oxygen by-product could be coupled with oxy-fuel capture technologies.

There are essentially two routes to CO_2 capture: either leaving the combustion technology unchanged (post-combustion) and capturing from large volumes of flue gases with low CO_2 concentrations (mainly in the range of 3–20% depending on the process and fuel used) or changing the combustion technology to directly create highly concentrated CO_2 streams (pre-combustion). Within the latter category, oxy-fuel combustion technologies utilise nearly

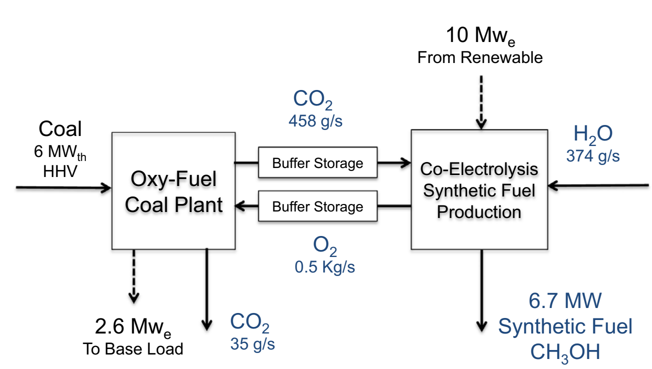


Fig. 1. A schematic energy balance of an integrated oxy-fuel and co-electrolysis processes [15].

pure oxygen instead of air for combustion, resulting in a flue gas that is mainly composed of CO_2 and H_2O, thereby facilitating the capture of CO_2 [22,63]. Nowadays, these technologies are in use in the aluminium, iron and steel and glass melting industries, whereas applications for new build pulverized coal fired power plants have not reached commercial scale yet but are at the prototype level [64].

In oxy-fuel plants, the oxygen is usually produced by low temperature (cryogenic) air separation and novel techniques to supply oxygen to the fuel, such as membranes and chemical looping cycles are being developed.

Based on the mass balance and taking into account the respective feedstocks and by-products of the two processes (co-electrolysis and oxy-fuel combustion), coupling the two technologies could represent an interesting option: the almost pure (over 95% with a small content of water) CO_2 stream from the oxy-fuel pulverized coal power plant could be used as a feedstock for the co-electrolysis process, while on the other hand the O_2 stream by-product could be used for the oxy-combustion.

In this configuration, the coal power plant provides a continuous production of electric energy that can be used to supply base load power, while the co-electrolysis process can be driven by intermittent renewable electricity. Oxygen provided from the electrolysis process does not require Air Separation Unit (ASU), increasing the final efficiency of the coal power plant, whereas the high-purity captured CO_2 is directly utilised for fuel synthesis, minimising transportation issues and avoiding altogether the challenges of carbon sequestration [22,23,64].

Fig. 1 shows a rough overview of the energy and mass balance of the integrated oxy-fuel and co-electrolysis process.

3. 2050 German RES-E scenarios modelling

This section aims to model an increase in RES installed capacity in Germany and calculate the resulting availability of surplus RES-E in 2050 and for different scenarios. RES-E load curve dynamics in Germany are based upon the 2012 data, while the assumptions, targets and boundaries for 2050 are taken from the UBA's scenarios.

3.1. Defining the model boundaries

As mentioned in the Introduction, recent studies from the German Federal Environment Agency have described a possible 2050 energy scenario relying on a RES-based primary energy supply and resulting in a 95% reduction in GHG emissions compared to 1990.

The key component is the production of H_2 through electrolysis powered by RES-E, and subsequent conversions to renewable synthetic fuels. The feasibility of this scenario is grounded on a number of assumptions and parameters which we adopt as boundaries for our model and which are as follows [35–37]:

- Electricity supply will be generated entirely from RES (predominantly wind and PV) [35]. In this scenario, RES-E also represents most of the primary energy supply (since all final energy carriers are produced from RES-E). Domestic RES-E production covers most or the totality of the final electricity consumption;
- Energy consumption in 2050 is almost halved, thanks to the implementation of energy efficiency measures across all sectors as well as a 12.5% decrease in population;
- Germany remains an industrial and exporting country, and consumption behaviours remain essentially unchanged;
- A number of technologies currently at pilot status will have reached industrial maturity by 2050;
- No growing of crops as biomass for energy production; the only biomass sources are waste and residues, and only play a limited role;
- Fossil fuels as well as nuclear energy are completely phased out;
- Carbon Capture and Sequestration (CCS) is not utilised.

In this scenario, RES-E production covers almost all of the final energy demand either directly (final electricity consumption) or indirectly through PtL and PtG conversions. Fig. 2 shows a schematic representation of the energy flows and the final energy carrier mix.

Based on the assumptions presented above, the estimated final energy demand in 2050 would amount to 1605 TW h/year, a 35% reduction compared to the current 2500 TW h/year. The final energy use per energy carrier is reported in Table 1.

3.2. Electric load curve and RES-E

The 2012 values for electricity consumption and RES-E generation in Germany are taken as reference data.

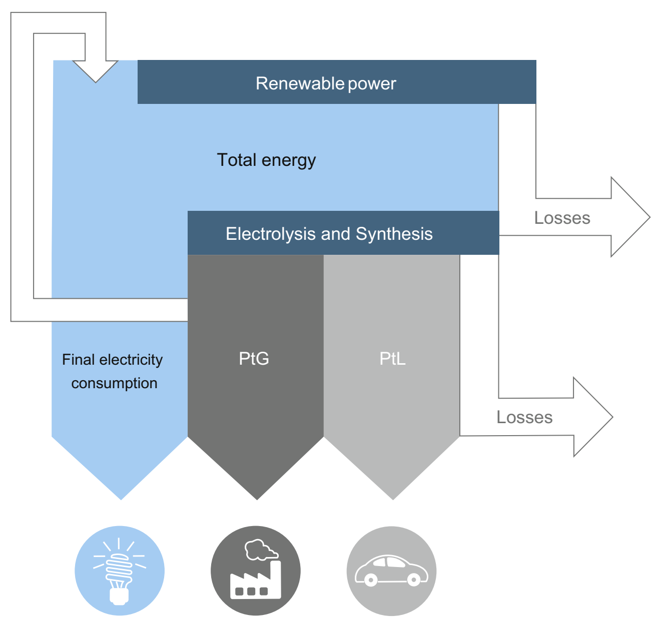


Fig. 2. Final energy carrier mix in a RES/renewable fuels scenario with extensive use of electrolysis and SOECs in particular (adapted from an original illustration from the UBA [49]).

Table 1
Total final energy use in 2050 in the UBA THGND 2050 Scenario [49] (GHD: Gewerbe, Handel, Dienstleisung Industry, trade, service.

Total final energy use in 2050 in the UBA scenario			
	Electricity in TW h	Renewable methane in TW h	Liquid renewable fuels in TW h
Private households	104.7	44.5	0
GHD	90.3	62.4	18.6
Industry energy[a,b]	179.7	198.8	0
Transportation	91.1	0	533.3
Total energy	465.8	305.7	551.9
	1323.4		
Industry material	282		
Total energy and material	1605.4		

[a] Excluding 15.1 TW h from internal production flow in the paper industry.
[b] Beyond the power requirements for the industrial processes themselves, heating, lighting and IT power requirements are also included.

The primary quantity Φ_L is defined as the total load of electric energy consumption during the year calculated as the integral of the load curve $L(t)$ using the hourly average load profile of 2012 published by the European Network of Transmission System Operators for Electricity (ENTSOE). This data refers to the hourly average active power absorbed by all installations connected to the transmission network or to the distribution network; it is not entirely precise but of sufficient quality for the purpose of this model.

The integral of the curve $L_{2012}(t)$ [65,66] corresponding to the total electric energy consumed in Germany in 2012 leads to a value of:

$$\Phi_{L2012} = \int L_{2012}(t) = 520\ \text{TW h}(1858\ \text{PJ})$$

In the same period, the RES-E generation in Germany (wind and PV [67]) is represented by the curve $WP_{2012}(t)$ whose integral corresponds to the total renewable electricity produced in Germany from wind and PV in 2012:

$$\Phi_{WP2012} = \int WP_{2012}(t) = 74\ \text{TW h}(264.2\ \text{PJ})$$

that corresponds to a ratio of about 14% of the total load Φ_{L2012}:

$$\frac{\Phi_{WP2012}}{\Phi_{L2012}} = 14\%$$

Including hydropower production ($\Phi_{H2012} = \int H_{2012}(t) =$ 21.2 TW h in 2012) the ratio of renewable electricity introduced into the electric grid is:

$$\frac{\Phi_{RE2012}}{\Phi_{L2012}} = 18\%$$

The two curves, representing the total load $L_{2012}(t)$ and the electric production from renewables introduced into the grid $RE_{2012}(t)$ (hydro+PV+wind) are shown in Fig. 3. For the sake of simplicity, the contribution of hydropower production is considered here as a constant value throughout the entire year.

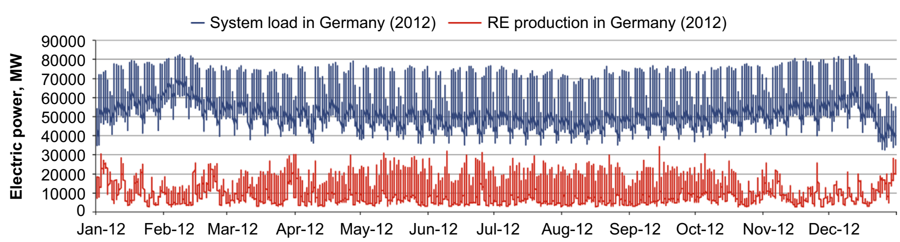


Fig. 3. Total electrical energy load (blue) and RES-E production (red) in Germany in 2012 [66–68]. RES-E production averages 18%, but fluctuates greatly. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

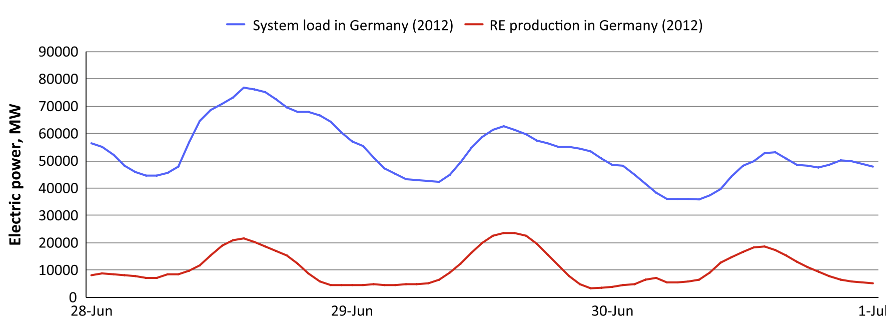


Fig. 4. Enlargement of Fig. 3 for the period 28 June–1 July 2012. This window shows a peak period of renewable share in the electric consumption.

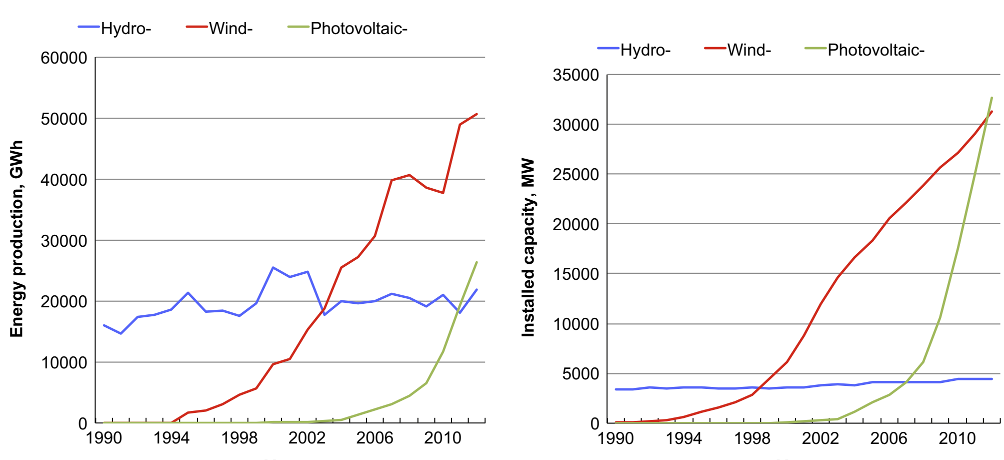


Fig. 5. Development of electric production (right) and installed capacity (left) of power generation facilities from RES in Germany in the period 1990–2012 [67]. Hydropower has remained constant whereas wind and photovoltaic have been increasing rapidly.

These two series will be considered as reference data for the elaboration of the model. Fig. 4 shows an enlarged window of three days with both series of data.

Fig. 5 shows the evolution of the installed power and electricity production of the three main RES-E in the period 1990–2012 in Germany [66]. The curves underline the exponential growth of PV and wind power in the last two decades.

3.3. Scaling up RES-E installed capacity in 2050

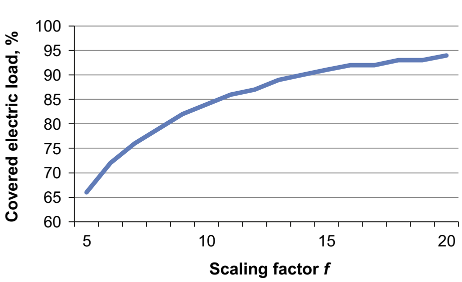
The long-term final energy demand in the 2050 scenario would be composed of approximately 466 TW h/a for final electricity consumption, 306 TW h/a for renewable methane, 552 TW h/a for vehicle fuel (such as renewable methanol) and 282 TW h/a for renewable inputs in the chemical industry (Table 1). The total electric load in 2050, $\Phi_{L2050,}$ is therefore expected to decrease from the current 520 TW h/year to 466 TW h/year. This 11% decrease is much lower than the overall 35% reduction in energy consumption (Section 3.1), because energy efficiency measures are partly offset by a forecasted shift towards electricity as final energy carrier in a number of sectors (greater share of electric vehicles for instance) [48].

We assume that the 2050 electric load curve and its integral value, $L_{2050}(t)$, can be scaled up from the 2012 curves:

$$\Phi_{L2050} = 0.89\Phi_{L2012} \quad \text{and} \quad L_{2050}(t) = 0.89L_{2012}(t)$$

Supposing that the RE installed power – wind and PV – can be increased indefinitely without technical limitations or geographical and/or economic constraints, the first step is quantifying the amount of installed RE capacity that is needed to cover a defined amount of the total electric load in 2050.

In other words, we suppose to be able to "rigidly" translate the wind and PV electricity production – multiplying the $WP_{2012}(t)$ curve by a scaling factor f—until the RES-E production RE_{2050} (t) covers a large part of the electricity load curve in 2050, $L_{2050}(t)$. This calculation obviously negates some of the issue's complexity – for instance, it assumes weather performances identical to 2012 – but it can nonetheless provide a good indication of RES-E load behavior in 2050.



f	$\%\Phi_L$
5	66
6	72
7	76
8	79
9	82
10	84
11	86
12	87
13	89
14	90
15	91
16	92
17	92
18	93
19	93
20	94

Fig. 6. Relationship between the scaled installed RES power and the percentage of the covered electric load, curve (left) and table (right).

Finally, another assumption is that there is no possibility to further increase the current hydropower production – $H_{2012}(t)$ – which in all the models is therefore kept constant at the 2012 values.

$$RE_{2050}(t) = f \times WP_{2012}(t) + H_{2012}(t)$$

The table in Fig. 6 right shows the relationship between the scaling factor f and percentage of final electricity consumption covered by RES-E. The asymptotic behavior of the trend is made apparent by the curve in Fig. 6 left. Of course, future improvements in RES efficiency could mean that the same level of RES-E output could be achieved with a lesser increase in installed capacity, but the consequences in terms of intermittency and surplus electricity generation remain the same.

Based on this overview, specific values for the scaling factor f can be selected in order to examine the implications of different RES-E scenarios.

3.4. The 2050, $f=20$, self-sufficient scenario

Our first scenario is based on a scaling factor f equal to 20.

Fig. 7 shows the same three-days interval as Fig. 4, but with $WP(t)$ scaled up by a factor $f=20$.

In this scenario, the total amount of electric load not covered by the RES-E production can be calculated as the integral of the blue areas not enclosed by the two curves:

$$\Phi_{out2050} = \int [L_{2050}(t) - RE_{2050}(t)]dt$$

when $RE_{2050}(t) < L_{2050}(t) = 0.06 \times \Phi_L$

Scaling 20 times the installed wind and PV power, RES-E production would fulfil 94% of the total electric load, that is to say 440 TW h/year out of 466 TW h/year.

However, RES-E production also generates large amounts of surplus power: this is reported in Fig. 8, with the positive electrical residual load in red, and the unfulfilled electrical demand in blue.

Accordingly, the *overflow ratio* can be defined as the ratio between the periods of time during which RES-E supplied to the electrical network exceeds consumption, and the yearly time frame.

In the case $f=20$, the overflow ratio amounts to 84%, which translates into 7343 h during the year or circa 1052 TW h of surplus RES power that can be used for PtL and PtG conversions. Using SOECs and assuming a total process efficiency of 70% (see Section 2.1), this surplus power could be transformed into 737 TW h of liquid and gaseous fuels.

This amount represents 64% of the 2050 total combined fuel needs (methane and liquid fuels), which correspond to 1140 TW h/year, or 85% of the fuels needed for energy purposes (i.e. excluding industry material—see Table 1).

Moreover, additional renewable energy can be provided by secondary sources such as firewood, peat, sewage, waste, etc. In 2012, the energy produced from these sources – and not fed into the grid – represented 343 TW h (see Fig. 9), and could be increased significantly in the future. Fig. 9 shows the trend of secondary renewable energy production in Germany up to 2012

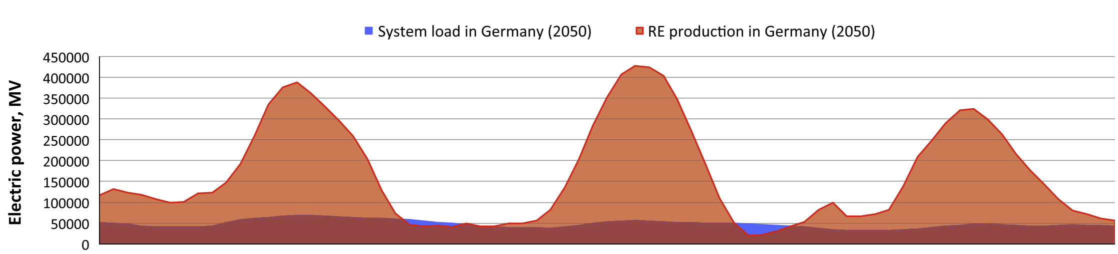


Fig. 7. The red curve represents the renewable electricity production scaled 20 times, while the blue curve represents the forecasted electric load in 2050. The blue regions show the 6% of non-covered electric load. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

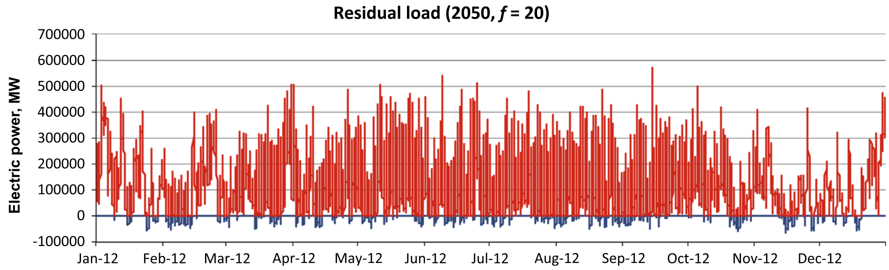


Fig. 8. Residual load for the case $f=20$. The red curve shows the redundant renewable electricity production, and the blue curve the share of total load not covered by renewable electricity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

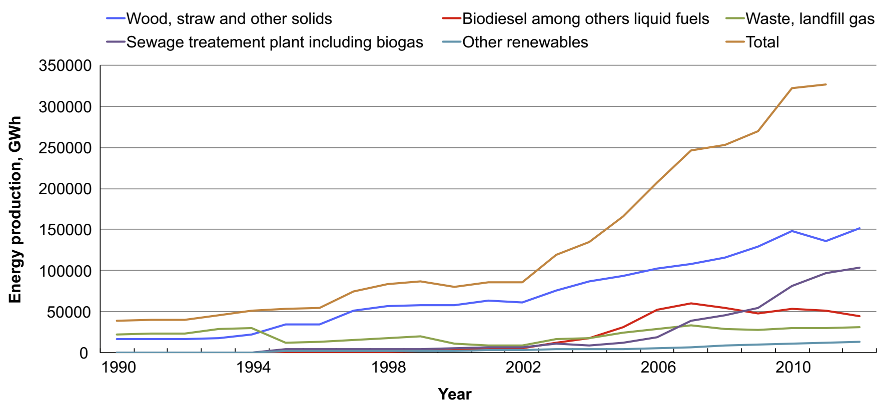


Fig. 9. Contribution to primary energy consumption of RES not used for electricity production in Germany in the period 1990–2012 [67].

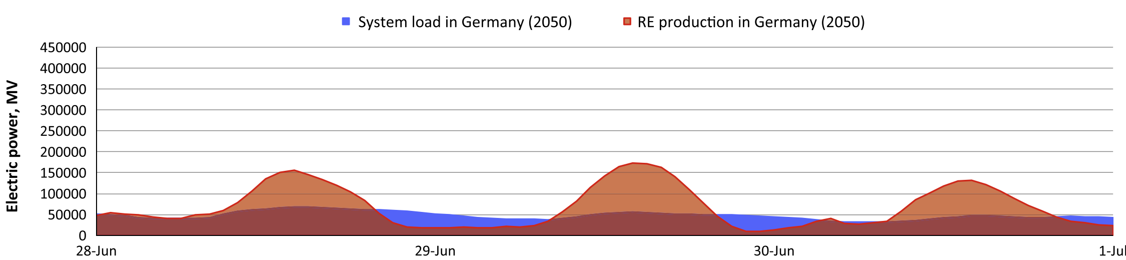


Fig. 10. Same as Fig. 7, but for the $f=8$ case. The vertical scale is left intentionally equal to that of Fig. 7 to highlight the differences in the final electrical production.

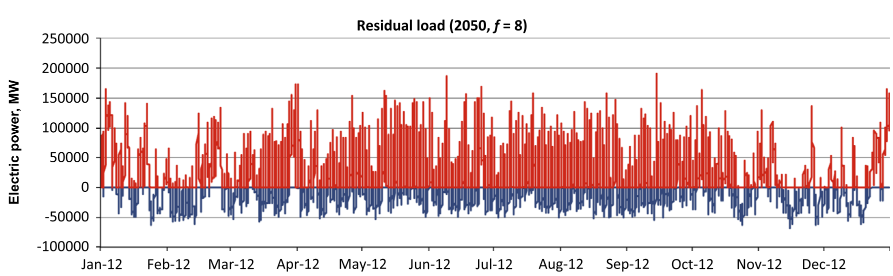


Fig. 11. Same as Fig. 8, but for the $f=8$ case. The share of electric load not covered by RES-E (blue curve) is greater, and the surplus RES-E production (red curve) is lower. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

[66]. The definition "secondary" refers to the energy that is not directly used for electricity production. Assuming a doubling of this amount in 2050[1] – to 697 TW h – the remaining synthetic fuel needs could be covered, i.e. the energy system would reach self-sufficiency based entirely on renewable energy.

3.5. Intermediate scenario: $f=8$

The $f=20$ scenario represents an extreme case study that eschews the many difficulties of massively increasing the RE installed capacity. It is more meant to demonstrate how RES-E and PtL/PtG conversions can be combined to indeed cover a large part of the forecasted energy needs in 2050.

In light of the curve behavior in Fig. 6, a lower scaling factor can be used in order to portray more realistic scenarios. A scaling factor of $f=8$ is selected for this second analysis, and the results are shown in Figs. 10 and 11.

[1] Federal Ministry of Food and Agriculture (BMEL), National Biomass Action Plan for Germany- Biomass and Sustainable Energy Supply http://www.bmel.de/SharedDocs/Downloads/EN/Publications/BiomassActionPlan.pdf?__blob=publicationFile.

Table 2
Summary of the main parameters and implications for the two RES-E scenarios.

	% of UBA forecast covered			Electric overflow in TW h	CO_2 input Mt (circa)
	Final electricity consumption	Renewable Fuels (without Industry materials)	Total energy and material		
f=20	*94*	*86*	*73*	*1052*	*147*
f=8	*79*	*19*	*33*	*238*	*36*

With $f=8$, the percentage of electric load covered by RES-E would amount to 79% (to be compared with the 94% of $f=20$). The overflow ratio amounts to 53%, i.e. 4695 h/year or 238 TW h, which can be converted into 167 TW h of liquid and gaseous fuels.

In this scenario, the share of the total electricity and fuel needs (including industry material) that can be covered with RES-E and PtL/PtG conversions would be 33%.

3.6. Results interpretation

The modelling of RES installed capacity increase helps provide insights on the possible energy production structure in a 2050 scenario based around RES-E and PtL/PtG. While the $f=20$ scenario might seem unrealistic, it actually matches the stated objective of supplying most of the electrical power used as final energy through domestic RE capacity [47–49]. In achieving this goal, our calculations show that the resulting surplus RE power could be used to potentially cover most of the renewable fuels demand as well (Table 2). This is less true in the $f=8$ scenario, where surplus power is lower and the remaining fuel needs would have to be met through imports (either electricity or fuels directly). However, the important fact demonstrated in both cases is that any attempt at substantially increasing the share of RES-E in the electric load will lead to significant overflow ratios, thereby confirming the need for practical energy storage options in any RES-heavy energy scenario.

One of the core requirements of an energy scenario centred on synthetic fuels is the adequate supply of a carbon source for the synthesis process. If the goal is the render the fuel cycle carbon neutral, this source should ideally be captured CO_2 in quantities that entirely offset the emissions generated during the fuels combustion. Based on our two RES-E scenarios, a basic estimate of the required CO_2 can be established: assuming 1 mol of CO_2 as input for every mole of produced fuel, and for an equally divided (50/50) production of the two fuels (methane and methanol), the total CO_2 needs amount to around 147 Mt/year for $f=20$, and around 36 Mt/year for $f=8$ (Table 2). As a comparison, Germany emitted approximately 800 Mt of CO_2 in 2012 [68]. However, in a fossils-free 2050 scenario, large point emitters of CO_2 like coal or gas power plants will have been mostly phased out, meaning that the availability of alternative, large-scale CO_2 capture technologies – and first and foremost atmospheric capture – represents an important pre-condition for the successful implementation of sustainable synthetic fuels.

4. PtL: Preliminary economic assessment

In order to provide a rough evaluation of what could be the economics of PtL and PtG conversions, this section presents a cost estimate of a 50 MW_e hypothetical PtL plant using SOECs and powered by surplus renewable power [69]. The cost per kW h of the final product (renewable methanol) is then derived based on the reference scenarios from Section 3.

While the standard indicators for the cost of the final product energy content (Levelized Cost of Energy (LCOE), expressed in Euro per kW h) are well known and easy to identify – e.g. cost of raw materials, economic indicators, plant lifetime etc. – for new technologies the main issues are related to the definition of the installation (capital) cost, operating and maintenance (O&M) and final efficiency for the process. The currently available data originates from prototype or small installation/production pilot plants, and needs to be scaled up to match what a commercial-sized plant could be. In this preliminary model, cost estimates assume mass production of the components, based on industry assessments of expected production levels/costs in the coming decades. All pricing assumptions in this section are purposely conservative, overestimating the future costs scenarios present in the literature and industry forecasts. The main economic parameters are summarized in Table 3 and explained below.

Table 3
Economic input parameters for a PtL plant using SOECs and RES-E.

Economic analysis parameters		
Capital cost	1000	Euro/kW
Power	50	MW_e
Plant lifetime	30	Years
O&M	5	% (of the capital Cost)/year
Interest rate	5	%
Number of annuities	20	Years
Capacity factor	50	%
Electricity price	50	Euro/MW he
Water price	2	Euro/t
CO_2 price	20	Euro/t

Capital cost. The investment cost (initial cost) is reported on a normalized basis, e.g. cost per kW. The calculations are based on the assumptions on SOEC operational mode (Section 2.1) and literature data related to stack cost, heat management and energy balance [43,69]. Technology development estimates expect the manufacture cost of 5 kW SOEC modules to reach 200 Euro/kW at a production rate of 500 MW/year, while the system price is estimated to be 2.5 to 3 times higher than the stack cost [41,43,70,71]. The Technology Data for Energy Plants [72] forecast report indicates a cost of 600 Euro/kW including installations and balance of plant cost in 2020. Based on these numbers and including the methanol synthesis process, a conservative capital cost of 1000 Euro/kW for the whole plant is assumed.

Operating and maintenance (O&M). O&M costs are composed of a fixed share and a variable one, and, in this case study, include the gradual replacement of the SOEC stacks. Following the TDEP report [72], total O&M costs are estimated to be of the order of 15,000 €/MW/year.

Efficiency of the process. The total efficiency of the combined electrolysis and synthesis processes is estimated to be 70% [43,73,74,75].

CO_2 price. The carbon dioxide price definition is a complex element to be evaluated with respect to both the current market price and future values. In this model, the carbon dioxide cost is defined as the price of a ton of carbon dioxide with the required quality for use in the conversion process. This price obviously

depends in part on national and international carbon regulations. At present, the European emissions trading – cap-and-trade – price of CO_2 is about 5 euro per ton and the estimated cost of CO_2 capture from industrial emissions is evaluated at around 60 Euro per ton [8]. In the future, we assume a well-developed CO_2 market, lower CO_2 capture costs (due to improvements in technology) and a higher carbon price. Accordingly, a value of 20 Euro per ton of CO_2 has been chosen for the economics modelling.

These parameters can be considered as constant. In addition, there are two variable input parameters that affect the final methanol production cost and will be used in a sensitivity analysis: the price of electricity and the plant capacity factor.

- *Electricity price*. When coupling SOECs and a Fischer–Tropsch process, part of the heat losses from the latter could be recycled to heat up the cells and drive the water and CO_2 reduction electrolysis. However, in this case study we conservatively assume that the electrolytic reduction process is driven only by electric energy. For the static model, we set an electricity price equal to 50 Euro/MW h.
- *Capacity factor*. The net capacity factor is defined as the ratio between the plant actual output over a period of time, and its potential output if it were possible to operate it at full nameplate capacity indefinitely. Assuming that 100% of the plant's electricity needs are supplied by RES-E, the capacity factor is dependent upon RES-E variability. For the static model, this factor is set at 50%.

It is worth noting that, in a real-world application, both the electricity price and the capacity factor can be strongly affected by the chosen configuration (decentralised vs centralised production, etc.). For instance, a PtL plant installed off-grid, and directly linked with an in situ RES-E source, would benefit from a much lower electricity cost, but its capacity factor would also be lower (as it is tied to the local RES installation's intermittency). A grid-connected plant would incur a higher electricity price, but could be operated on a more constant basis.

Given the scope of this economic assessment, we assume a grid-connected plant that is however only fed electricity produced from renewable sources.

Fig. 12 represents a basic sensitivity analysis of the two variable parameters:

In Fig. 12-left the electricity price is varied within an interval of 10–70 Euro per MW he, keeping the capacity factor constant at the reference value of 50%. In Fig. 12-right, the capacity factor is varied within an interval of 20% to 80%, keeping the electricity price

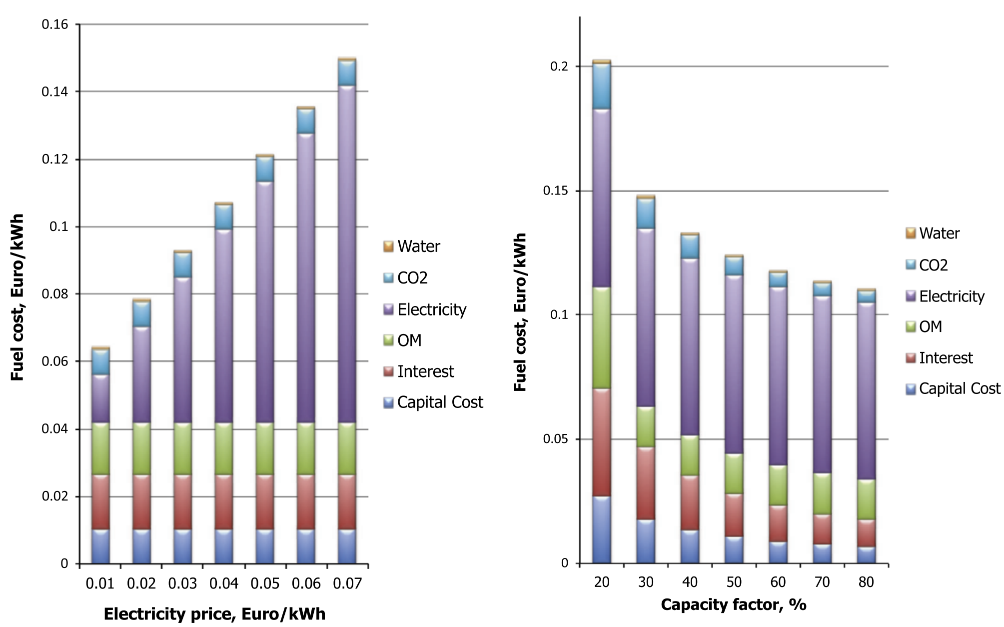


Fig. 12. Sensitivity analysis results; variation of the electricity price (left) and capacity factor (right).

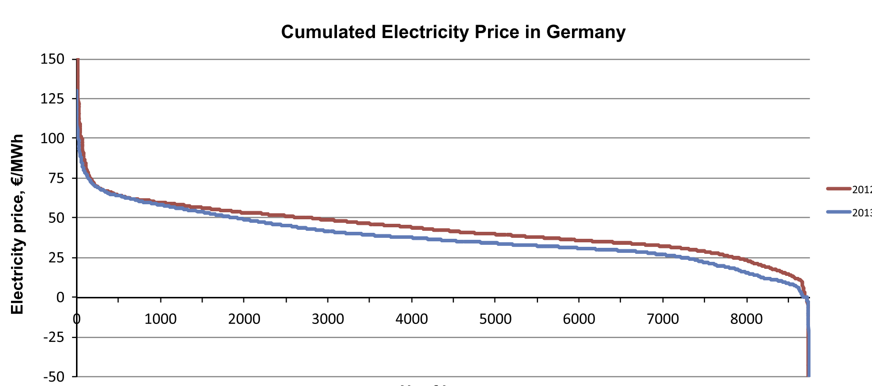


Fig. 13. Ordered annual load duration curve of the day-ahead spot market results in the years 2012–2013 in Germany.

Table 4
Methanol final cost, comparison of model results with the current market price.

	Electricity average price (€/MW h)	Capacity factor (%)	Methanol production (GW h/year)	Methanol cost (€/MW h)	Methanol cost (€/BOE)
f=8	26.3	53	162.5	87.5	142
f=20	32.7	83	254.5	81.4	132
Methanol market price (average Jan–Nov 2014)	–	–	–	70.3	114

constant at the reference value of 50 Euro per MW he. As shown in the figure, it appears that the final fuel production cost is heavily affected by the electricity price across the entire interval, while the capacity factor impacts it significantly only in the low values range.

In order to establish the capacity factor and electricity price parameters, this cost estimate framework can be combined with the RES-E scenarios developed in Section 3. For the $f=20$ and $f=8$ scenarios, the yearly electricity production overflow ratio amounts to respectively 83% and 53% (Sections 3.4 and 3.5). We can therefore assume that this ratio – i.e. the periods when surplus renewable electricity is fed into the grid – matches exactly the periods of operation of the PtL plant (the capacity factor). This translates into 7316 h per year for the $f=20$ scenario, and 4695 h per year for $f=8$.

Regarding the electricity price, the reference value range is the cumulated price represented in Fig. 13, which shows the day-ahead spot market results in Germany (2012 and 2013). We assume that the periods of operation of the PtL plant are optimised in order to take advantage of the lowest possible electricity prices.

Based on the 2013 data and referring to the $f=20$ scenario, the average price of electricity would be 32.7 Euro per MW h (0.0327 cent/kW h). In the $f=8$ case, the average price of electricity falls to 26.3 Euro per MW h (0.0315 cent/kW h).

By combining both parameters, the estimated methanol production cost per kW h can be calculated for the two reference scenarios. The results are shown in Table 4, and compared to present-day market prices for methanol (March 2014, European contracts [76]). It appears that the production cost of renewable methanol is very close to the current price of commercial methanol produced from conventional technologies. Of course, the final market price of renewable methanol would be higher, as other factors affect the price structure (profit margin, transportation, taxes, etc.); moreover, this economic assessment represent only a rough estimate based on a number of assumptions, regarding in particular technology development trends. Yet, the results show that RES-PtL schemes could be potentially competitive with conventional production techniques, thereby reinforcing the argument in favour of renewable fuels as a practical option for energy transition strategies such as the *Energiewende*.

5. Conclusions

The main purpose of this work was to draft a basic model able to describe the possible contribution of RES combined with PtL/PtG to a future sustainable energy system. Based on the present-day characteristic of the German electricity system (and RES-E production) as well as assumptions and forecasts on the future situation, the implications of different RES-E increase scenarios have been examined, and the results fed into a preliminary economic assessment of a RES-PtL plant. At every stage of this analysis, the widespread use of Solide Oxide Electrolysis Cells (SOECs) with a final process efficiency of 70% represents the core feature and premise.

The results of the different modeling steps can be summarised in three main points:

(1) SOECs can support greater RES penetration by storing redundant electricity production in an efficient and practical way;
(2) In a scenario with an unrestricted expansion of RES installed capacity ($f=20$) the entire energy demand can be fulfilled from renewable power;
(3) A basic estimate of the production economics – relying on current industry forecasts – indicates that the final cost per energy content could be competitive with present-day commercial production methods.

Overall, these elements indicate that RES-PtL/PtG schemes are a strong candidate option for transforming the energy system into a more sustainable one and achieving the GHG emissions reduction targets while ensuring sufficient energy supply. However, this approach is not put forward as a “silver bullet” solution: the models presented here, and particularly the $f=20$ case, represent ambitious scenarios that might not be entirely feasible. Many assumptions regarding future trends – and especially technology development – might be invalidated or fulfilled later than expected. The feasibility of such a significant and rapid increase in RES installed capacity also depends on many factors not analysed here, like the necessary redesign of the electrical network. In this perspective, the $f=8$ case study (Sections 3.5 and 3.6) can be viewed as exemplifying what could be an intermediary stage in the energy transition process, or even a final scenario in which RES-PtL/PtG schemes only represent one part of a wider portfolio of new technologies. For instance, given current trends, a complete phasing out of fossil fuels seems an unlikely goal. In this case, PtL and PtG can still play a role alongside fossils, possibly in a complementary manner (see Section 2.2).

Finally, the likelihood that PtL and PtG based on RES-E will take place in an energy transition strategy like the German *Energiewende* is dependent on other factors beyond technological maturity: first and foremost, a comprehensive assessments of the economic costs and benefits is required in order to delineate more clearly a practical pathway.

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