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Utilization of renewably generated power in the chemical process industry

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Abstract

Background: The chemical process industry, mainly the production of organic and inorganic base chemicals, has a significantly high demand for electrical and thermal energy. This demand is constant in time and quantity due to mostly continuous production. On the contrary, the dependency of electricity supply in Germany on volatile wind and solar power increases. To use this power effectively, we propose the direct utilization of it in the chemical process industry.

Methods: To analyze the potential of the utilization of renewably generated power in the chemical process industry, the energy supply and demand has to be quantified. Therefore, methods are developed to calculate possible excess energies from the volatile renewable sources wind and sun. Furthermore, through a literature review, important production processes of the German chemical industry are characterized.

Results: The developed methods lead to time series of the future power generation by wind turbines and photovoltaic systems with a high temporal resolution. The overall gross energy consumption and the full load hours per year show a good consistency with numbers extracted from literature. Additionally, the specific energy consumption per ton product and the yearly production volume are chosen as process parameters to evaluate the potential.

Conclusions: A comparison between the calculated excess energy and the energy consumption for specific chemical products leads to the conclusion that the German chemical industry can function as energy sink for renewably generated power in the future. As a consequence, strategies have to be developed to make production processes more flexible in their operation.

Keywords: Renewable energy; Chemical process industry; Energy sink

Background

After the political decision to end power generation by nuclear power stations until the year 2022 in Germany [1], agreements to decrease CO_2 emissions [2], and increasing public awareness to decrease the dependency on fossil resources [3], the utilization of renewable sources increases constantly. Their proportion of the gross power production in Germany increased from roughly 8% in the year 2002 to more than 22% in the year 2012 [4]. Particularly, the utilization of wind and solar energy as well as biomass underwent a very dynamic development as indicated in Figure 1. Their share in the gross power production accounted for 3.5% in 2002 and increased to 18.5% in the year 2012.

Due to the possibility that biomass can be utilized by directly burning it solely or by co-firing it in fossil power stations, high full load hours per year can be reached [5]. Thus, this renewable electricity generation is mostly constant in time and therefore projectable. The latter is important for the overall balance in the power grid. In contrast, the utilization of wind and solar energy is highly dependent on local weather conditions and therefore not predictable and is volatile. This leads to temporal mismatches between the electricity supply and demand in Germany. To avoid problems in the power grid, power stations have to decrease their output or wind turbines or photovoltaic systems have to shut down. Alternatively, electricity has to be stored.

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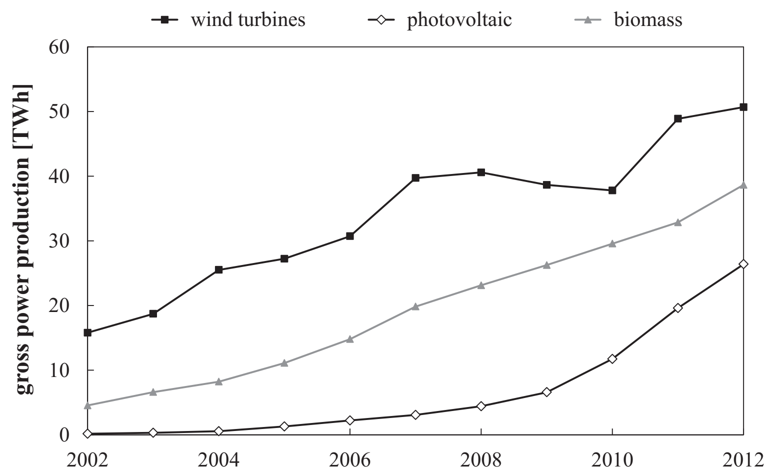

Figure 1 Development of the gross power production from wind turbines, photovoltaic systems, and biomass [4].

Traditionally, large amounts of electricity are stored by pumped-storage hydropower stations, which account for >99% of the long-time electricity storage in Germany [6]. But a further extension is restricted mostly due to retentions in society. Other direct options for long-time storage are compressed air energy storages and redox-flow batteries. Disadvantages are high costs and low development status, respectively [6].

In contrast to the concept presented in this article, long-term storage can be realized by chemical compounds, like hydrogen and methane or liquid hydrocarbons, e.g., methanol and ethanol [7]. These concepts require a conversion of electricity into a chemical product via water electrolysis, the storage of this compound, and an adjacent reconversion into electricity. For some of the named chemicals, storage facilities are already in place. Methane, for example, can be stored in the natural gas grid. For others, an infrastructure has to be established, e.g., hydrogen. The main disadvantage of these concepts is low efficiencies for the overall process chain below 30%.

As an alternative to the presented possibilities of energy storage, we propose the direct utilization of renewably generated power in the energy-intensive production of base chemicals. Due to the early position of base chemicals within value-added chains of the chemical industry, most processes have a high yearly production volume to provide their products for very diverse subsequent processing. Therefore, production capacities for one production site are large and the production is mostly continuous. Additionally, the production of base chemicals has a significantly high demand for electrical and thermal energy. The yearly energy demand in the overall chemical industry accounts for more than 200 million MWh whereof 25% represent electrical energy [8]. An electricity consumption of approximately 50 TWh accounts for 9% of the total electricity consumption in Germany [4].

Thus, an analysis of the potential of the German chemical process industry to function as an energy sink for excess energy, generated from the volatile renewable sources wind and sun, is carried out. At this point, a differentiation between the definition of excess energy from thermodynamics and the one used in this article has to be done. As shown in Figure 2, we define excess energy as that amount of energy that is available when the energy supply by wind and solar power plants (grey line) is higher than the overall energy demand (black line). Assuming that each hatched square in Figure 2 accounts for 1 GWh, the overall excess energy in this example sums up to 5 GWh.

Nevertheless, to utilize renewably generated energy, the operation of chemical production processes has to be adapted to the occurrence of excess energy. A summary of the background and motivation is given in Figure 3. Part (a) shows the already described the state of the art regarding the relationship between energy supply and production volume. This part is used to illustrate that continuous production is enabled by continuous power supply which is mostly made possible by fossil power stations. Due to the transformation of the energy supply system, the challenge will be to adapt the operation of already existing processes to a volatile energy supply (Figure 3b). But before developing strategies for this kind of adjustment, which will not be part of this article, it is necessary to evaluate the potential for the utilization of renewably generated energy within the process industry.

Hence, in further parts of this article, we present an analysis of those potentials. Firstly, the methods and results to quantify excess energy and identify processes that can function as energy sink are presented. Subsequently, the results of this identification and quantification are presented. In

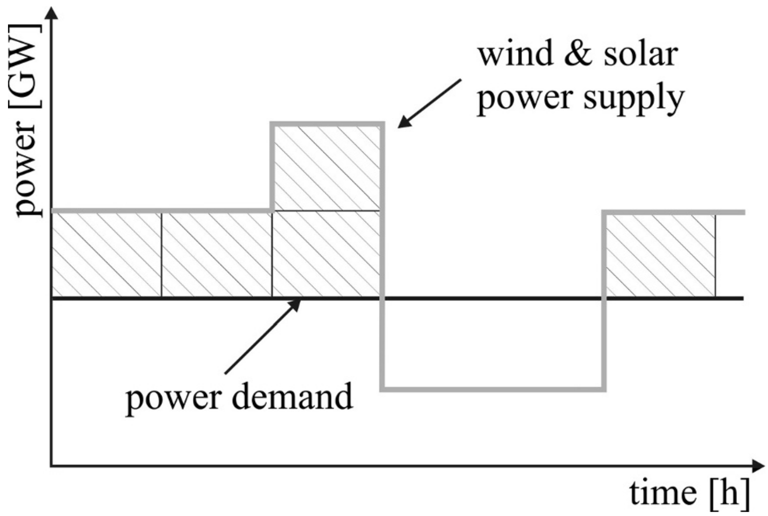

Figure 2 Schematic explanation of the term 'excess energy.'

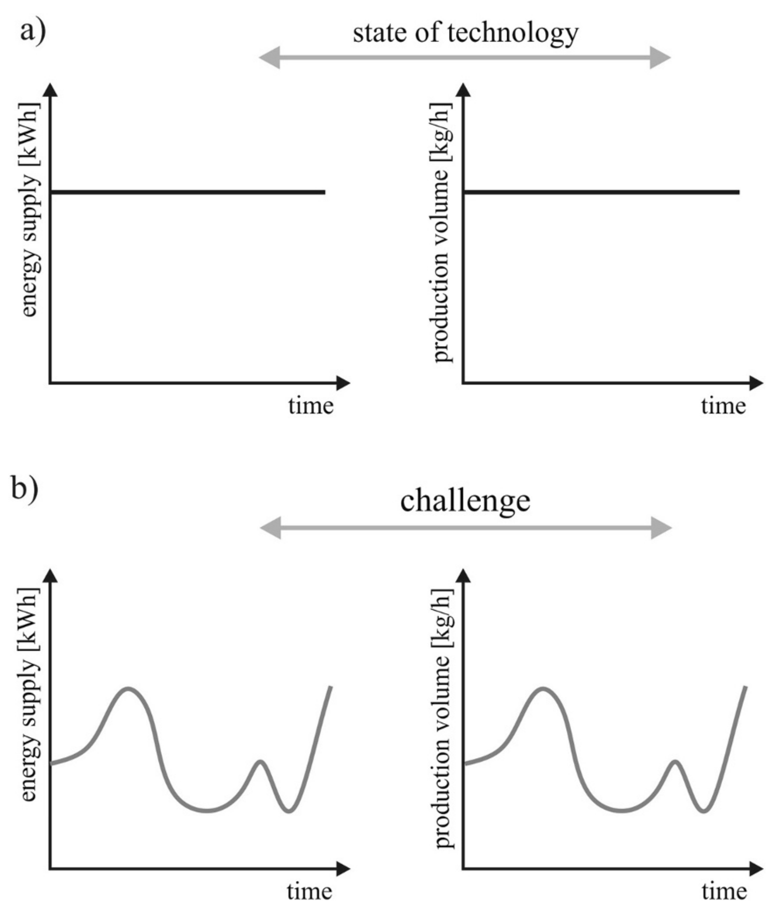

Figure 3 Background of this research (a) state of the art and (b) future challenges.

the 'Discussion' section, these results are analyzed and compared to data extracted from the literature. In the end, we give conclusions and an outlook on further steps of this research project.

Methods

The first step was to carry out a capability analysis to quantify the potential of directly using renewable generated power in the chemical industry. Therefore, the two most important questions were the following:

1. How much volatile renewable energy is available under politically and economically reasonable boundary conditions?
2. Which production processes of base chemicals can function as a suitable energy sink?

Following these questions, we firstly develop methods to quantify the possible excess energy and subsequently characterize important production processes of Germany's chemical industry.

Quantification of excess energy

To answer the first question, it was necessary to specify the availability of volatile renewably generated power in terms of energy and time. Therefore, a calculation of the excess energy was carried out for the year 2020 within the system boundary Germany. First, we defined the boundary condition that the base load was covered by fossil energy sources, e.g., coal and natural gas and renewable sources with many full load hours, most likely water power or power production from biomass. To carry out this calculation, detailed knowledge of the overall power demand within Germany was mandatory. From [9] an estimation of the power demand for the year 2006 with a temporal resolution of 15 min was presented. Those numbers were also used for the year 2020, although the gross energy consumption in Germany is expected to decrease about 6% until then [11]. With regards to the development in the past years, this expectation was questionable [4], which was why we neglected this decrease of the gross energy consumption in our calculations.

Regarding the power supply by renewable sources, the focus was laid on wind and solar power due to their high dependency on weather conditions and consequently their high volatility. Furthermore, those renewable energy sources were identified to be most important in the future [11]. Those calculations were dependent on a variety of boundary conditions and assumptions which are described in the following paragraphs for both wind and solar power.

For the power supply by wind turbines in the year 2020, it was necessary to distinguish between onshore and offshore production. For both, the meteorological data was the wind speed obtained by research platforms in the North Sea and the Baltic Sea. Those data was available from the year 2004 (North Sea) and 2008 (Baltic Sea), respectively, until today [12]. The objective was to develop a time series for the wind speed with low effort representing a year in which untypically or hardly predictable weather conditions were excluded. The most straightforward way to do so was to calculate the time average wind speed for both platforms. Additionally, the values had to be scaled according to the hub height of the wind turbine.

To calculate the possible power generation by wind turbines, one had to know the installed capacities. For the year 2020, [11] predicts an installed capacity of 10 GW offshore and 42 GW onshore. To calculate the overall offshore power production, it was assumed that only wind turbines with a nominal output of 5 MW were installed. For the onshore power production, the calculation was based on three reference wind turbines with a nominal output of 2.3, 3, and 4.5 MW, respectively. Their share of the total installed capacity was assumed according to [10]. To calculate the power production, a characteristic curve for each wind turbine was developed in the form of a logistic function. As the last step, it was necessary to consider any kind of losses, for example, due to transmission or availability [13]. Losses due to shadowing were considered for 80% of all wind turbines. At this point, it has to be stated that no adjustment of the installed capacity within the year 2020, caused for example by repowering, was taken into account.

The possible power production by photovoltaic systems can be calculated by the same general approach to design a method in which calculations are dependent on weather data. Firstly, a time series of data for the solar radiation on flat surface in Germany was developed. Unlike before, commercial data is available from [14], in which numbers were obtained by performing a factor and cluster analysis of the overall weather situations for Germany. In this way, the solar radiation for 1 year with a temporal solution of 1 h was available. The numbers represented a model year close to the mean of the last 30 years.

To develop this time series, Germany was divided into 15 model regions whose borders do not match the borders of the 16 federal states within Germany. Therefore, with the help of *ImageJ*, a freeware to digitally measure pixels, the solar radiation was determined for each federal state by performing the following steps:

1. Digital measurements of every model region and every federal state in the same scale and resolution
2. Estimation of the share of every model region i in every federal state j

3. Estimation of the average solar radiation per federal state *j* weighted by unit area

With this data, the performance ratio, and the installed capacity per federal state, an estimation of the power generation from photovoltaic systems within Germany for the year 2020 became possible. The performance ratio is an indicator of the solar modules which describes the ratio between actual generated power and possible generated power under standard test conditions [15]. In other words, this number sums up efficiency losses and losses due to reflection, shading, or pollution. Here, the performance ratio was assumed to be 79.6% [11]. The installed capacity of grid-connected photovoltaic systems was predicted to be 53.5 GW in 2020 [11]. The share of every federal state was calculated from [16] and afterwards scaled up to a total number of 53.5 GW under the assumption that the installation of new modules was equal in each federal state. Finally, the overall power production for Germany was calculated with the suitable equations from [15]. For this analysis, an increase in accuracy by taking into account a distribution of incline and orientation of the solar modules with the help of correction factors was disproportionate to the effort.

After presenting a method to quantify possible excess energies, in the following part of this article, we describe the characterization of production processes within the German chemical industry. With this process screening, we gained a pool of interesting products whose production can be described as energy intensive.

Characterization of production processes

In the second step, it was necessary to quantify the potential of chemical production processes to function as an energy sink for renewable generated power. For this reason, an extensive literature survey was conducted to identify energy-intensive production processes. Due to the overall system boundary Germany, [17] gave a good overview of the major chemicals in Germany and their yearly production volume. For this analysis, products with a high yearly production volume were of particular interest for further characterization, which included the identification of valid process parameters.

At the beginning, we distinguished between different production processes for one product to prevent an exclusion of a process that seemed negligible in the first place. For each production process of the above-identified relevant products, the following parameters were extracted from literature: Those included the reaction mechanism and subsequently information about the reaction enthalpies. For positive enthalpies, heat has to be supplied to start the reaction, and for negative enthalpies, heat has to be removed during or after the reaction. The reaction enthalpy has a high influence on the overall structure of energy demand [18]. The reaction equations itself provided information on the required reactants and possible side products. Furthermore, the reaction equilibrium led to the required temperature and pressure levels within the reactor [19]. Together with the required reactants and possible products, the treatment of those before and behind the reactor was defined. For most cases, the complexity of the overall process was led by the requirements for reactant and product treatments.

Although the reaction enthalpy was helpful to define the quality and quantity of energy for the reactor itself, more detailed information about the energy consumption for the overall process was necessary. Additionally, the economic characteristics and fields of application for each product were analyzed. In contrast to the quantification of the excess energies with a high temporal solution, data concerning the chemical process industry was available from different references. Hence, an analysis of abovementioned process parameters could be conducted with less effort.

Results

Like the 'Methods' section, the 'Results' section is divided in two parts before regarding both aspects to quantify potentials by discussing the results.

Quantification of excess energy

Performing the calculation of wind power generation for the year 2020 under the above-defined assumptions led to a gross onshore power generation of 77.8 TWh and 2,000 full load hours for the year 2020. In contrast to these values, the gross offshore power generation was calculated to be 33.6 TWh. In this case, one would end up with 3,350 full load hours per year. For the gross power generation from photovoltaic systems, we gained values of 41 TWh and 770 full load hours per year. These numbers are summarized in Table 1.

By comparing the time series conducted in this study with the mentioned time series for the gross power consumption in Germany, Figure 4 was generated. The figure shows the cumulative excess energy for the assumption that the base load is generated by fossil sources over the length of each interval of excess energy. The calculation was performed as schematically illustrated in Figure 3.

Table 1 Calculated gross power generation and full load hours for wind and solar power

	Onshore power generation	Offshore power generation	Photovoltaic systems
Gross power generation (TWh)	77.8	33.6	41
Full load hours (h/a)	2,000	3,350	770

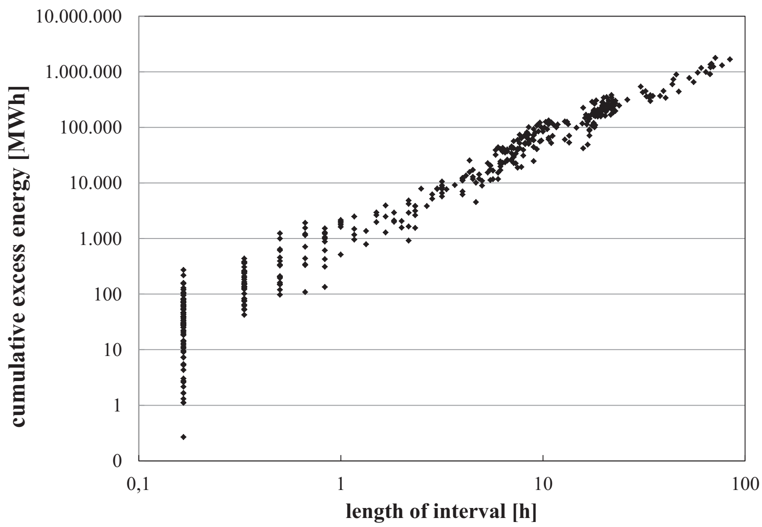

Figure 4 Temporal distribution of energy excesses from wind and solar power in 2020 in Germany.

The total amount of these excess energies summed up to 63.18 TWh, whereupon the total length of intervals was 5,675 h/year. It is important to note that a lot of intervals were shorter than 1 h. By taking those intervals out of the summation, the total length was 5,586 h. Consequently, in 3,173 h/year, no excess energy was available. The longest duration of an interval was 90 h with a total amount of energy of 1.7 TWh.

Characterization of production processes

In this part, the results for the process parameters are described. As most important, the process parameters pressure and temperature in the main apparatus, the overall specific energy consumption, and the yearly production volume were identified for further analysis. For major German chemicals, these figures are quantified in Table 2.

These numbers do not represent the temperature and pressure levels for one specific possible production process but for different process variants. For example, the production of polyvinyl chloride could be carried out as suspension or solution polymerization [23]. On the other hand, the numbers for the yearly production are independent from the production process and the energy consumption was broken down to an acceptable average, expect for those products with a broad variation

Table 2 Process parameters for selected chemical products [17,19-25]

Product	Temperature level reaction (°C)	Pressure level reaction (bar)	Production (1,000 t/a)	Energy consumption (kWh/t product)
Ammonia	280 to 320	400 to 500	2,700	4,000 to 8,000
Methanol	250 to 400	50 to 350	1,500	4,000 to 8,000
Sulfuric acid	200 to 500	1 to 5	4,500	40
Ethylene oxide	230 to 270	10 to 20	1,050	1,500
Adipic acid	80 to 170	5 to 15	100	9,200
Chlorine	80 to 90	1 to 5	4,000	2,300 to 3,700
Polyethylene	75 to 105	15 to 40	2,000	1,500
Polypropylene	60 to 85	20 to 45	2,000	325
Polyvinyl chloride	40 to 75	6 to 12	1,850	915
Ethylene			5,060	6,500 to 9,000
1,3 Butadiene			2,400	2,500
Benzol			1,880	3,500
Acetic acid	150 to 200	15 to 30	150	1,850
Propylene oxide	35 to 50	2 to 3	810	4,300

in literature (e.g., ammonia or ethylene). Due to the fact that ethylene, butadiene, and benzol are produced by fluid-fluid separation techniques [19], no values for temperature and pressure levels were listed.

From a superordinate point of view, the pressure level could be understood as an indicator for the proportion of electricity demand for the process because a change in pressure can be induced with a pump for fluid or a compressor for gases, respectively. Those apparatus can be based on a transformation of electrical energy in mechanical energy to increase the pressure. On the other hand, the temperature level could be understood as an indicator for the use of thermal energy because for most applications heat is supplied by steam which is generated by evaporation of a fluid [19]. However, on a generic level, this discrimination between electrical and thermal energy is possible, and literature does not state numbers for every process taken into account. As a consequence, a further discrimination had to be neglected, although it is important to keep in mind.

Apart from those parameters, more detailed knowledge on the potential within the German chemical process industry could be generated from the more specific parameters, specifically energy consumption per ton product and yearly production volume. Therefore, Figure 5 shows those two values for the abovementioned products.

Discussion

Comparing the obtained results from our calculation with data extracted from literature, a good consistency for the gross power production and full load hours was reached. In [11] a gross onshore power generation of 82 TWh and 2,100 full load hours per year for 2020 were predicted. These numbers led to deviations of −2.75% and −4.7%, respectively. For the gross offshore power production, [11] stated values of 33 TWh (+1.8%) and 3,300 (+1.5%) full load hours per year. For the last case, power generation from grid-connected photovoltaic systems, the values found in literature [11] are 45 TWh and 840 h/a. In this case, the deviation was −8.9% for the gross power generation and −8.3% regarding full load hours per year. Table 3 gives an overview of this comparison.

In summary, for the calculations regarding the wind power generation, the values we generated were in good agreement with the literature. The relative deviation was <5% for each parameter. Still, the relative deviation predicted an underestimation for the solar power generation of >5%. This was because in [10], a value of 83.1% for the year 2020 was applied for the performance ratio. In our calculation, we used a lower value (79.6%) as a more passive assumption due to the fact that the solar module market is hard to predict. Nevertheless, the presented methods to estimate the power generation from wind turbines and photovoltaic systems for the year 2020 were proven to be reliable.

To draw a conclusion with respect to the potential of the German chemical process industry to function as an energy sink, a comparison between the energy demand and energy supply has to be conducted. For this case, the energy demand by the named chemical products was calculated by multiplying the yearly production with the

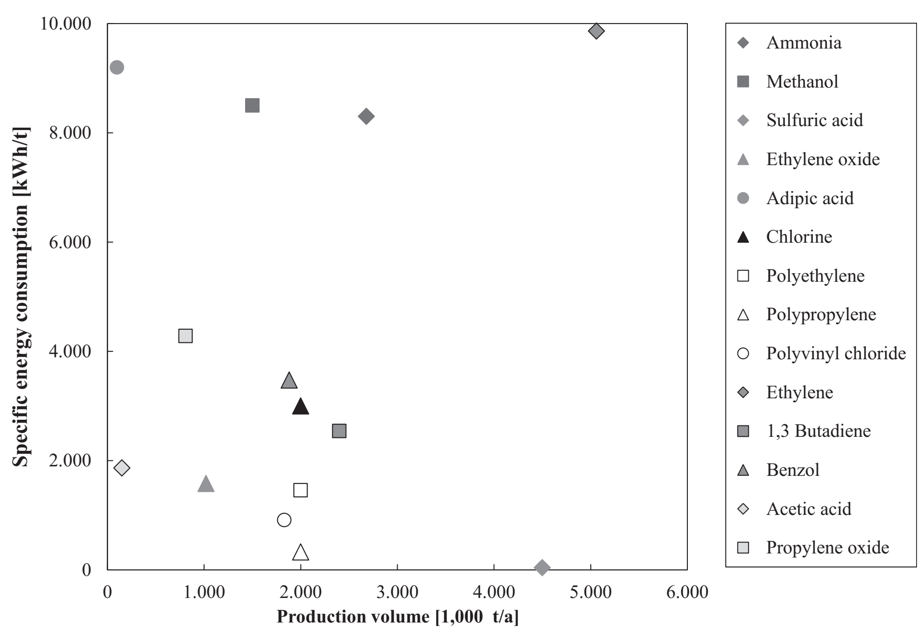

Figure 5 Specific energy consumption and yearly production volume for selected chemical products [17,20].

Table 3 Comparison of own results with numbers extracted from literature

	Onshore power generation	Offshore power generation	Photovoltaic systems
Results of own calculations			
Gross power generation (TWh)	77.8	33.6	41
Full load hours (h/a)	2,000	3,350	770
Results extracted from [11]			
Gross power generation (TWh)	82	33	45
Full load hours (h/a)	2,100	3,300	840
Relative deviation			
Gross power generation (%)	−2.75	+1.8	−8.9
Full load hours (%)	−4.7	+1.5	−8.3

specific energy consumption for each product. On the other hand, the energy supply was the summation of the calculated excess energies presented in the 'Results' section.

For methanol, for example, the energy consumption for the overall yearly production volume within Germany accounted for roughly 16.2 GWh, assuming a specific energy consumption of 6,000 kWh/t. This means that with 20% of the overall excess energies, the total yearly production volume of methanol could be generated. For ammonia, 35% was calculated and 80% for ethylene, respectively. From these numbers, it can be seen that the excess energies might not be high enough to enable production of all identified energy-intensive production processes for the chemical process industry in Germany. Nevertheless, to sum it up, these numbers indicate that the chemical process industry has a high potential to function as an energy sink for renewable generated excess energies.

Table 4 Input data and results for cost analysis

Chemical process			
Power requirement (MW)	5		
Operating hours (h/a)	8,000		
Average energy costs (Mio. €/a) [4]	6.5		
Electricity supply			
	Wind turbine		Photovoltaic
Capacity per plant (MW)	2.5		5
Full load hours (h/a) [11]	2,100		840
Capital cost, operating costs, and WACC			
	Capital cost (€/kW) [26]		Capital cost (€/kW) [26]
	Lower bound		Upper bound
Wind turbines (2 to 3 MW)	1,000		1,800
Photovoltaic (5 MW_p)	1,000		1,400
	Operating costs (ct/kWh) [26,15]		Nominal WACC (%) [26]
Wind turbines (2 to 3 MW)	1.8		5.9
Photovoltaic (5 MW_p)	24		4.8
Results for different sources of electricity supply			
	Scenario I	Scenario II	Scenario III
	100% wind power	100% sun power	50%/50% mix
Installed capacity (MW)	20	50	10 (wind turbines)
			25 (photovoltaic)
Σ capital cost (Mio. €)	20 (lower bound)	50 (lower bound)	35 (lower bound)
	36 (upper bound)	70 (upper bound)	53 (upper bound)
Operation costs (Mio. €/a)	0.72	9.6	5.16
Payback period (a)	5.7 (lower bound)	Not within lifetime (> 4·lifetime)	40 (not within lifetime)
	10.5 (upper bound)		

Besides an evaluation of potentials, a cost analysis for this approach in terms of payback periods was conducted. Therefore, the capital cost for the installation of renewable energy converter was compared with possible savings in energy costs. These possible savings were calculated under the assumption that instead of the electricity prize, the operation costs for the renewable energy converter were taken into account. The electricity prize was extrapolated from the data available from [4]. For this analysis, three scenarios (100% wind turbines, 100% photovoltaic systems, and a mix of 50% wind turbines and 50% photovoltaic systems) of electricity supply for one exemplary demand of a base chemical production site were compared based on the total amount of energy per year. Furthermore, the lifetime of the energy converter was assumed to be 20 years. All input data and important results are summarized in Table 4. As a result, only the 100% wind turbines scenario reached a payback time which is shorter than the assumed lifetime, 5.7 years for the lower bound of capital cost and 10.5 years for the upper bound. This result was reasonable due to high operating costs and comparably low full load hours resulting in high installed capacity for photovoltaic systems.

Conclusions

In this article we introduced the direct utilization of renewably generated power in production processes of the chemical industry as a way to minimize the mismatch between power supply and demand with increasing shares of renewably generated power in Germany's power grid.

Before illustrating the potentials of this concept, we presented methods to calculate time series of wind and solar power for the year 2020 exemplary. It was shown that the results are in good agreement with values presented in the literature for the expected power generation from wind and solar energy. Afterwards, a comparison of the overall Germans' power demand and the power supply by wind turbines and photovoltaic systems was conducted for the year 2020. As a reference case, a supply of the base load by fossil power plants was assumed, resulting in values for possible excess energy and a distribution of the temporal length of these intervals.

Additionally, a review regarding the structure of Germany's chemical industry was carried out. This review led to a matrix of various products and parameters of their production processes from which suitable processes could be identified. The overall potential was illustrated by a comparison between energy demand of the identified processes and energy supply by excess energies. Additionally, an analysis regarding energy costs for an exemplary production site showed that at least an investment in an energy supply by wind turbines might be economically possible.

Due to the challenge illustrated in Figure 3, in subsequent steps of this research project, detailed examinations regarding start-up and shutdown of apparatus, which are sensitive towards disturbances in the operation conditions, will be performed, leading to the development of strategies on apparatus level to decrease operation limits. This might subsequently give recommendations for future apparatus design.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

JR developed the methods, quantified and analyzed the potentials and costs, and drafted the manuscript. All authors read and approved the final manuscript.

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