Challenges of Renewable Energy Sourcing in the Process Industries: The Example of the German Chemical Industry

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Abstract: The ongoing move toward carbon neutrality in Europe and, more recently, towards reducing Russian natural gas as an energy source poses a significant challenge to energy-intensive processes such as the German chemical industry. While many current research studies focus on the transformation of the electrical grid required for the transition to renewable energy sources and the related technical problems and market design, little research has been conducted on the practical feasibility and requirements of energy transformation in energy-intensive process industries. This publication addresses this gap using the projected future energy demand of the German chemical industry and simulation of its coverage by different renewable energy production scenarios using past data on power outputs from renewable energies. Ten-gigawatt offshore wind power installed without additional storage would reduce the natural gas consumption of inflexible large-scale processes in the German chemical industry by 63% or fossil energy consumption by 42%. Hydrogen energy storage has little effect unless employed at sizes comparable to the entire current German storage volume for natural gas. In consequence, while the substitution of fossil energies is technically feasible, the undertaking of reaching a high level of substitution is of a magnitude that makes the time frames currently set seem somewhat optimistic without massive reductions in energy consumption by shutting down large parts of the industry.

Keywords: chemical industry; renewable energies; electrification; Germany; decarbonization; energy storage

1. Introduction

Climate change resulting from human activities and its consequences present some of the biggest challenges for future generations [1,2]. International organizations such as the UN, the EU, and others, as well as countries all over the world reacted by establishing and enacting binding frameworks to reduce carbon dioxide (CO₂) and other greenhouse gas (GHG) emissions [3–6]. One of the transition fuels considered to facilitate the extension of renewable energy and reduction of direct carbon dioxide emissions is natural gas [7–10]. Still, the current conflict in Ukraine has put enormous strain on Western European natural gas supply from Russia and energy-intensive industries relying on this energy source [11,12]. Substitution of natural gas seems therefore imperative where possible, preferably by energy from renewable sources. The industrial sector and especially the energy-intensive process industries are an integral part of reaching these climate and natural gas substitution targets [9]. Many of their processes use fossil fuels for heating purposes on a grand scale, which makes decarbonization particularly difficult [13]. The main goal of this publication is to evaluate potential contributions to reaching these targets by the energy-intensive industries using the German chemical industry as an example, the largest one in Europe, representing a significant portion of the national economy [14].

The challenges presented to the chemical industry by the transition to renewable energy and raw material sources have been investigated from numerous perspectives [15].
The current heavy usage of natural gas and other fossil fuels for the generation of process heat and other purposes [16] implies major alterations for the future and the necessity for disruptive innovation [17]. To implement renewable energy sourcing the chemical industry focuses on three different approaches: process improvements for increased variability, higher energy efficiency, and storage solutions [18,19]. A first incremental step in adapting the chemical industry to fluctuating renewable energy supply is the exploitation of flexibility potential in processes, a topic already addressed by numerous investigations [20–23]. Still, many present large-scale fundamental processes do not have the right characteristics for operational flexibility, requiring a constant energy and feed-stock supply to run efficiently [24,25]. Energy efficiency has been at the core of industrial chemical development for decades [26], probably leaving limited mid-term optimization potential with conventional approaches.

Despite these challenges, high inflation rates [27], and a bleak economic perspective [28], politicians in the EU and in Germany are not only set on diversifying natural gas supply but also on considerably reducing dependency on natural gas as energy source [29]. While the extension of renewable energies seems imperative from this point of view, obligatory planning procedures for infrastructure on land have taken at least a decade in the past [30].

Past research studies mainly focused on the transformation of the electrical grid related to the increased usage of renewable energies [31], the related technical problems [32], and market design [33,34] or macroeconomic setup [35]. However, little research has been conducted on the practical feasibility and requirements of energy transformation in the energy-intensive process industries, the topic of this investigation. Various studies addressed technical improvements to ease the transition such as increased flexibility [22,36] or electrification of certain chemical processes [37,38], sometimes even including calculation of the required energy storage capacities [37]. Other studies are limited to calculating the overall energy demand without considering the fluctuations in renewable power supply [39,40]. While these are all necessary prerequisites for natural gas substitution or decarbonization of the energy supply, there is a considerable gap uncovered by current research on practicability and temporal alignment of the transition to policy directives in energy-intensive industries. Therefore, the current investigation aims at elucidating potential paths to natural gas substitution of carbon neutrality by developing different scenarios and calculating their decarbonization potential from a technical point of view. These scenarios provide a solid basis for the current discussion on policy targets and timelines and can serve as reference points. The focus is therefore neither regulatory nor technical detail but rather the magnitude of the undertaking and its general technical requirements. The approach is founded on a data-based perspective on the decarbonization of the energy supply or energy transition of the chemical industry, one of the main challenges to the industry’s carbon neutrality.

The remainder of this article is organized as follows: Section 2 presents the literature review related to the conducted study. The methodology adopted to carry out the study is detailed in Section 3, and the setup of the scenario modeling in Section 4. The results obtained are presented in Section 5. The discussion ends the paper in Section 6.

2. Literature Review

2.1. Policy and General Background

The policy of the European Union has been set on reducing GHG and especially CO₂ emissions for some time and more recently on reducing natural gas consumption in particular [3,41,42]. Energy-related emissions are the main driver behind the increased greenhouse gas concentration levels in the atmosphere, an issue which can be addressed on the supply as well as on the demand side [43]. The EU, therefore, adopted a 55% net emission target by 2030 [3,44], although not a single EU member state yet has fully addressed the respective EC recommendations and success in reduction of GHG emissions is highly heterogeneous [45,46]. While the European Environmental Agency (EEA) estimated
that the EU’s net emissions in 2020 were 34% lower than in 1990 [44,47], this still leaves a reduction target of more than 20% of the emissions from 1990 in just one decade. In addition to that, a considerable part of the reduction of approximately 10% in 2020 can be attributed to the one-time effects of the COVID pandemic which will probably not last in the long term [47]. Another aspect currently driving industry politics in the EU is the conflict in Ukraine and the dependency of Western Europe on Russian natural gas deliveries [29,41]. However, diversification of gas supply, as well as substitution by other fossil-based primary energy sources, comes at a high price both economically and ecologically [8,48,49].

The industrial sector is facing this political situation and the challenge of decarbonization in a comparatively short time. The task of decarbonization or more precisely defossilization of the industries itself has several aspects such as enhancing process efficiency, circular material usage, alternate raw material sourcing of non-fossil origin, and many more [50,51]. These aspects are at the very core of the chemical industry’s expertise and are approached by many major industrial players [52,53]. Another aspect is the energy supply for the industry, in the past readily available by fossil fuels and mainly cheap natural gas [54]. In consequence, the transformation from fossil to renewable energy sourcing puts great strain on the process industry [15]. Overall, in particular the energy-intensive industries in Western Europe are facing a ground-breaking challenge of substituting their current energy sources with more sustainable options such as renewable energies.

In Germany, the country with the largest economy in Europe, the move towards electric power generation from renewable sources has been encouraged by legislation since 2000 with the introduction of the “Erneuerbare-Energien-Gesetz” [55,56]. In addition to this legislation and its revisions, the German government has implemented many policies to support offshore wind energy [57]. Despite these initiatives, the move towards renewable energy supply has been increasingly sluggish [58] and the GHG emissions have diminished only slowly due to fading out of nuclear energy [59]. Several factors slowing down the expansion of renewable energies have been identified in the past: very long planning durations [60], local opposition, for example to onshore wind power projects [61], sluggish strengthening of the electrical grid [62,63], conflicting goals in politics [58], and lack of economic viability [57]. Another factor putting additional stress on the electrical power supply is the fading out of nuclear energy finalized by the German government after the Fukushima accident [64,65], which is unlikely to be reversed by the current government under the participation of the green party, which is strictly against nuclear power [66].

2.2. Chemical Industry Energy Consumption and Usage

The chemical industry has a very high energy demand, and commodization in the chemical industry and source of increasing profitability of companies in Western countries was driven by cheap natural gas as the main energy source [67]. Nevertheless, expenses for energy consumption are still a considerable part of manufacturing costs, making its consumption and usage a core topic for the chemical industry [68]. Past optimization efforts resulted in considerable energetic efficiency gains which at the same time limits the immediate potential for further energy savings [69]. Some processes such as ammonia production in modern facilities even approach the thermodynamic minimum energy required, leaving virtually no possibility for significant improvement [70]. However, there are still some options left for reducing the overall energy consumption, for example, by upcycling waste heat using heat pumps [71].

The past development of the primary energy consumption of the German chemical industry (WZ08-20, excluding manufacturing of coke and oil processing or pharmaceuticals) is depicted in Figure 1 [72], covering a time frame from 2008 to 2020.
Figure 1. Primary energy consumption by class of the German chemical industry from 2008 to 2020. Note: authors’ elaboration based on data from [72].

There are no official data available for the energy usage types of the German chemical industry. Still, the last survey of the US chemical industry excluding petrochemicals in 2018 by the US Energy Information Administration revealed the energy end usages depicted in Figure 2 [73].

Clearly, more than half of the overall energy consumption can be attributed to various types of heat for processes with or without power generation.

Projected future energy demand for decarbonization of the German chemical industry ranges between 223.7 and 684.6 TWh/a in 2050 according to a study by the DECHEMA Society for Chemical Engineering and Biotechnology [39]. Several approaches have been developed to reduce the carbon footprint of the chemical industry [40,74]. One possibility is to source the most energy-intensive base chemicals such as hydrogen or ammonia externally from sources producing them with renewable energies [35,75,76]. Another possibility is to use electrochemistry [38], which would potentially even open new income streams from demand response for electricity and the balancing market [36]. However, the demand response of the chlor-alkali electrolysis, the most important electrochemical application in Germany, is limited by the constant supply requirements of subsequent reactions and the not permitted storage of large quantities of the highly toxic chlorine (unpublished communication with Covestro). From a demand perspective, the complete decarbonization of Germany’s fertilizer production alone by electrolytic hydrogen production for the Haber-
Bosch process would require 6.12 GW wind power installed producing annually 26.82 TWh of electrical energy [37] (including respective supplemental material). The most traditional approach to reduction of the carbon footprint is to increase energy efficiencies in chemical processes by use and optimization of catalysts, a task addressed by entire specialized business units and even companies [77]. Aims of such catalyst optimizations can more specifically target catalysis leading to higher yields and fewer side products, higher conversion rates, lower temperatures or pressures, as well as more robust catalysts that are less prone to be poisoned [78,79]. Better process monitoring and control can also contribute to higher conversion rates hence lower energy consumption per unit of product manufactured [80]. In a more recent effort, machine learning has been extensively used to optimize the most energy-intensive processes in the chemical industry such as steam cracking and increase their energy efficiency [81]. Currently, a consortium of large companies from the chemical industry developed a steam cracker using renewable energy with a projected operating prototype available in 2030 [82]. In the long term, carbon capture and utilization has the potential of reducing the carbon footprint considerably but requires immense amounts of renewable energy [83]. Still, despite all past and current efforts, according to the International Energy Agency (IEA), the global chemical industry is far behind in decarbonization processes [84].

This decarbonization of the energy supply in the chemical industry faces similar issues globally, unless a constant supply of large amounts of renewable energy, for example by hydropower, is available. However, the pressure towards industrial decarbonization is very different between industrialized Western countries. For example, the large chemical sectors in India or China face much lower targets for GHG reductions [6]. In addition to that, the movement for natural gas substitution is rather low in some countries such as the USA or Australia due to their large natural gas deposits [73,85]. The chemical industry in these countries relies heavily on natural gas as energy supply, covering more than 60% of the industry’s total energy demand in the USA. China and India on the other hand still import large amounts of Russian oil and gas at comparatively low prices [86,87], providing them with a cost-competitive energy source and little incentive to switch to renewable alternatives.

2.3. Power Grid and Storage Solutions

As previously stated, the energetic dimension of industrial decarbonization is based on the electrification of many processes and in particular heating. Since the transformation of electrical power generation to renewable sources has been a political target for decades, the issue of this transformation has attracted extensive research activities [31]. The composition of current electrical energy production and demand in Germany including their fluctuations is visualized in Figure 3, using a random interval of nine days.

![Figure 3. Energy production and demand in Germany between April 21 and April 29, 2021. Note: authors’ elaboration based on data from [72].](image-url)
It is clearly visible that photovoltaics and wind power are the energy sources with the largest fluctuations except for pump storage, which is mainly used as balancing power [88]. Natural gas and hard coal seem to act mainly as backup power supply while nuclear power and lignite cover the grid base load [7,31]. For an energy supply based on renewable sources in countries such as Germany or Great Britain with little potential for hydropower, the large fluctuations from wind and solar power present a considerable challenge for the electrical grid and a stable electrical energy supply [89].

One of the key elements in dealing with these fluctuations from wind or solar power and in reaching complete carbon neutrality is energy storage [90,91]. Even today, energy storage and timely availability are crucial to electrical power grid stability. The respective regulating power is traded in separate markets according to the time frame covered [92]. However, high-efficiency, large-volume, long-term energy storage is still a problem to be technologically as well as economically solved [93]. This situation results in considerable inefficiencies already by curtailment of renewable energy [94].

To address these issues a number of storage technologies are available or under development [89]. Currently, pump storage is the only established large-scale storage system for electrical energy currently in operation. Pump storage requires two water reservoirs and a sufficient difference in height between them to work. They are, therefore, limited to sites with the respective geographic features [95]. Various forms of electrochemical storage technologies or batteries have been developed for different storage purposes. While batteries provide immediate availability of the energy contained they suffer from comparatively low energy density and high costs [96,97]. Higher energy densities require molecular chemical storage, for example, in hydrogen. In fact, fossil fuels contain chemically transformed solar energy from the geological past [98]. Nearly all currently considered chemical molecular energy storage technologies are based on hydrogen, potentially further processed with nitrogen to ammonia or with carbon dioxide to methane [99–101]. For this publication, only the simplest storage option using hydrogen is considered due to its technical maturity and highest overall efficiency. All further processing to ammonia or natural gas reduces the amount of energy recoverable [99,101]. Hydrogen generation in large-scale electrolyzers can reach an overall electrical efficiency of up to approximately 80% [102,103]. Currently, two main technologies exist: proton exchange membrane (PEM) electrolyzers and alkaline electrolyzers. Recent research results indicated further development of technologies with efficiencies of up to 98% promising future increases in industrial electrolysis performance [104], but scale-up, stability, and endurance tests are still pending. Transformation of the chemical energy back to electrical energy is the second step in reducing overall efficiency. Electrical efficiencies in modern gas power stations can reach more than 60%, which is also applicable for large high-temperature fuel cells [105,106]. Including the use of waste heat, the overall efficiency of the discharging step can rise to 80% or even more [106].

Renewable electrical energies have increased tremendously over the last decades, globally, in the EU, and in Germany [64]. However, the expansion of renewable energies depends on their availability, either determined by geographical features such as landscape or coastline, by geological features in the case of geothermal energy, or by latitude and meteorological factors in the case of solar energy [107]. In Germany, the expansion potential of hydropower is rather limited and geothermal energy is still at the evaluation stage [108], leaving primarily the options of expanding wind and photovoltaic energy [62]. Past efforts in Germany were fueled by subsidizing renewable energies from payments of the Renewable Energy Act (EEG, Erneuerbare-Energien-Gesetz) surcharge, leading to one of Europe’s highest electrical energy prices for end consumers [109]. However, energy-intensive industries are exempt from paying the subsidies, which reduces their electrical energy prices considerably [110]. As mentioned above, strengthening of the electrical grid has been another issue not only in Germany, since production sights of renewable energies often do not coincide with existing locations of high energy demand such as areas with larger populations or industrial consumers [111,112]. In Germany, the main industrial consumers are located in the southern part while wind energy is primarily generated in
northern Germany, closer to the coastline or even offshore [113]. Still, although planning for large energy transmission lines (A-Nord, Ultranet, SuedLink, and SuedOstLink) was initiated by law in 2013 [114], it has not been finalized yet due to resistance from local governments, lengthy lawsuits, and political debates [115,116]. The beginning of operation is targeted for 2027 and 2028 [116], giving a lead time of approximately 15 years. The net strengthening is especially important due to the targeted decarbonization of car traffic and residential heating which requires far higher electrical grid capacities than currently available [117].

3. Methodology

The methodology of this investigation was determined by the purpose of answering several underlying research questions:

1. What are the main alternatives for the replacement of traditional natural gas or fossil fuel consumption in the chemical industry?
2. What are the main barriers to the implementation of the decarbonization process in the chemical industry?
3. What are the main risk factors which are tied to the substitution of natural gas or the energy decarbonization process in the chemical industry?

To answer these questions, different scenarios had to be developed based on currently available technologies using past data for energy consumption, power generation, and power plant capacities to simulate future power generation. In agreement with prior literature, scenarios in this context are understood as plausible imagined future environments described by a set of parameters [118]. The scenario approach represents an advanced method for risk analysis as well as a tool for effective strategic planning [119]. Scenarios also identify key driving forces of development, including their mutual dependencies which furthermore interlink with existing opportunities and risks [120]. In the course of the scenario approach, multiple pictures of future environment development are developed combining qualitative and quantitative characteristics [121,122]. The above research questions were used as guidance for the formation of a decision-driven scenario analysis [123].

Two main targets for the energy demand by the German chemical industry were considered when developing the scenarios: substitution of natural gas only by renewable energy and of all fossil-based primary energy by renewable energy. Both targets do not include a switch to sourcing raw materials of renewable origin, assuming similar to prior literature continuation of fossil-based chemical production [124].

Based on these targets and prior literature, a set of fundamental assumptions was derived for the quantitative scenario development of the energy transition. These assumptions are summarized in the following:

- Balancing energy capacity by pump storage or import/export of electrical energy is needed for decarbonization of vehicle traffic and heating and utilized completely by the existing electrical power grid and current electrical power demand; its storage capacity is therefore not available for the additional energy balancing the demand of the chemical industry;
- Renewable energy sources providing base load such as biomass, hydroelectric power, bio-gas, etc. cannot be significantly extended for use in the chemical industry; the remaining renewable energy sources comprise solar, offshore, and onshore wind power;
- Different storage capacities and loading powers are included in the scenarios; energy storage is at a large scale, and potentially necessary short-term storage for buffering fluctuations is neglected;
- If power generation exceeds process demand for the chemical industry plus the respective storage loading, power generation is reduced by switching off the respective portion of renewable power plants;
- The residual load, defined as load not covered by solar power and wind power, has to be covered by controllable power generation meaning conventional power generation;
• A total of 70% of the respective primary energy demand is consumed by large scale mostly continuous processes with continuous energy demand; (the estimate was validated by several interviews with experts from the chemical industry and represents the lower limit of estimated non-flexible power demand) the scenarios do not allow for the rest of the energy demand estimated to be covered by the existing electrical grid;
• Electrification of the energy supply for process heat, etc. results is assumed to result in a gain in efficiency so that only 75% of the respective energy is needed.

Data on electrical energy production, production capacity, and consumption are based on official data available from the German Federal Network Agency (Bundesnetzagentur) for the years 2015 to 2021 [125]. Data for production and consumption were used at a quarter-hour time resolution while production capacities are only available on a yearly basis. Time series data were cleaned, removing duplicates prior to usage for quantitative evaluation. To align data production capacity data were interpolated to quarter-hour time resolution. The primary energy consumption presented above covers the manufacturing of chemical products and the average was used to calculate the energy demand for the scenarios.

4. Quantitative Evaluation

The quantitative evaluation of the attainability of the two targets is based on scenario analysis using simulation of different sets of overall power generation capacities from five- to fifty-gigawatt (GW) installed power combined with different storage settings. For the overall power settings, all combinations for the three renewable power sources were considered in five-percent intervals, resulting in 231 combinations for each overall power calculation. The simplest and potentially economically most advantageous storage setting is the usage of large power generation capacities without storage and curtailment of excess energy at certain times despite the considerable losses [31,126,127]. Other storage settings used are based on large-scale hydrogen storage, not considering potentially necessary short-term buffering by other means.

The calculations of the scenarios were performed using the first three years from 2015 to 2017 as the charging period to reach an equilibrium and the subsequent four years from 2018 to 2021 as the evaluation period. In all scenarios, the residual load, defined as load not covered by solar power and wind power, has to be covered by controllable power generation meaning mostly conventional power generation.

The different renewable energy sources have largely fluctuating outputs depending on the season, time of day, and weather conditions, as depicted in Figure 4. The darker 30-day gliding averages show the seasonal fluctuations while the lighter areas display the overall fluctuations by quarter hour.

Figure 4. Capacity usage of volatile renewable energies in Germany 2015–2021 and total output. Note: authors’ elaboration based on data from [72].
Based on these data, a basic model was developed including grid losses as well as energy storage considering the loading and the discharging efficiency of the storage (see Figure 5). Excess energy by renewables is used to load the storage until the maximum capacity is reached, at which point in time additional excess is curtailed. No discharging limit was set so that the storage can cover the entire energy demand if necessary, for example by using the hydrogen in high-temperature fuel cells.

Figure 5. Energy supply schematics for renewable energies. Note: authors’ elaboration.

Some basic model parameters were derived from the literature, including efficiencies for energy transformations and grid losses. These parameters are summarized in Table 1.

Table 1. Basic parameters for modeling.

| Parameter                        | Value             | Comment                                      |
|----------------------------------|-------------------|----------------------------------------------|
| Grid losses                      | 5%                | Combined from different voltage levels [128]  |
| Loading efficiency               | 80%               | Upper end of efficiency [102]                |
| Discharging efficiency           | 80%               |                                              |
| ⊘ Annual consumption natural gas | 81.17 TWh         | 70% ≈ 56.82 TWh                              |
| ⊘ Annual consumption fossil fuels| 144.86 TWh        | 70% ≈ 101.40 TWh                             |

1 Not including low-voltage grid. 2 For details see paragraph on energy storage. 3 Calculated for the years 2010–2020.

As an example, a set of scenarios with extreme storage capacities (storage scenario set 5) was developed assuming that the entire German underground gas storage capacity can be employed as hydrogen storage for the natural gas substitution or decarbonization of the energy supply of the chemical industry. Data for the storage capacity were gathered from the Aggregated Gas Storage Inventory (AGSI) by Gas Infrastructure Europe (GIE) [129]. The calculation is described in Equation (1).

\[
\text{Total } H_2 \text{ storage capacity} = \frac{\text{Stored energy}}{\text{Usage level}} \cdot \frac{\text{Energy density hydrogen}}{\text{Energy density natural gas}} \quad (1)
\]

Setting the respective values [129,130] results in:

\[
\text{Total } H_2 \text{ storage capacity} \approx \frac{156.7203 \text{ TWh}}{0.6453} \cdot \frac{280 \text{ kWh} \cdot \text{m}^{-3}}{1100 \text{ kWh} \cdot \text{m}^{-3}} \approx 61.8 \text{ TWh} \approx 60 \text{ TWh}
\]

A summary of the different settings for the scenarios is given in Table 2.
Table 2. Scenario parameters for modeling.

| Scenario Set                  | Parameter                  | Value                | Comment                                      |
|-------------------------------|----------------------------|----------------------|----------------------------------------------|
| All                           | Nominal Power              | 5, 10, 25, 50 GW     | Various overall capacities                   |
| Storage Scenario Set 1        | Storage Capacity           | 100 GWh              | One large gas cavern [130]                   |
|                               | Max. Charging Power        | 1 GW                 | 100 large PEM electrolyzers [131]            |
| Storage Scenario Set 2        | Storage Capacity           | 1 TWh                | Ten large gas caverns                        |
|                               | Max. Charging Power        | 5 GW                 |                                              |
| Storage Scenario Set 3        | Storage Capacity           | 1 TWh                | Ten large gas caverns                        |
|                               | Max. Charging Power        | 10 GW                |                                              |
| Storage Scenario Set 4        | Storage Capacity           | 5 TWh                | ≈8% of German gas storage                    |
|                               | Max. Charging Power        | 10 GW                |                                              |
| Storage Scenario Set 5        | Storage Capacity           | 60 TWh               | Entire German gas storage                    |
|                               | Max. Charging Power        | 25 GW                |                                              |

5. Results

The results from simulating the scenarios described above are summarized in Table 3 for the substitution of natural gas, and in Table 4 for the substitution of the entire fossil energy demand of the German chemical industry. Both tables only list the optimal compositions of energy supplies from photovoltaics (PV), onshore wind power (wind power land, WPL), and offshore wind power (wind power sea, WPS). The optimal scenarios are defined as the scenarios with the highest respective actual energy coverages supplied at the point of consumption including grid losses.

Table 3. Results from modeling for substitution of natural gas.

| Capacity | Best Scenario | Nom. Energy Coverage | Act. Energy Coverage | Act. Energy Supply/Year | Nom. Energy Usage |
|----------|---------------|----------------------|----------------------|-------------------------|-------------------|
| No Storage Scenario Set 1    | 5 GW          | 0% PV, 0% WPL, 100% WPS | 39.48%              | 37.51%                  | 15.99 TWh         | 100%              |
|                                   | 10 GW        | 0% PV, 0% WPL, 100% WPS | 78.96%              | 63.33%                  | 27.00 TWh         | 84.42%            |
|                                   | 25 GW        | 20% PV, 0% WPL, 80% WPS | 168.51%             | 82.64%                  | 35.24 TWh         | 51.63%            |
|                                   | 50 GW        | 20% PV, 35% WPL, 45% WPS | 272.10%             | 93.03%                  | 39.67 TWh         | 35.99%            |
| Storage Scenario Set 1          | 10 GW        | 0% PV, 0% WPL, 100% WPS | 78.96%              | 63.38%                  | 27.03 TWh         | 84.54%            |
|                                   | 25 GW        | 0% PV, 45% WPL, 55% WPS | 155.68%             | 83.96%                  | 35.80 TWh         | 58.32%            |
|                                   | 50 GW        | 0% PV, 55% WPL, 45% WPS | 292.82%             | 94.90%                  | 40.47 TWh         | 35.01%            |
| Storage Scenario Set 2          | 10 GW        | 0% PV, 0% WPL, 100% WPS | 78.96%              | 63.39%                  | 27.03 TWh         | 84.55%            |
|                                   | 25 GW        | 0% PV, 15% WPL, 85% WPS | 183.50%             | 85.58%                  | 36.50 TWh         | 50.57%            |
|                                   | 50 GW        | 5% PV, 95% WPL, 0% WPS  | 204.19%             | 95.44%                  | 40.70 TWh         | 52.08%            |
| Storage Scenario Set 3          | 10 GW        | 0% PV, 0% WPL, 100% WPS | 78.96%              | 63.39%                  | 27.03 TWh         | 84.55%            |
|                                   | 25 GW        | 0% PV, 15% WPL, 85% WPS | 183.50%             | 85.60%                  | 36.50 TWh         | 50.59%            |
|                                   | 50 GW        | 5% PV, 95% WPL, 0% WPS  | 204.19%             | 95.45%                  | 40.70 TWh         | 52.09%            |
| Storage Scenario Set 4          | 25 GW        | 0% PV, 15% WPL, 85% WPS | 183.50%             | 86.65%                  | 36.95 TWh         | 51.58%            |
|                                   | 50 GW        | 5% PV, 95% WPL, 0% WPS  | 204.19%             | 96.81%                  | 41.28 TWh         | 53.24%            |
| Storage Scenario Set 5          | 25 GW        | 0% PV, 20% WPL, 80% WPS | 178.86%             | 93.51%                  | 39.88 TWh         | 59.6%             |
|                                   | 50 GW        | 0% PV, 100% WPL, 0% WPS | 209.37%             | 99.98%                  | 42.64 TWh         | 54.97%            |

A more detailed overview of the coverages of energy demand in selected scenarios is presented in Figure 6, depicting the demand coverage in scenarios without storage and installed capacities of 10 GW and 50 GW as well as storage scenario 2 with an installed capacity of 25 GW power. The ternary diagrams show the various proportions of the respective energy source and the resulting levels of demand coverage with the lines depicting levels of the same coverage.
Figure 6a displays the actual energy coverage for the natural gas substitution by 10 GW of renewable energy production capacity without any storage. Depicted is a continuous gradient of energy demand coverage rising from solar power to onshore and then offshore wind power in the lower right corner with the highest coverage. In scenarios without storage and little or no curtailment, the energy mix with the highest nominal output will also achieve the highest actual energy coverage. In contrast to that, item (b) displays a comparison of the demand for natural gas substitution at a high-power production capacity of 50 GW. A steep gradient from solar power towards wind power segues seamlessly into an area of similar demand coverage at a level between 90% and 95%. The overall optimum is at 20% solar power, 35% onshore, and 45% offshore wind power with 93% demand coverage (see Table 3). Finally, item (c) displays the distribution of energy demand coverage for a total installed power production capacity of 25%, a storage capacity of one TWh, and a charging power of five GW. The resulting slight slope with increasing energy demand coverage and a maximum at 15% onshore and 85% offshore wind power. The optimal proportion of solar power in the renewable energy mix is in most scenarios rather low or even zero. This difference from the normal electrical power grid can be attributed to the constant energy demand, while in the electrical grid production maxima of solar power coincide with the times of highest energy demand (see Figure 3). Reaching degrees of natural gas substitution by electrical energy beyond 80% requires approximately 25 GW installed production capacity of renewable energies. Curtailment is a common phenomenon in most scenarios but energy storage only contributes significantly to demand coverage when employed at unrealistic large sizes such as in storage scenario set 5.

Similar results at a lower level of demand coverage were found for the substitution of all fossil fuels in base processes of the chemical industry, as shown in Table 4.

Curtailment is less common at the same power generation capacities than for the scenarios describing the natural gas substitution due to the increased energy demand. Not surprisingly, the demand coverages are also lower than in the previous scenarios. Patterns of demand coverages similar to the ones depicted above in Figure 6 can be found for the scenarios of full fossil-based fuel substitution (see Figure 7).

Again, a continuous gradient of demand coverage is found from low coverages at high proportions of solar power to higher coverages for onshore and offshore wind power in Figure 7a. As previously found, in item (b) the gradient flattens for higher production capacities and more frequent curtailment, while energy storage in item (c) flattens the gradient at higher levels of demand coverage.
Table 4. Results from modeling for substitution of fossil-based primary energy.

| Capacity | Best Scenario                      | Nom. Energy Coverage | Act. Energy Coverage | Act. Energy Supply/Year | Nom. Energy Usage |
|----------|------------------------------------|----------------------|----------------------|------------------------|------------------|
|          |                                    |                      |                      |                        |                  |
| No Storage Scenario Set 1 | 5 GW 0% PV, 0% WPL, 100% WPS | 22.14%               | 21.03%               | 15.99 TWh              | 100%             |
|          | 10 GW 0% PV, 0% WPL, 100% WPS     | 44.28%               | 42.06%               | 31.99 TWh              | 100%             |
|          | 25 GW 0% PV, 0% WPL, 100% WPS     | 110.69%              | 71.39%               | 54.30 TWh              | 67.89%           |
|          | 50 GW 25% PV, 0% WPL, 75% WPS     | 180.87%              | 84.69%               | 64.41 TWh              | 49.29%           |
| Storage Scenario Set 1 | 10 GW 0% PV, 0% WPL, 100% WPS | 44.28%               | 42.06%               | 31.99 TWh              | 100%             |
|          | 25 GW 0% PV, 0% WPL, 100% WPS     | 110.69%              | 71.45%               | 54.34 TWh              | 67.99%           |
|          | 50 GW 0% PV, 65% WPL, 35% WPS     | 153.79%              | 85.04%               | 64.67 TWh              | 60.00%           |
| Storage Scenario Set 2 | 10 GW 0% PV, 0% WPL, 100% WPS | 44.28%               | 42.06%               | 31.99 TWh              | 100%             |
|          | 25 GW 0% PV, 0% WPL, 100% WPS     | 110.69%              | 71.63%               | 54.47 TWh              | 68.26%           |
|          | 50 GW 0% PV, 25% WPL, 75% WPS     | 195.38%              | 87.62%               | 66.64 TWh              | 48.72%           |
| Storage Scenario Set 3 | 10 GW 0% PV, 0% WPL, 100% WPS | 44.28%               | 42.06%               | 31.99 TWh              | 100%             |
|          | 25 GW 0% PV, 0% WPL, 100% WPS     | 110.69%              | 71.63%               | 54.48 TWh              | 68.27%           |
|          | 50 GW 0% PV, 20% WPL, 80% WPS     | 200.38%              | 87.66%               | 66.69 TWh              | 47.49%           |
| Storage Scenario Set 4 | 25 GW 0% PV, 0% WPL, 100% WPS | 110.69%              | 71.71%               | 54.54 TWh              | 68.39%           |
|          | 50 GW 0% PV, 25% WPL, 75% WPS     | 195.38%              | 88.32%               | 67.17 TWh              | 49.34%           |
| Storage Scenario Set 5 | 25 GW 0% PV, 0% WPL, 100% WPS | 110.69%              | 72.29%               | 54.98 TWh              | 69.30%           |
|          | 50 GW 0% PV, 25% WPL, 75% WPS     | 195.38%              | 93.95%               | 71.45 TWh              | 54.33%           |

Figure 7. %Power output required by energy source for fossil-based primary energy substitution (a) without storage and 25 GW overall production capacity, (b) without storage and 50 GW overall production capacity, and (c) with storage scenario 2 and 50 GW overall production capacity. The scale for percentages is on the right.

From a practical point of view, capacities of ten GW and higher installed renewable power generation capacity would require an additional installation of renewable power equivalent to a considerable portion of currently installed renewable energy facilities in Germany, adding up to approximately 57 GW onshore and 7.8 GW offshore wind power, as well as approximately 59 GW solar power [125,132,133]. The scenarios calculated for 25 or 50 GW power capacity would even need additional offshore wind power exceeding current overall installations. Furthermore, these capacities would have to be installed in addition to the extensions targeted for the normal electrical grid. Since in most scenarios investigated energy demand significantly exceeds supply from renewable sources at some point in time, fossil power plants have to be kept as backup for these situations mostly at their full capacity, implying significant additional costs for the overall energy supply.

6. Discussion

Overall, while a significant reduction of natural gas demand of up to 95% and total fossil fuel demand of up to 85% of total fossil fuel demand for continuous processes is
technically feasible (storage scenario 1 with 50 GW power capacity), the practical short- and mid-term feasibility seems somewhat questionable. The assumptions made in this investigation are in fact even rather optimistic compared to energy demands calculated in other studies estimating the increase of energy consumption from the use of renewable raw materials [39,134]. From a methodological point of view, this investigation used a simulation approach similar to the one used by Sinn for estimating the limits of transition to renewable energies for the electrical grid [31] based on past production of renewable energies. Past studies covering the chemical industry mainly calculated the overall energy demand without considering fluctuating supply from renewable energies [39]. Other studies considering energy storage used average energy productions, which ignores seasonal fluctuations in renewable energy supply [37]. The approach of this publication using time periods of several years as a simulation basis seems therefore superior, especially when considering deep decarbonization scenarios. Other, more long-term oriented studies rely on technologies not yet available such as efficient industry-scale ammonia cracking units and large-scale infrastructure not yet built such as transcontinental hydrogen grids [35,74]. This approach is certainly suitable for longer periods but does not address the immediate issue of natural gas substitution and GHG emission reduction until 2030. Furthermore, while many storage technologies have been developed [90,135], it has been demonstrated by this study that storage technologies at their current technological state cannot contribute significantly to the reduction of natural gas demand or CO\(_2\) emissions. Only scenarios with very high demand coverage by renewable energies and with unrealistic storage capacities based on current technologies would be able to do that. However, even for the scenarios with large storage capacities, a significant temporary lack of energy supplied was found, and, therefore, conventional backup up to the full demand would be required, leading to considerable added costs of investment, maintenance, etc., and an overall increase of energy prices. In addition to that, expansion of renewable energy supply and especially electrical grid strengthening has been increasingly sluggish over the last years as outlined above [58]. Therefore, given planning durations in Germany and construction times required for the additional power grid, a significant short-term reduction in natural gas demand or other fossil fuels from substitution by renewable energy sources seem rather unlikely.

In conclusion, to increase the speed of decarbonization bureaucracy has to be reduced and politics needs to be aligned with current technological and practical limitations. One way to reduce the industry’s energy demand might be the import of energy-intensive base chemicals [35,74,75], thereby easing the task of decarbonization. To achieve this, in addition to increasing the respective transport capabilities, chemical production, and renewable energy, power generation would have to be established in the exporting countries, a prerequisite with a rather uncertain outcome entailing a high risk for the supply chain of the German chemical industry. Carbon capture and storage might be considered as a transition technology for at least temporarily decreasing atmospheric CO\(_2\) emissions until the necessary technologies exist and the required facilities are built. In summary, a large gap exists between current political expectations or planning and realistic timelines for establishing the respective required renewable energy infrastructure. The chemical industry, therefore, faces one of the biggest challenges since its existence with an extraordinary demand for innovation on a technological as well as on a structural level.

While this article’s purpose is mainly to offer a new perspective on the potential for short- and mid-term natural gas replacement and decarbonization by renewable energies, the approach offers policymakers an easy and transparent means of estimating the scale of infrastructure needed for certain targets. Companies or industrial associations from the energy-intensive industries on the other hand can use the methodology to get a realistic picture of the implications of upcoming changes in regulations and policies on fossil-based fuels. The results can further be used as input for investments or where to locate certain facilities.

Future research in this area could improve the current study by focusing on several aspects omitted in this investigation. One simplification made was that no additional
short-term regulating energy storage, e.g., by battery, was included in the calculation. This simplification would imply a fully flexible energy supply by the conventional backup power generation, most likely natural gas driven. The main reason for this was not of a technical nature but rather to keep the number of assumptions small and the overall scenarios comprehensible. Furthermore, this investigation does not consider costs but rather technical solutions, giving only a first impression of the size of the effort ahead for the chemical industry.

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Abbreviations

The following abbreviations are used in this manuscript:

- Act. Actual
- COVID Coronavirus Disease
- EC European Commission
- EEA European Environmental Agency
- EU European Union
- GHG Greenhouse Gas
- GW Gigawatt
- GWh Gigawatt-hour
- IEA International Energy Agency
- kWh Kilowatt-hour
- Nom. Nominal
- PEM Proton Exchange Membrane
- PV Photovoltaics
- TWh Terawatt-hour
- UN United Nations
- US United States (of America)
- WPL Wind Power Land (onshore wind power)
- WPS Wind Power Sea (offshore wind power)

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