




## RESEARCH ARTICLE OPEN ACCESS

# Defossilisation of the Energy Supply of a Chemical Site by Integration of a Carnot Battery

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**Received:** 26 November 2025 | **Revised:** 16 March 2026 | **Accepted:** 26 March 2026

**Keywords:** Carnot battery | chemical site | defossilisation | energy supply system | techno-economic analysis

## ABSTRACT

The energy supply of the chemical industry in Germany relies to a large extent on natural gas as an energy carrier. In order to achieve the climate targets, natural gas must be replaced by other CO<sub>2</sub>-neutral energy carriers in the future. There is a wide range of technologies that can be used for this purpose. In this study, a variety of energy supply concepts are analysed and compared on the basis of an existing industrial application. This work focuses on a techno-economic analysis of integrating a Carnot battery, that is, a power-to-heat-to-power system. The results show that hybrid concepts using both biogas and renewable electricity as an energy carrier and a thermal energy storage are the most economical and offer the greatest flexibility in terms of energy procurement.

## 1 | Greenhouse Gases in the Chemical Industry and Possible Ways of Defossilisation

The chemical industry accounts for a measurable proportion of Germany's energy consumption (165 TWh in 2023 [1], i.e., 7.3% of Germany's final energy consumption [2]). At present, almost half of this is covered by burning natural gas [1]. By 2045, this natural gas consumption must be substituted by other, climate-neutral energy sources in order to fulfil Germany's climate goals [3]. In addition to climate protection, the unpredictable rise in the price of natural gas in Germany in 2022 [4] and its economic consequences [5] are another reason to reduce dependence on natural gas as an energy source. To achieve this, alternative energy supply concepts must be developed that guarantee a

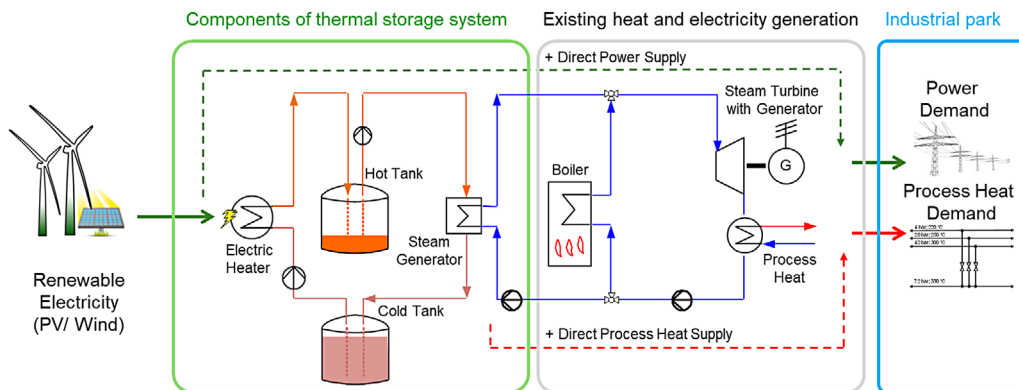
climate-neutral energy supply while at the same time ensuring economic efficiency and security of supply.

A large number of alternative energy supply concepts are available for reducing dependence on natural gas. One option is to switch from natural gas to CO<sub>2</sub>-neutral fuels. For example, hydrogen produced by electrolysis [6, 7] or biomass and biogas [8]. With this fuel switch, the same type of components can be further used. However, individual components may have to be modified to the new fuels. Another option is the electrification [9, 10] of the energy supply. Electricity from renewable energy sources is used to cover electricity and heat demands. Various technologies, such as electric boilers [6, 7, 10, 11], heat pumps [12, 13] or electric heaters [14], are available for electrical heat

**Abbreviations:** B, boiler; BAT, battery; BG, biogas; BM, biomass; CCGT, combined cycle power plant; CST, concentrated solar thermal; EB, electric boiler; EH, electric heater; GT, gas turbine; HP, high pressure; HPU, heat pump; HPFC, hourly price forward curves; HRSG, heat-recovery steam generator; H<sub>2</sub>, hydrogen; LCOE, levelised cost of energy; LP, low pressure; MP, medium pressure; NG, natural gas; PAP, pay as produced; PPA, power-purchase agreement; OPEX, operation cost; QFD, quality function deployment; Ref, reference concept; SG, steam generator of the thermal storage; ST, steam turbine; TES, thermal energy storage.

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**FIGURE 1** | Schematic representation of an integration of a Carnot battery in an existing power plant of an industrial park with power and heat demands. The power plant is expanded by an electric heater, a thermal storage and a steam generator [18].

generation. These technologies can also be combined with battery [14] and thermal storage [6, 14] to compensate for the volatility of electricity generation and electricity prices. A third option is direct solar heat generation. Concentrating solar thermal energy (CST) [15, 16] can also be used to provide process heat at high temperatures and store it in thermal storage units for later use.

The focus of this study is on the integration of a Carnot battery [17] into the energy supply of a chemical park. The structure of the Carnot battery consists of an electric heater, a thermal energy storage and a steam generator and is shown in Figure 1. High-temperature heat is generated from volatile electricity from renewable sources and stored in the thermal storage. When required, the stored heat is used to fuel the steam cycle of the already existing power plant to generate electricity. This allows us to decouple the generation of renewable electricity and the electricity demand. In addition, the stored heat can also be used to cover heat demands at high temperatures in a CO<sub>2</sub>-neutral way.

In this study, a variety of possible energy supply concepts were developed and compared to each other using a real example of a chemical park in Germany. The possible technologies are used both individually and in combination. Due to the lack of available construction spaces nearby the site under consideration, the solar generation of electricity and heat was not considered in this study. The respective design and operation of the concepts were optimised for two future model years. The aim was to identify energy supply concepts that optimise climate neutrality, economic efficiency and security of supply for this chemical site.

## 2 | Methodology

### 2.1 | Demand Analysis, Boundary Conditions and Scenario Definition

A systematic approach is necessary in order to compare the multitude of options. The first step was to analyse the demands of the chemical site under consideration, define the boundary conditions to be met and define prices for various energy sources.

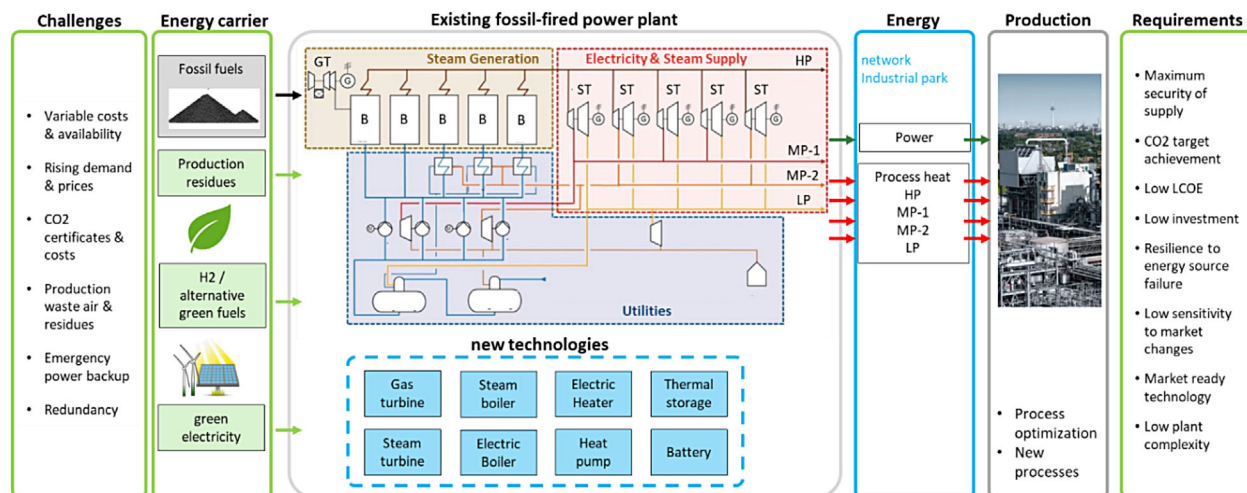
This study looks at a real chemical site located in Duesseldorf-Holthausen, Germany. The chemical processes require electricity supply and heat supply at four different pressure levels (high

pressure (HP), medium pressure (MP-1, MP-2) and low pressure (LP)). For this study, the minimum required power was 220 MW thermal and 60 MW electric, as starting point for the techno-economic optimisation. Overall, 80% of the demanded energy is heat, and 20% is electricity. Energy demand is expected to fall to 94% in 2030 and 85% in 2045 compared to 2018, and the share of electricity demand is expected to rise to 30% in 2045. Currently, demand is largely covered by burning fossil fuels in a combined cycle power plant (CCPP) on site. The power plants, shown in Figure 2, consist of a gas turbine, various boilers and a steam turbine [19]. Grid electricity can be purchased if required. In addition to the fossil fuels, production residues are also burned in the steam boilers, which can be categorised as greenhouse gas free fuel. Hourly resolved time series were generated for the five energy demand flows and the production residues flow for the years 2030 and 2045.

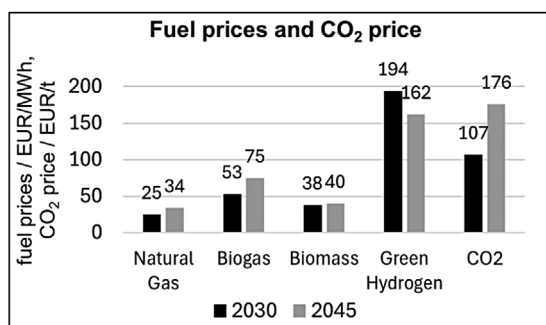
The challenges for the future energy supply concept are, among others, redundancy of the steam generation in order to protect against the failure of individual generators, as well as an emergency energy supply, which guarantees emergency operation in the event of a failure of the grid connection for electricity or gas (see Figure 2). The main requirements are, among others, fulfilment of security of supply and compliance with greenhouse gas emission limits (also Figure 2). The company's internal emission limits stipulate that greenhouse gas emissions are to be reduced to 40% of 2018 emissions by 2030 and that no greenhouse gases are to be emitted from energy supply by 2045.

One possible option for reducing greenhouse gases, as already mentioned, is to switch from fossil fuels to climate-neutral green fuels. In order to model the concepts with green fuel, the fuel prices for the two model years 2030 and 2040 were required. A meta-study of public [20–25] and internal company price forecasts was carried out for this purpose. The values used in this study are shown in Figure 3.

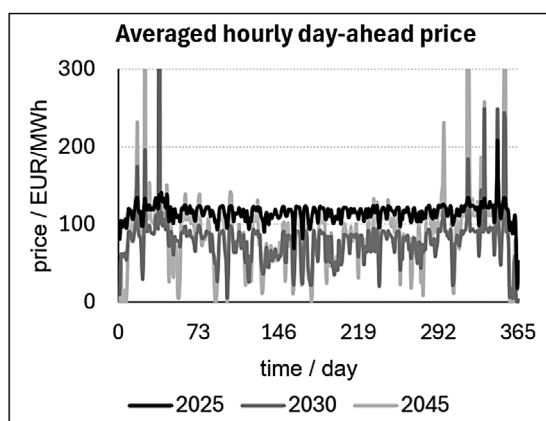
Grid electricity was considered an additional energy source in this study. The price forecasts for the model years were obtained from an external provider [18]. Four different procurement types were analysed: (1) Day-ahead market, (2) a green baseload power-purchase agreement (PPA), (3) a green pay-as-produced (PAP) PPA based on electricity produced by solar power and (4) a green PAP PPA based on electricity produced by solar and wind power.



**FIGURE 2** | Scope of the study. The current fossil fuel-fired energy supply system of the chemical site is shown in the middle. The main components are a gas turbine (GT), boilers (B) and a steam turbine (ST). Moreover, technologies and energy carriers considered for a new supply system are shown. On the left, additional challenges are given, and on the right, the requirements for the energy supply system are listed [18]. LCOE, levelised cost of energy; LP, low pressure; MP, medium pressure.



**FIGURE 3** | Forecast of fuel and CO<sub>2</sub> prices for the years 2030 and 2045 [18].



**FIGURE 4** | Hourly day-ahead market electricity price averaged for each day of the years 2025, 2030 and 2045 [18].

The direct procurement from the day-ahead market was analysed using hourly resolved electricity price time series (HPFC: hourly price forward curve). The diagram in Figure 4 shows the average hourly electricity prices on the day-ahead market. These will fluctuate more in future due to the higher proportion of volatile

**TABLE 1** | Electricity prices for different types of renewable power-purchase agreements for the years 2023, 2030 and 2045 [18].

Electricity price/€/MWh	2023	2030	2045
PPA baseload	137	106	118
PPA pay-as-produced solar	104	57	43
PPA pay-as-produced solar/wind	103	66	60

renewable electricity sources. This is reflected by high price peaks in individual hours and an increase in the number of hours in which the electricity price falls below 5€/MWh, which is rising sharply. Both of these factors increase the potential benefits of energy storage in the energy system.

Green PPAs were considered a further type of electricity procurement. On the one hand, there are baseload PPAs, where the contracted power can be used at any time of the year for a fixed price. On the other hand, there are PAP products, where electricity is supplied at lower prices according to the energy generation curves of the renewable energy sources. In this study, the production profiles of solar and the production profiles of a mixed generation of solar and wind were used. The prices for the different PPA products in the two model years are shown in Table 1.

For each of the electricity procurement types, an individual scenario was defined for the two model years 2030 and 2045 with the corresponding energy demands, emission limits and energy prices. The composition of the eight scenarios is shown in Table 2.

## 2.2 | Concept Selection

Out of the many possibilities to defossilise the energy supply system of a chemical site, 16 concepts were developed and

**TABLE 2** | Definition of the eight scenarios consisting of electricity procurement type and model year.

Scenario	Electricity tariff	Model year
1	HPFC	2030
2		2045
3	PPA baseload	2030
4		2045
5	PPA pay-as-produced Solar	2030
6		2045
7	PPA pay-as-produced solar/wind	2030
8		2045

examined in the further course of the study. In addition to the reference concept, which corresponds to the structure of the current energy supply system with natural gas, there are three concepts (H03–H05) based on fuel switching, seven concepts (H06–H12) with electrification of the heat supply but without their own on-site power generation and five concepts (H13–H17) with an integrated Carnot battery with own on-site power generation. The exact structure of each concept is shown in Table 3.

The first four concepts are standard power plants that utilise different fuels. Concepts H01, H03 and H04 are CCP systems consisting of gas turbine, heat-recovery steam generator, boiler and steam turbine. The reference variant H01 is fuelled with natural gas, whereas the other two concepts use biogas and green hydrogen. Concept H05 is a biomass-fuelled steam power plant consisting of a boiler and steam turbine. The second category of concepts relies on partial electrification of the heat supply and does not include on-site power generation. However, an emergency power supply is ensured by power generators using liquid fuel, although this is not used in normal operation. The concepts H06–H09 consist of both fuel-fired and electric boilers and an electricity storage. The same four fuels are used as in the first category. The H10 and H11 concepts use natural gas and biogas and are equipped with an electric heater, a high-temperature thermal storage and a steam generator

instead of an electric boiler and a battery. The H12 concept is using biogas and has no thermal storage but does have a heat pump that can supply the lowest pressure level with steam.

The third category includes concepts that integrate the Carnot battery into a steam power plant. The concepts H13–H15 consist of a fuel-fired boiler, a steam turbine and the components of the storage cycle as electric heater, thermal storage and steam generator. The boilers are fuelled with natural gas, biogas or hydrogen. In concept 16, LP steam is generated exclusively by a heat pump. MP and HP steam is provided by boiler and steam generator similar to concept H14. H17 corresponds to concept H14 and is expanded by a gas turbine and heat-recovery steam generator. H16 and H17 are both fuelled with biogas.

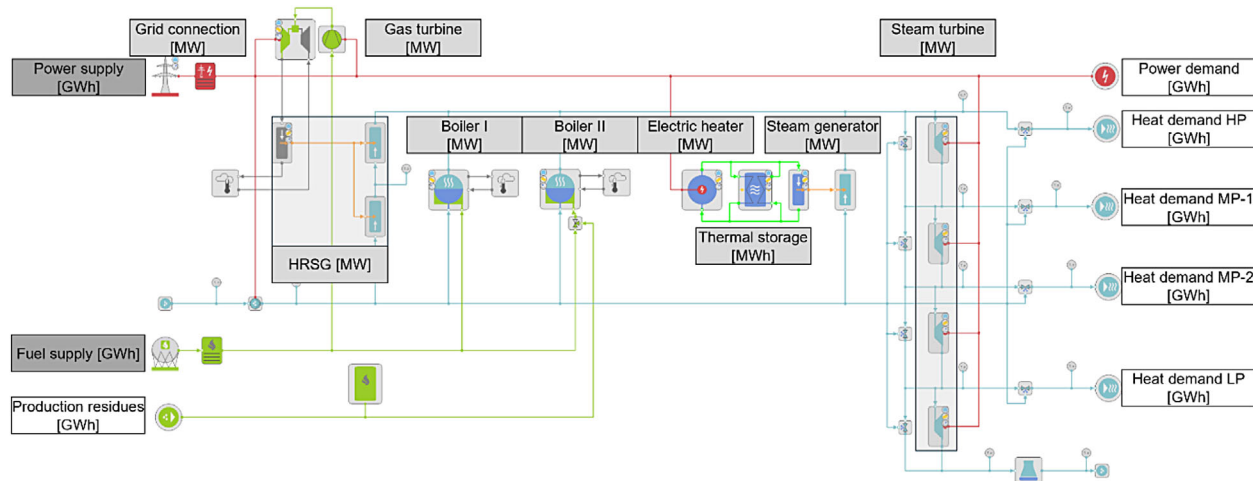
### 2.3 | Techno-Economic Analysis

To determinate the most suitable concept for the energy supply of the chemical site, a techno-economic analysis was carried out. The main objective of the techno-economic analysis was the economic optimisation of the overall system, taking into account the economic and technical boundary conditions (components, availability of renewable energies, load requirements for electricity and heat, etc.). Complex models were required to combine the various energy sources and technology paths that optimise the economic efficiency under the same constraints on the basis of the annual energy yields and the optimum use of renewables.

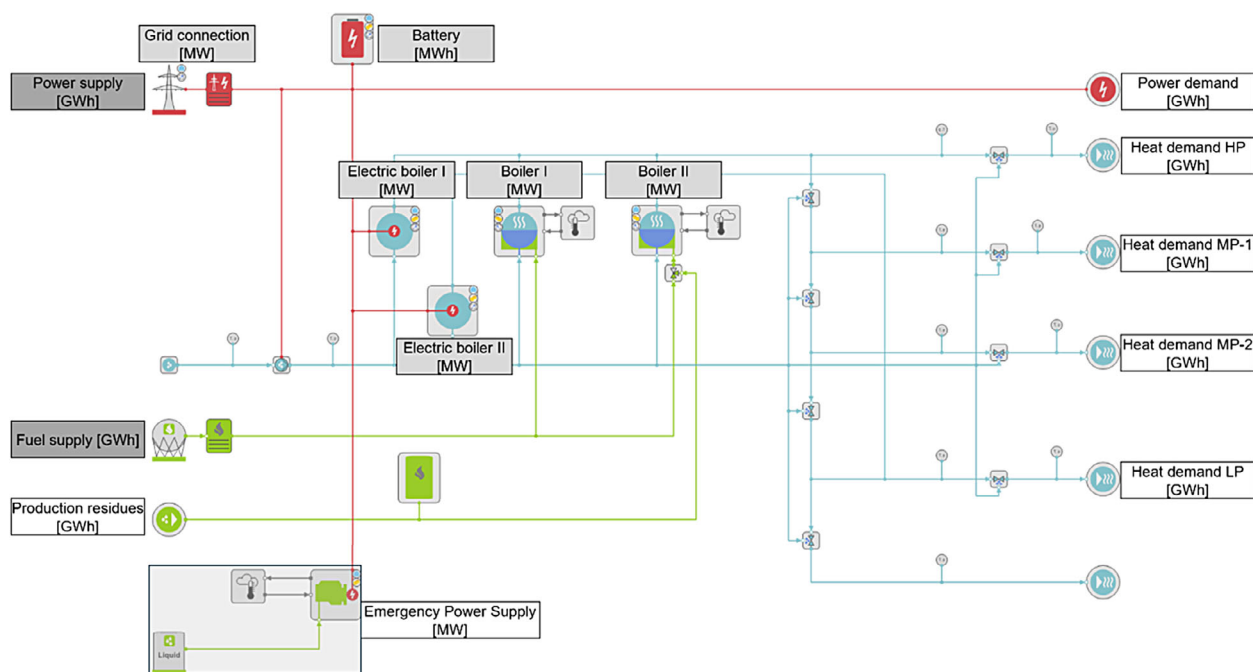
For this purpose, a mixed-integer linear optimisation problem was defined for each concept for each scenario. The aim of the optimisation was to minimise the annualised costs of the energy supply system over a 20-year period. To this end, the design of the energy system was optimised, including the nominal installed power of the energy converters and the storage capacities. At the same time, the operation of the system was optimised for every hour of the year, taking into account the use of the installed technologies and the procurement of energy sources. In addition to satisfying the model equations, the optimisation results also had to ensure security of supply at all times and meet emission targets.

**TABLE 3** | Fuels and technologies used in the 16 concepts: natural gas (NG), biogas (BG), hydrogen (H<sub>2</sub>), biomass (BM), gas turbine (GT), steam turbine (ST), boiler (B), heat-recovery steam generator (HRSG), electric boiler (EB), electric heater (EH), heat pump (HP) and steam generator of the thermal storage (SG), battery (BAT) or thermal energy storage (TES).

Category	Ref.	Fuel switch				Electrification						Carnot battery				
Concept	H01	H03	H04	H05	H06	H07	H08	H09	H10	H11	H12	H13	H14	H15	H16	H17
Fuel	NG	BG	H <sub>2</sub>	BM	NG	BG	H <sub>2</sub>	BM	NG	BG	BG	NG	BG	H <sub>2</sub>	BG	BG
Power generation	GT ST	GT ST	GT ST	ST								ST	ST	ST	ST	GT ST
Steam/Heat generation	B HRSG	B HRSG	B HRSG	B	B EB	B EB	B EB	B EB	B EH	B EH	B EB HP	B EH SG	B EH SG	B EH SG	B EH HP SG	B HRSG EH SG
Storage					BAT	BAT	BAT	BAT	TES	TES		TES	TES	TES	TES	TES



**FIGURE 5** | Model of the energy system of concept H17 in the software TOP-Energy. H17 has the capability of on-site power generation with a gas turbine and a steam turbine and additional power grid connection. Heat is generated with fuelled boilers, electric heater and thermal energy storage. LP, low pressure; MP, medium pressure.



**FIGURE 6** | Model of the energy system of concept H07 in the software TOP-Energy. H07 has no capability of on-site power generation, but it has the grid connection. Therefore, emergency power supply is necessary. Heat is generated with fuelled or electrical boilers. HP, high pressure; LP, low pressure; MP, medium pressure.

The optimisation problem was solved in the TOP-Energy software [26]. A graphical representation of the concepts H17 and H07 is exemplarily shown in Figures 5 and 6. Because of space limits, the other models are not shown, but the models of the reference (H01), the fuel switching concepts (H03–H05) and the other Carnot battery concepts (H13–H16) correspond to the model in Figure 5 with minor adjustments to the available technologies (see Table 3). The remaining electrification concepts correspond to Figure 6 with additional heat storage (H10, H11) or heat pump (H12). For example, in Figure 5, the energy sources are shown on the left of the model, the energy converter technologies in the

centre and the energy demands on the right. During optimisation, the nominal outputs and storage capacities (light grey boxes) as well as the hourly energy procurement (dark grey boxes) are optimised. The energy demands, production residues and the emergency power supply are fixed input variables for the models.

## 2.4 | Evaluation of the Concepts

The evaluation of the concepts is a three-stage process. First, the basic requirements were fulfilment of the security of supply and

compliance with the greenhouse gas emission limits. Concepts that did not fulfil these requirements were not evaluated further.

The next important criterion was the economic viability of the individual concepts based on the levelised cost of energy (LCOE). The LCOE (Equation 1) is the annualised cost, consisting of the costs for operation and maintenance  $C_{O\&M}$ , electricity  $C_{Electricity}$ , fuel  $C_{Fuel}$  and the annuity of the investment costs and the revenues for sold electricity for every hour of the year, divided by electricity  $E_{Electricity}$  and heat demand  $E_{Heat}$  of 1 year. The annuity was calculated for 20 years and an interest rate of 7%:

$$LCOE \left[ \frac{\text{€}}{\text{MWh}} \right] = \frac{\sum \{C_{O\&M} + C_{Electricity} + C_{Fuel} + \text{Annuity} - \text{Revenues}_{Electricity}\} \left[ \frac{\text{€}}{a} \right]}{\sum \{E_{Electricity} + E_{Heat}\} \left[ \frac{\text{MWh}}{a} \right]} \quad (1)$$

At the end, a final evaluation was carried out using the QFD method (quality function deployment). The QFD method [27] was used to compare the large number of concepts. The QFD method enables the objective evaluation of different alternatives. A list of weighted requirements is defined, and the fulfilment of the requirements is evaluated individually for each of the alternatives. On the basis of the resulting score, the alternatives can be categorised in terms of their suitability. In this study, the QFD method was applied to the various concepts with regard to the following requirements: Low LCOE and low investment costs were evaluated quantitatively on the basis of the optimisation results. Low cost sensitivity to energy prices and high resilience were assessed qualitatively on the basis of the options for energy carrier procurement, energy conversion and energy storage defined by the concept definition. High market maturity, low system complexity and a high degree of innovation were assessed qualitatively on the basis of the technologies defined in the concept definition. The degree of innovation was seen as a measure of the amount of potential government funding.

### 3 | Results of Techno-Economic Analysis

The design and operation of the 16 concepts (see Table 3) of the energy supply system were optimised for all eight scenarios (see Table 2) for every hour of the year. The LCOE resulting from the design and operation optimisation of the individual concepts is shown for the year 2030 in Figure 7 and for the year 2045 in Figure 8. For each concept, the result for the scenario with the lowest LCOE is shown, divided into the shares for fuel costs, CO<sub>2</sub> costs, electricity costs, operating costs (OPEX) and annuity. In addition, the range of LCOE values from the other scenarios is marked by the black line in the diagram. All concepts fulfil the two basic requirements, with the exception of the reference variant, which cannot comply with the emission limits.

In both model years, the largest share of costs in all concepts is attributable to the procurement of energy carriers (fuel costs, CO<sub>2</sub> costs and electricity costs). The OPEX and the annuities resulting from the investments only play a subordinate role. In the case of concepts with a large share of electricity costs, the LCOE

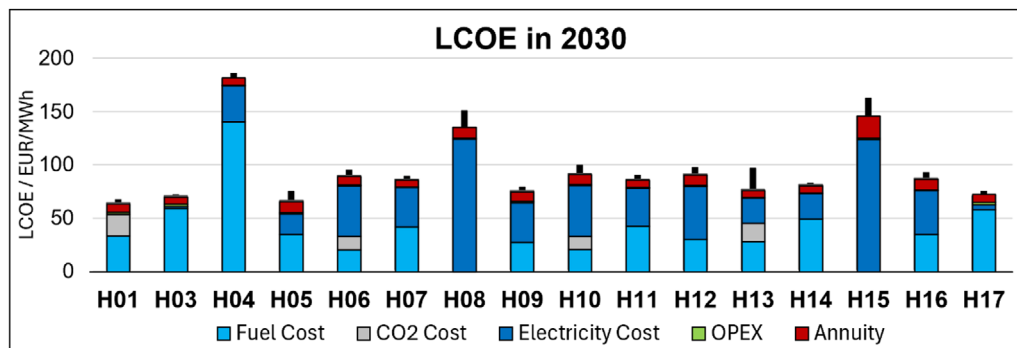
varies particularly strongly with regard to the type of electricity procurement.

In 2030, the reference concept (H01), the concepts with biogas and gas turbines (H03, H17) and the biomass concepts (H05, H09) have the lowest LCOE. The higher costs of biogas compared to natural gas are nearly offset by the additional CO<sub>2</sub> costs. The H05 biomass concept shows, despite the favourable fuel price, a high share of purchased electricity. This is due to a lack of a gas turbine and thus a less efficient on-site production. The concepts based on hydrogen (H04, H08, H15) have by far the highest LCOE. Due to the high fuel price, fuel procurement is minimised as far as possible in the respective concepts. This leads to an almost complete electrification of the energy supply in concepts H08 and H15, whereas the heat requirements in concept H04 must be provided via expensive hydrogen due to the lack of electric heat generation.

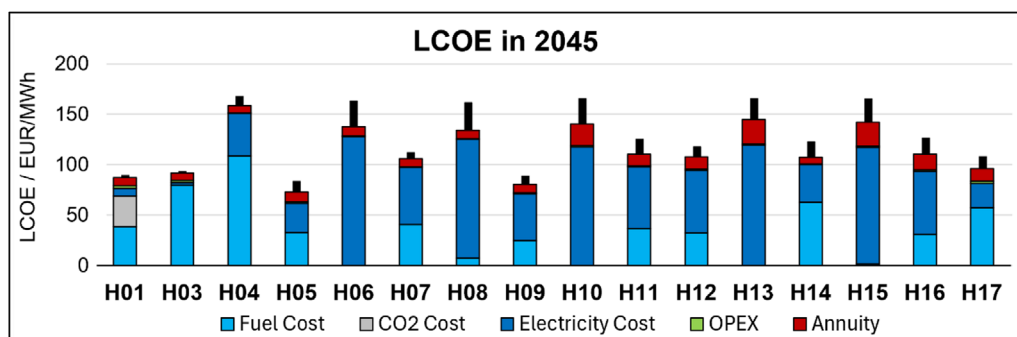
The LCOE's of the electrification concepts (H06–H12) all show a large proportion of electricity costs. On the one hand, this is due to the fact that the electricity demands must inevitably be covered by the electricity grid due to the lack of on-site electricity generation and, on the other hand, that heat can be provided electrically when electricity prices are favourable. The same applies to concepts with Carnot batteries without a gas turbine (H13–H16). Although these can provide electricity via the steam turbine, their electricity generation is less efficient than in concepts with an additional gas turbine. The direct purchase of electricity is the more economical alternative at some times of the year. The strongly increased electricity procurement leads to a rapid expansion of the electricity grid connection. This can be a limiting factor for these concepts, which has to be evaluated economically, technically and timely.

The integration of a heat pump for a part of the heat demand in concepts H12 and H13 does not lead to a noticeable reduction in the LCOE due to higher investment costs. The use of thermal storages in concepts H10, H11, H13, H14, H16 and H17 does not increase the economic efficiency either, which is why the thermal storages built by the optimiser are rather small. The only exception is concept H15, that is, Carnot battery with hydrogen. Due to the exclusive purchase of electricity, it is economically to use the thermal storage to optimise the electricity purchase, and the storage system is built with a larger capacity.

Compared to 2030, the LCOE increases in 2045 in all concepts with natural gas (H01, H06, H10 and H13) or biogas (H03, H07, H11, H12, H14, H16 and H17) due to the rising fuel price and CO<sub>2</sub> price. The LCOE of the biomass concepts (H05, H09) remains at a similar level, whereas the concepts with hydrogen (H04, H08 and H15) have a lower LCOE because of an assumed lower H<sub>2</sub> fuel price for 2045. For concept H03, due to low-cost in-house electricity generation, and for concepts H08 and H15, due to full electrification in 2030, the share of electricity costs remains the same or decreases. In all other concepts, the share of electricity costs rises noticeably. This is due to a relative increase in electricity demand on the one hand and the development of energy prices on the other. Natural gas concepts H06, H10 and H13 show a particularly sharp rise in electricity costs. Due to the emission limits, natural gas consumption is completely substituted by grid electricity.



**FIGURE 7** | The lowest LCOE of each concept for the year 2030 divided in fuel cost, CO<sub>2</sub> cost, electricity cost, OPEX and annuity. The black line indicates the range of the LCOE for the other scenarios of 2030.



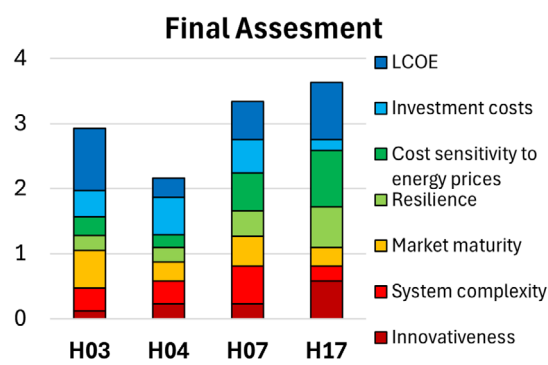
**FIGURE 8** | The lowest LCOE of each concept for the year 2045 divided in fuel cost, CO<sub>2</sub> cost, electricity cost, OPEX and annuity. The line indicates the range of the LCOE for the other scenarios of 2045.

For the concepts that are almost completely electrified (H06, H08, H10, H13 and H15), the construction of a thermal storage for the optimisation of electricity purchase is economic in 2045. Moreover, thermal storages will also be built for concepts with the comparatively cheap fuel biogas (H11, H14, H16 and H17) in order to optimally integrate the temporarily cheap available grid electricity into the energy supply of the chemical park.

The results of the optimisation show that energy costs in particular have an impact on the chemical park's energy supply. The use of expensive fuels such as hydrogen is uneconomical and leads to a substitution of the fuel by grid electricity. Although the use of biomass as an energy source is economical, the sustainable provision of the necessary quantities is questionable. During the optimisation, the use of biomass was not restricted by an upper limit, which resulted in a high biomass consumption. Hybrid concepts show interesting potential. They enable the use of electricity in phases of low electricity prices and can bridge phases of high electricity prices through the use of relatively cheap fuel. At the same time, these hybrid concepts fulfil the greenhouse gas emission limits. In 2045, the increased use of grid electricity in combination with thermal storage can increase the economic viability of some concepts.

#### 4 | Final Assessment

The final assessment according to the defined criteria of the applied QFD method (Section 2.4) is shown for four concepts.



**FIGURE 9** | Result of the final assessment of the concepts H03, H04, H07 and H17.

These include the three most promising concepts with biogas with varying degrees of electrification H03 (fuel-switch with CCPP and biogas), H07 (electrification with E-boiler and biogas), H17 (Carnot battery with CCPP and biogas) and the hydrogen variant H04 (fuel-switch with CCPP and H<sub>2</sub>) as a contrast. The result of the final assessment is shown in Figure 9. The two mandatory criteria, compliance with the emission limits and the secure supply of the chemical park, were fulfilled by all four concepts.

The first two criteria are the economic key figures. As shown in detail in the previous subchapters, concept H03 leads to the

lowest LCOE, closely followed by concept H17. Concept H07 has a higher LCOE, whereas H04 has by far the highest LCOE of the four concepts. Concepts H04 and H07 have the lowest investment costs, followed by concept H03. The high number of components in concept H17, such as gas turbine, steam cycle, electric heater and thermal storage, leads to comparatively high investment costs.

Concepts H03 and H04 can only provide heat via fuel and therefore cannot switch completely to grid electricity as an energy source if fuel prices rise. Heat has the largest share of energy demand. Both concepts therefore have a low rating in terms of cost sensitivity to energy prices. The H07 concept can provide the heat demand using both electricity and fuel, but the electricity demand can only be covered by the grid. This leads to a slightly higher rating. Concept H17 receives the highest rating. The entire energy demand can be supplied by both grid electricity and fuel. In addition, short-term fluctuations in the electricity price can be bridged by the thermal storage.

The resilience of the concepts was assessed in a similar way. If the fuel supplies are cancelled, the heat demands can no longer be covered with concepts H03 and H04, which leads to the lowest rating. With the H07 concept, electricity demands can no longer be covered if the power grid fails. The H17 concept can cover both energy demands exclusively with fuel as well as exclusively with grid electricity and is therefore rated highest.

The H03 concept receives the highest rating for the market maturity criterion, as all the technologies used have already been in successful use for decades. The electric boilers used in the H07 concept are also already increasingly being used, which leads to the second highest rating. Hydrogen-fuelled gas turbines and the high-temperature thermal storage are still in the early stages of development and result in a low rating for H04 and H17.

The H07 concept has the lowest plant complexity, as it only uses electric and fuelled boilers for steam generation and an electricity storage. The second-best assessment is for the H03 and H04 concepts, which consist of a gas turbine and steam cycle. The most complex system is concept H17, which, in addition, has a storage cycle consisting of an electric heater, heat storage and steam generator.

Due to the use of mature technologies in known systems, concept H03 receives the lowest rating in terms of innovativeness, closely followed by H07. Although concept H04 utilises an innovative technology in the form of the hydrogen-powered gas turbine, this is used in a classic CCPP, which is why it only receives a slightly higher rating. Concept H17 is rated highest because it combines new technologies, such as electric heaters and thermal storage at high temperatures, with a new system interconnection, CCPP, combined with a Carnot battery.

The results of the evaluation show that the H17 concept, closely followed by the H07 concept, achieved the highest score. Both concepts are convincing due to the flexible procurement of both energy sources with moderate economic efficiency.

## 5 | Summary and Outlook

This study presents the results of a techno-economic analysis of CO<sub>2</sub>-free energy supply concepts for electricity and heat for the defossilisation of a chemical park in Germany. At the beginning, the requirements for the system were formulated, and concepts were designed on this basis. With the help of an optimisation tool, both the design and the hourly operation were optimised for two model years. The results of the optimisation were examined with regard to the LCOE for the two model years 2030 and 2045. It was shown that hybrid concepts that use both cheap green fuel, such as biogas, and electrical energy as energy sources for the electricity and heat supply perform particularly well while meeting the CO<sub>2</sub> targets. They result in LCOE of 71–87€/MWh in 2030 and 93–112€/MWh in 2045. To increase the electricity procurement, a rapid grid expansion is necessary. The use of hydrogen is uneconomical in all concepts due to the high fuel prices. The use of biomass is also affordable, but its sustainability is questionable. The integration of a thermal storage is in 2030 only economical in concepts with a large share of grid electricity as energy carrier, whereas in 2045, it is also economical in hybrid concepts. The energy cost account for about 71%–96% of total annual cost and are thus dominant. This means that sensitivity to investment costs is low. This enables investment in slightly more expensive technologies that are significantly more flexible. Finally, the most promising concepts were assessed qualitatively according to various criteria. Here, too, the hybrid variants scored particularly well due to their potential flexibility. The techno-economic analysis and subsequent final assessment resulted in a concept variant of a biogas-fired CCPP in combination with an electric heater and a thermal storage as the technical concept that best met the previously defined criteria.

The energy costs dominate the total annual costs. Therefore, in future studies, it is recommended to analyse in more detail the influence of uncertainties in the future prices of energy carriers on the energy supply system of a chemical site. Additionally, for industrial parks with sufficient space, solar resources and suitable temperature ranges, it is recommended to consider on-site self-generation with solar technologies as PV and CST.

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### Nomenclature

#### Symbols

$C_{O\&M}$	costs of operation and maintenance
$C_{Electricity}$	costs of electricity procurement
$C_{Fuel}$	costs of fuel procurement (inc. CO <sub>2</sub> costs)
$E_{Electricity}$	electricity demand
$E_{Heat}$	heat demand

### Acknowledgements

The authors thank the Ministry of Economic Affairs, Industry, Climate Action and Energy of the State of North Rhine-Westphalia for the financial support given to this work in the project StoREN with the funding reference EFO 0187.

Open access funding enabled and organized by Projekt DEAL.

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