Climate-neutral industrial sites: technological strategies for flexible, market-driven and low-carbon energy systems

Klaus Görner, Margit Thomeczek, Carsten Kolligs, Simon Wenzel, Rocco Altieri, Torsten Buddenberg, Tobias Hirsch, Steffen Klöppel and Jana Stengler

Introduction – Objectives of the energy transition, particularly for industry

In order to achieve the established climate neutrality targets, the transformation of the chemical industry must begin using technologies that are already available today, even though the assessments presented below indicate that gaps will initially remain, which will need to be addressed by emerging technologies once they reach commercial maturity. Experience from other structural transformation processes shows that such transformations require decades. Germany's coal phase-out, i.e. the phase-out of "only" a single energy source, will take approximately 20 years, from the political decision taken in 2020 until the decommissioning of the remaining coal infrastructure in 2038. The defossilisation of the chemical industry – meaning the substitution of fossil feedstocks in both energy and material flows – requires close cooperation between the chemical industry, component manufacturers, research organisations and the energy sector in order to develop viable concepts, align industrial requirements with the technologies currently available and available in the medium term, and provide directed impetus for innovation.

This paper was prepared under the coordination of Rhein Ruhr Power e.V. (RRP) [1]. RRP regards itself as a think tank for strategic future topics such as the use of green energy carriers, for example hydrogen and its derivatives, sector coupling, power-to-products and related fields. RRP is not a lobbying organisation. Rather, its members are united by the common objective of promoting innovative energy technologies for an economically viable, secure and socially accepted energy system with the goal of achieving climate neutrality. RRP combines the expertise of its member organisations and organises cross-sector stakeholder projects, from their initiation through to implementation.

The project presented in this paper was developed following this approach, with all authors representing member organisations of RRP. To illustrate the challenges associated with the climate-neutral operation of an industrial site, the authors selected Marl Chemical Park as a reference site (Figure 1). The site has a long history and is now operated by the infrastructure service provider SYNEQT. Production at Marl Chemical Park focuses on the conversion of petrochemical feedstocks such as benzene, ethylene, propylene, methanol and phenol into basic chemicals, fine chemicals and speciality chemicals – from petroleum gas and refinery C4 streams to downstream products, from chlor-alkali electrolysis to PVC, from acetylene to tetrahydrofuran, from fatty alcohols and ethylene oxide to surfactants, and from acrylic acid to butyl acrylate, to name just a few examples [2]. The feedstocks are supplied mainly by the nearby refinery in Gelsenkirchen, which processes

Fig. 1. Aerial view of Marl Chemical Park (CPM) [5] © Evonik Industries AG.

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approximately 12 million tonnes of crude oil annually. Around 4 million tonnes of products for various markets are manufactured each year at Marl Chemical Park from these feedstocks. This illustrates the close integration that characterises today's chemical industry [3] [4].

Status quo – System analysis of the Marl site

Marl Chemical Park is a highly integrated industrial production site in which material and energy processes are closely interconnected. External material links exist, for example via pipelines, to other refinery and chemical plants in the northern Ruhr region and beyond. One example is the hydrogen pipeline connection established as part of the GetH2 project [6]. A characteristic feature of the site is the separation between the production plants and the central infrastructure and energy supplier, SYNEQT GmbH, whereby the energy and utility supply is organised from the perspective of an independent site operator. The energy infrastructure includes, in particular, electricity, steam, cooling, compressed air, cooling water systems and a district heating network. Some of these networks are interconnected. A central role is played by the site-wide steam network, which extends over approximately 80 km, serves different pressure levels and continuously supplies the production processes. The heating network functions as an internal district heating network (internal hot water network) with a supply temperature of 80 °C and a return temperature of 60 °C. The core of the energy system consists of four highly flexible combined-cycle gas turbine (CCGT) power plants operating according to the combined heat and power (CHP) principle, providing both electricity and process steam at different pressure and temperature levels. The plants are operated according to the heat demand in order to ensure the continuous supply of the chemical production processes. At the same time, the use of Advanced Process Control enables electricity generation to be largely decoupled from steam production, allowing flexible operation. Figure 2 shows the basic structure of the system, including a future expansion option (highlighted in blue).

In addition to natural gas, site-specific residual gases and other process-related residual materials are used as fuels, enabling material by-products to be utilised energetically. This close coupling of the production and energy systems is a key characteristic of the site and contributes significantly to the efficiency of the overall system. In the reference year 2025, approximately three-fifths of the required steam was generated by the central power plant system, while around two-fifths originated from production processes and were fed back into the steam network, underlining the high degree of internal integration at the site.

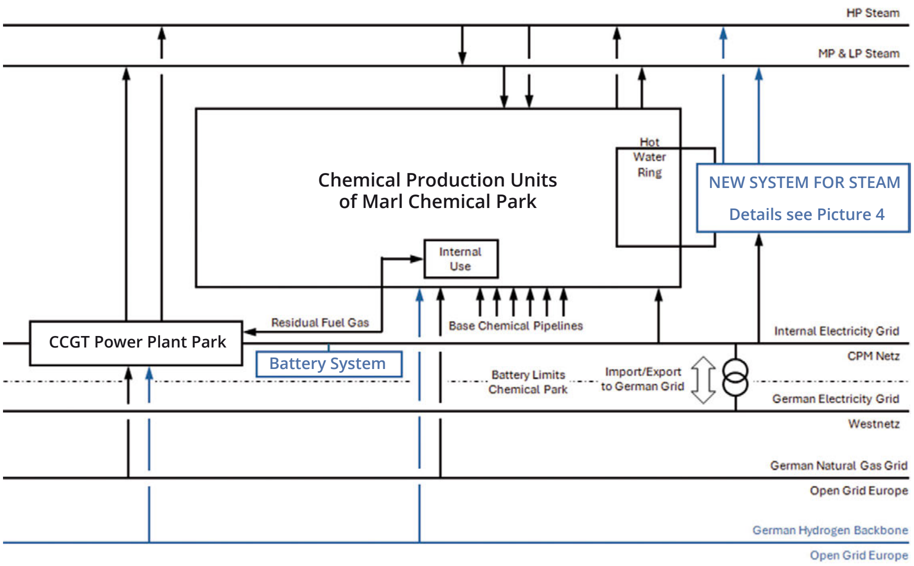

Fig. 2. Structure of the energy system at Marl Chemical Park (CPM): a) existing system (black) b) expansion option (blue).

Figure 3 shows a simplified overview of the site's energy consumption [7]. Further data originate from internal site sources and can therefore only be presented in a highly simplified form for legal reasons. Around the transition from June to July, the figure additionally contains an overlay of actual operating data, illustrating that the smoothed curves represent only a simplified picture of real operation. Actual plant operation is subject to significant fluctuations, making a highly flexible energy system essential. Nevertheless, it can clearly be seen that, while electricity demand and high-pressure steam demand remain relatively constant, the demand for medium-pressure and low-pressure steam shows strong seasonal variation and is considerably higher during the winter months. The reasons include increased district heating demand and higher heat requirements of the chemical plants, for example for thermal separation processes. The lower heat demand during summer explains the higher electricity imports and the lower natural gas demand. At reduced thermal load, the combined-cycle gas turbine plants also produce less electricity. The site's total emissions are closely linked to this integrated structure and arise mainly from two sources: the central power plants and the emission-intensive processes within the chemical production facilities. In the reference year 2025, the gross CO_2 emissions of the power plant fleet amounted to approximately 700,000 tonnes, with energy-related emissions representing a major share of the site's overall emissions profile. An important characteristic of the energy system is its high operational flexibility, which is made possible by both the technical design of the power plants and the site-wide integrated control system. This allows electricity generation and steam production to be largely decoupled and ensures that fluctuations in demand from the production plants can be balanced within a very short time. At the same time, this system architecture enables active participation in the electricity market. The site operates both as an electricity producer and as an electricity consumer and trades

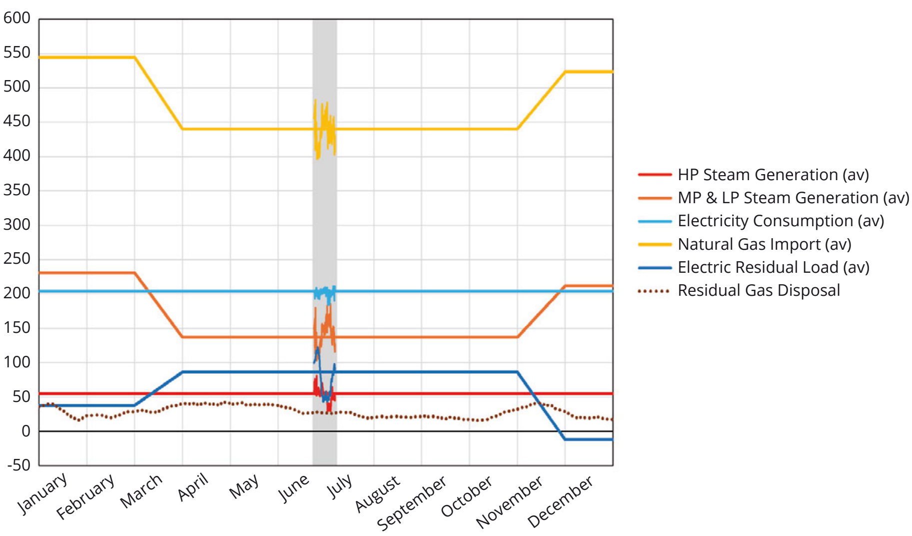

Fig. 3. Energy consumption and energy imports in MW at Marl Chemical Park in 2025 (positive values indicate consumption).

electricity volumes, particularly on the day-ahead and intraday markets. The current system configuration is the result of a comprehensive transformation of the site's energy supply, the key element of which was the complete phase-out of coal-fired energy generation. With the shutdown of the last coal-fired generating units in 2024, an energy supply structure that had existed for several decades came to an end and was replaced by a modern, gas-fired and highly flexible power plant fleet. Besides providing improved operational characteristics, this new fleet also exhibits a significantly lower emissions intensity. Compared with the former coal-fired system, it reduces annual CO_2 emissions by up to approximately one million tonnes. At the same time, the control technology of the integrated energy system was fundamentally modernised, enabling dynamic and market-oriented operation of the entire system. This transformation represents the first integral step on Marl Chemical Park's pathway towards climate neutrality. In particular, it should be noted that in the future the gas turbines currently employed can be operated partly – and, following the necessary technical modifications, entirely – on hydrogen [8].

Overall, the system analysis shows that Marl Chemical Park should be regarded as a complex, closely integrated energy system characterised by a high degree of internal integration, centrally coordinated energy supply and extensive flexibility options. The combination of continuous industrial load profiles, integrated utilisation of by-products as energy carriers and active participation in energy markets makes the site a representative example of an energy-intensive industrial cluster with optimised sector coupling. However, even a modern site such as Marl Chemical Park continues to face ongoing transformation pressure resulting from changing framework conditions and future challenges. Under the current German Heat Planning Act (Wärmeplanungsgesetz), the framework conditions require that by 2040, 80 % of the heat supplied by the site's heating network must originate from renewable energy sources in order to achieve climate neutrality by 2045 [9]. Figure 2 illustrates two possible approaches to meeting this challenge. One option is electrification. The other is the gradual replacement of natural gas by renewable fuels such as green hydrogen, biomethane or similar alternatives.

Description of the technologies under consideration

The following section describes a possible extension of the existing energy system, with a particular focus on the technologies under consideration. Two aspects are discussed in greater detail: electrification and the implementation of carbon capture and storage/utilisation (CCS/CCU). As the objective is the optimisation of the overall system, the site-specific boundary conditions are described first.

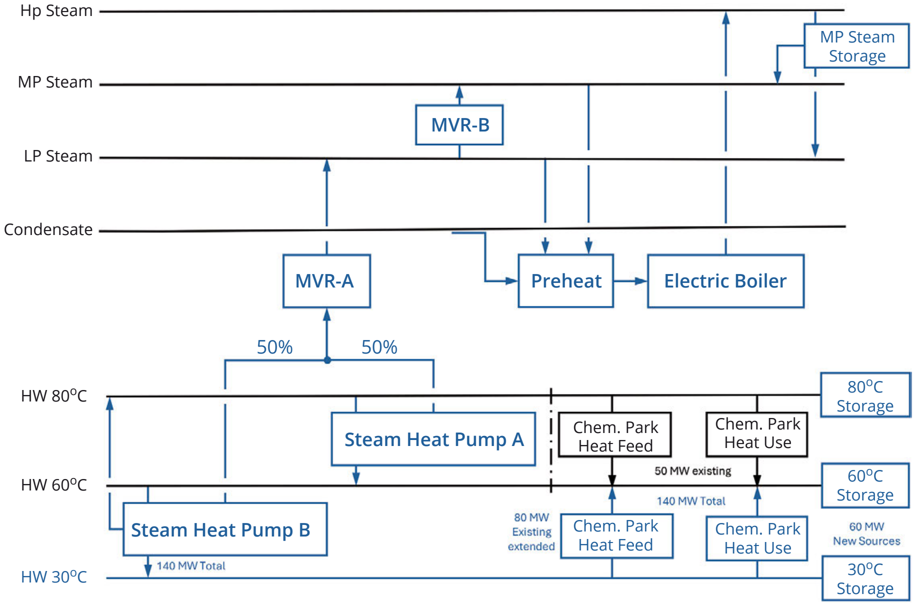

Fig. 4. Concept for the electrification of the steam system at Marl Chemical Park.

Site-specific boundary conditions

In the short to medium term, changes in customer demand profiles are expected at Marl Chemical Park. On the one hand, the chemical plants continuously strive to implement further measures to improve energy efficiency. On the other hand, technological changes are expected both in the chemical production processes themselves and in the way these processes are heated. Consequently, the overall energy demand is expected to decrease. In addition to technological changes such as vapour recompression, these measures include improved thermal insulation, increased utilisation of waste heat, optimised user behaviour, more efficient control systems, as well as operational and maintenance-related improvements. When designing the future asset portfolio, further site-specific boundary conditions must be taken into account which continue to require the operation of combined-cycle gas turbine (CCGT) plants and combustion systems. A key requirement results from security of supply. For safety reasons, Marl Chemical Park must always be capable of switching to island mode operation in the event of a disruption to the public electricity grid. Consequently, the current operational requirement is to keep at least two gas turbines and one steam turbine available in minimum-load operation at all times.

Furthermore, the CCGT plants fulfil an essential function in the thermal disposal of various residual material streams originating from the chemical production plants. Some of these residual streams cannot be stored and therefore have to be safely combusted in supplementary firing systems. These disposal requirements and the need to ensure continuous availability make it necessary to operate at least one boiler with supplementary firing, thereby defining a lower limit for the site's natural gas or fuel demand. At the same time, this minimum operating mode already covers a large proportion of the required high-pressure steam demand. Against this background, the installation of electrically driven steam generation systems may be economically and systemically beneficial. However, their operation must be integrated into the existing minimum operating requirements of the CCGT plants and therefore remains subordinate to these operational constraints.

Electrically driven steam generation system using heat pumps and mechanical vapour recompression

Description of the technical concept

The new steam generation system shown schematically in Figure 2 is illustrated in greater detail in Figure 4. Process steam is generated primarily by means of heat pump and mechanical vapour recompression technology, which has reached full commercial maturity in recent years through developments by various manufacturers. The concept initially makes use of waste heat from the existing hot water network operating at temperature levels of 60 °C and 80 °C. Steam Heat Pump A, in combination with a steam compressor (MVR-A) (Mechanical Vapour Recompression – MVR), utilises this waste heat to supply the low-pressure steam network. Medium-pressure steam is generated from the low-pressure steam by means of a second steam compressor (MVR-B). The high-pressure steam network is supplied by electric boilers, which are already commercially available for operating pressures of up to 85 bar.

A decisive factor for the electrification concept is the availability of suitable heat sources at the site. According to the previously mentioned German Heat Planning Act *(Wärmeplanungsgesetz)*, "unavoidable waste heat" represents one of the recognised renewable heat sources. The basic concept is to install, in addition to the existing hot water network, a cold water ring operating at approximately 30 °C, allowing the 60 °C return flow of the existing network to be used as the heat source for the heat pumps. In this arrangement, Steam Heat Pump A further cools the 80 °C return flow in a second heat exchanger, thereby recovering additional heat as hot water at a temperature level of 80/60 °C. This hot water can subsequently be supplied, in a cascade arrangement, to Steam Heat Pump B via the existing 60 °C hot water network [10]. In the current conceptual design, the heat pump system is intended to provide a maximum thermal output of approximately 250 MW_{th}. This requires approximately 140 MW_{th} of waste heat at a temperature level of 60/30 °C.

Of this amount, the waste heat sources already available today at the 80/60 °C temperature level can provide approximately 80 MW_{th} of thermal power through further cooling to 30 °C. At the same time, this would reduce the load on the site's cooling water network. A further 60 MW_{th} of thermal power at the 60/30 °C temperature level would have to be made available from additional heat sources. One possible source is the site's refrigeration system, which continuously produces low-temperature cooling energy in the medium double-digit megawatt range. The site's compression refrigeration system alone could provide the required waste heat at an adequate temperature level. The analysis demonstrates that Marl Chemical Park is capable of providing the required heat flows in a redundant and resilient manner.

Figure 5 shows an overview of a steam-generating heat pump of the type envisaged for this application, as previously presented in an earlier article in the vgbe energy journal [11]. For the total thermal output of 250 MW_{th}, individual units with capacities exceeding 50 MW_{th} can be constructed. From a technical perspective, the limiting factor is often the electricity grid, since the power consumption of individual electric motors should not exceed 10 MW_{el} in order to ensure reliable switching of these units. In the event of island mode operation, the electricity supply, and to a certain extent also the steam supply, of the site must be maintained. This is achieved primarily by the four CCGT plants, which are ramped up from minimum load to full-load operation. This provides not only increased electricity generation but also the required steam production. During the transition period of approximately 30 to 60 minutes until the CCGT plants reach full-load operation, the electricity supply can be maintained by means of a battery energy storage system. As the basis for the economic assessment, the coefficients of performance (COP) for the different steam pressure levels were determined for the system. Based on an annual analysis using operating data from 2025, an average COP of 2.15 was calculated for the complete steam generation system (Table 1).

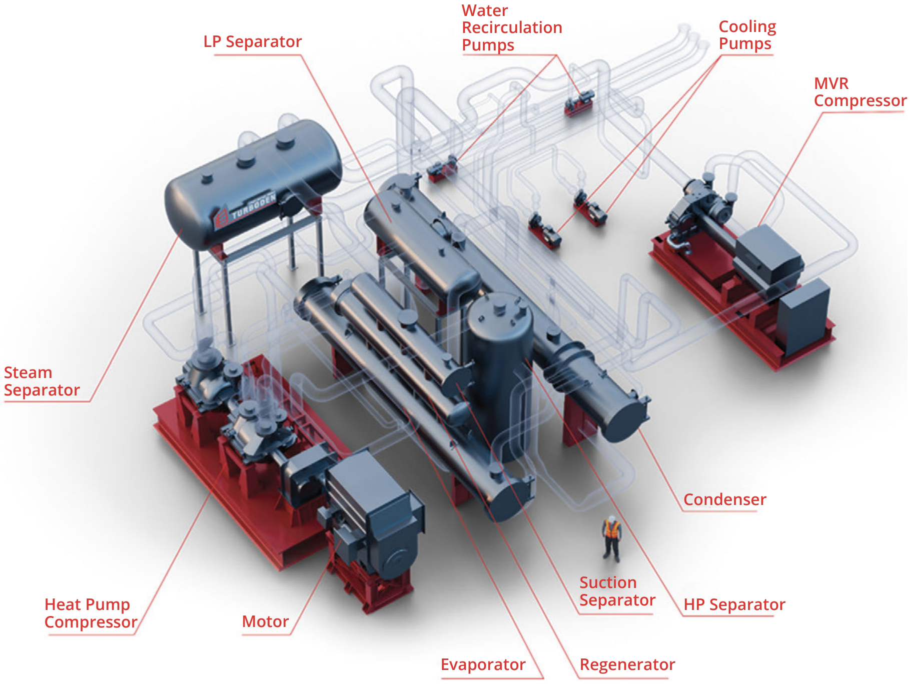

Fig. 5. General overview of a large heat pump for steam generation consisting of a heat pump and a steam compression © Turboden S.p.A.

Tab. 1. Coefficients of performance (COP) for the individual pressure levels and average system COP determined using operating data from 2025.

Pressure Level	COP	2025 av. COP
High Pressure Steam HP (by electric steam boiler with LP+MP steam pre-heating)	1.12	
Medium Pressure Steam MP (by LP steam and second steam compressor)	1.75	2.15
Low Pressure Steam LP (by heat pump array A+B and steam compressor)	2.30	

This indicates that, for the reference year 2025, the entire steam demand could theoretically have met the site's annual steam demand. A particular feature of the concept is that preheating the boiler feedwater using steam generated by the heat pumps results in the electric boiler also achieving a COP greater than 1. The analysis demonstrates that, under continuous year-round operation, every 1 MWh of electricity supplied to the system generates 2.15 MWh of useful heat. Assuming an efficiency of 90 % for the existing natural gas-based steam generation system, 1 MWh of electricity would replace approximately 2.39 MWh of natural gas, based on the lower heating value.

A preliminary investment assessment was carried out for the concept shown in Figure 4, based on values reported in the literature. The results are summarised in Table 2. The annual fixed costs for the proposed system, including financing, personnel and maintenance, are estimated to be between €30 million and €35 million. In addition, operating costs result from electricity consumption, with a large proportion of the required electricity having to be imported from the public grid.

Tab. 2. Investment assessment for the proposed electric steam generation system (working estimate, excluding contingencies).

System Unit	Unit Rating	Investment
Large Heat Pump System	250 MW(th)	200 MioEUR
Electric Steam Generator	100 MW(th)	30 MioEUR
Battery System (50 MWh)	50 MW(el)	10 MioEUR
Balance of Plant all Units	20% [-]	50 MioEUR
Total electric thermal System	400 MW	290 MioEUR

Based on the technical data, and assuming continuous year-round operation of the system, the resulting changes in energy demand can be derived from Figure 3. These changes are shown in Figure 6. The results indicate that natural gas (or fuel) consumption would be reduced by approximately 65 %, while the residual

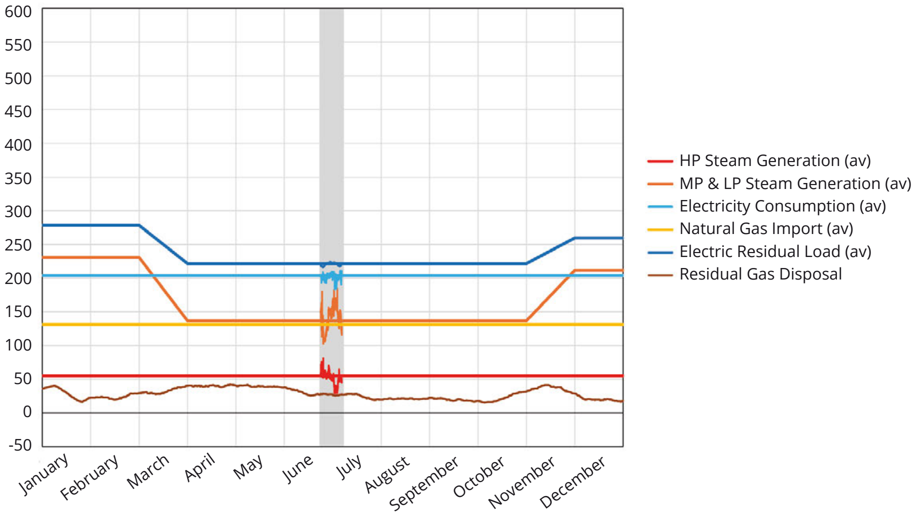

Fig. 6. Energy consumption and energy imports in MW at Marl Chemical Park in 2025 with the proposed electrified system (electricity demand shown excludes the consumption of the heat pumps and electric boilers).

Tab. 3. Comparison of energy demand for the reference year 2025.

Energy Comparison	Base Case	Electrification
Electricity	100 %	389 %
Residual Gas	100 %	100 %
Natural Gas	100 %	36 %
Total Energy	100 %	86 %

electricity demand from the public grid would increase by almost a factor of four (Table 3).

Any future expansion of the plant portfolio is evaluated from the outset from an energy economics perspective and integrated into the commercial optimisation of the existing asset portfolio. The objective is to improve the overall business case by generating additional revenues through electricity trading enabled by sector coupling. All assets connected to the electricity grid are therefore operated in accordance with electricity market signals. Day-ahead and intraday optimisation of plant operation forms an integral part of the business cases developed for the site. These additional revenues have not been included in the present assessment, although their positive contribution is undisputed. Depending on electricity prices, the site is already capable of switching between electricity imports from and exports to the distribution grid operator, thereby making a significant contribution to the flexibility of the German electricity system. A further result of the technical assessment based on the current legal framework shows that, by 2040, the existing CCGT-based energy system would require 80 % renewable fuels, such as green hydrogen, in order to comply with the Heat Planning Act. In the electrification scenario, the required quantity of renewable fuels would be reduced by approximately 75 %. In neither scenario would hydrogen have to be used before 2040. Up to this point, only technologies that are already commercially available and supported by guaranteed technical performance and operating references have been considered. However, research is progressing rapidly, particularly in the field of heat pump technology. Therefore, one possible future technological extension is briefly discussed in the following section.

Future technological developments

As an example, the preheating of the boiler feedwater for the high-pressure steam boilers is considered. Owing to the almost constant specific heat capacity of water, an almost linear temperature profile exists between the condensate return temperature (assumed here to be 80 °C) and the boiling temperature of approximately 287 °C (70 bar). One promising future technology for this application is the use of transcritical heat pumps employing carbon dioxide (R-744) as the working fluid. In such a cycle, the CO_2 is compressed beyond its critical pressure of 73.8 bar. During the subsequent heat rejection process, no phase change occurs; instead, a continuously varying temperature profile is obtained, the slope of which depends on the operating pressure. Through appropriate design of the thermodynamic cycle [12] [13], an almost linear temperature profile can be achieved, thereby reducing heat transfer losses, as heat is supplied at the required temperature level throughout the process. The heat source for such a heat pump may either be the cooling water already mentioned or an additional cooling source operating at -20 °C. In the following example, the latter case is considered, in which the CO_2 evaporates at 17 bar, corresponding to an evaporation temperature of -24.7 °C.

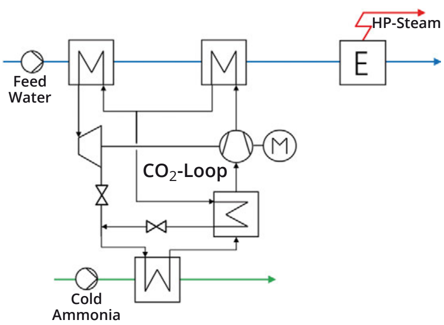

Fig. 7. Possible process flow diagram of a CO_2 heat pump for preheating the boiler feedwater of the electric boiler.

Assuming a high-pressure steam generation unit with a thermal output of 40 MW, the heat required for feedwater preheating amounts to 14.36 MW. A CO_2 heat pump could provide this heat with a coefficient of performance (COP) of 1.45. In this concept, the latent heat of evaporation would be supplied by an electrode boiler, resulting in an overall COP of 1.13 for the heating process. Compared with the concept described above, an additional cooling capacity of 5.53 MW could also be utilised. However, the operating conditions required for such a heat pump differ considerably from those of commercially available systems. In addition to the high compressor discharge temperature of approximately 410 °C, operating pressures of around 250 bar would be required. Consequently, the development of concepts aimed at reducing these operating pressures is currently the subject of ongoing research [14].

Implementation of carbon capture and utilisation

In addition to electrification, another option for reducing direct emissions at the site is the implementation of carbon capture and, where appropriate, carbon utilisation, thereby lowering greenhouse gas emissions [15]. Carbon capture, utilisation and storage (CCUS) remains a subject of ongoing debate. [16]. Nevertheless, both industry and the scientific community assume that these technologies will become indispensable in certain sectors in the future [17]. It is also expected that carbon dioxide will be required as a carbon source for the production of refinery products using green hydrogen, since biomass resources alone will not be sufficient to provide all the necessary carbon feedstock [18]. Current studies indicate that, even if global demand for refinery products decreases by more than 45 %, biological feedstocks would only be capable of supplying approximately half of the required carbon. The remaining demand would therefore need to be met through carbon capture and utilisation in combination with green hydrogen.

Against this background, it is reasonable for an industrial site integrated with a refinery to consider carbon capture as a means of contributing to the long-term security of carbon feedstocks within the integrated production network. In this context, an assessment was carried out to identify which carbon dioxide sources at the site are likely to remain available in the long term. The anal-

Tab. 4. Sources of carbon dioxide at Marl Chemical Park and the resulting capture potential.

Carbon Dioxide Source	Source	CO_2-Amount	
Chemical Production Units on Site	Public Data by Umweltbundesamt [19]	550	kt CO_2/year
Site near Waste Incineration Units	Own calculation from Permit data	260	kt CO_2/year
Total Potential for Carbon Capture	Public and own calculation	810	kt CO_2/year
Capture Rate	95% Capture set by MHI	770	kt CO_2/year
Naphtha Equivalent	Calculates by 14u/44u = 0.32 of CO_2	245	kt Naphtha/ year

ysis identified several CO_2 sources originating from chemical production processes and associated waste treatment facilities that are expected, with a high degree of probability, still to be in operation in 2050. These sources are therefore fundamentally suitable for contributing to a future carbon cycle. If the power plant fleet is converted to hydrogen operation in the future, intermediate storage of captured CO_2 will become necessary in addition to carbon capture itself, in order to ensure a continuous and reliable carbon dioxide supply. The total technically available CO_2 recovery potential at Marl Chemical Park is estimated at approximately 770,000 tonnes per year (Table 4).

Capturing these 770,000 tonnes of CO_2 per year by means of an amine scrubbing process would require approximately 60 MW of low-pressure steam, 20 MW of electricity, and approximately €4 million per year for chemicals [20] [21] [22]. Including transport to the integrated refinery site, the total costs are estimated at approximately €75 per tonne of CO_2, corresponding to annual costs of around €60 million. Further utilisation of the captured CO_2 would ideally take place at the integrated refinery site, since Marl Chemical Park itself is not designed for refinery processes. The captured CO_2 corresponds to a naphtha equivalent of only approximately 245,000 tonnes per year. Even if crude oil processing at the integrated refinery site were reduced from today's approximately 12 million tonnes of crude oil equivalent to less than 7 million tonnes, this would still represent only a very small share of less than 4 % of the required feedstock. Consequently, if the assumed future requirement of 50 % carbon from captured CO_2 is to be achieved, substantially larger quantities of CO_2 will be required. It should also be taken into account that the majority of the direct CO_2 emissions from the chemical plants originate from combustion systems used for high-temperature heat generation. In future, these systems could themselves be replaced by hydrogen-fired or electrically heated technologies. However, much of the required technology is still under development [23].

Economic impacts and overall costs

This section considers exclusively the economic impacts and the overall costs of the new electrified energy supply system and asset configuration. A further economic assessment of carbon capture has deliberately not been included, as this can only be evaluated in conjunction with the associated feedstock value chains. The economic structure of Marl Chemical Park has evolved from a largely self-contained chemical production site towards an increasingly market-oriented and sector-coupled energy system. Historically, the site's energy supply was characterised by internal optimisation, with electricity and heat generation organised largely independently of external energy markets. The first major increase in efficiency was achieved through the establishment of the site-wide hot water network in the 1970s, which enabled improved integration of individual plants and the shared utilisation of the steam networks. The system was subsequently opened to external energy consumers through the connection to external heat sinks, most notably by supplying district heating to the town of Marl. This established, for the first time, a direct link between the industrial energy supply system and the municipal heat supply. A further opening of the system was achieved through the connection of the energy generation facilities to the energy markets, enabling real-time participation in electricity trading. However, the requirement of the German Heat Planning Act that 80 % of the heat supply must originate from renewable energy sources during the coming decade creates additional challenges. These challenges are primarily economic rather than technical in nature. To analyse these economic implications, an energy price scenario was developed. Figure 8 illustrates the annual energy price assumptions used for the assessment [24] [25] [26] [27] [28] [29].

The following cost comparison is based on annual base prices and does not consider intra-day price fluctuations. The analysis focuses exclusively on variable operating costs. The fixed costs associated with the new electrified steam generation system have not been included. Using the energy demand shown in Table 3 together with the price scenario presented in Figure 8, the annual operating costs for both scenarios were calculated in their respective pure forms. In other words, the analysis assumes either exclusive operation of the existing

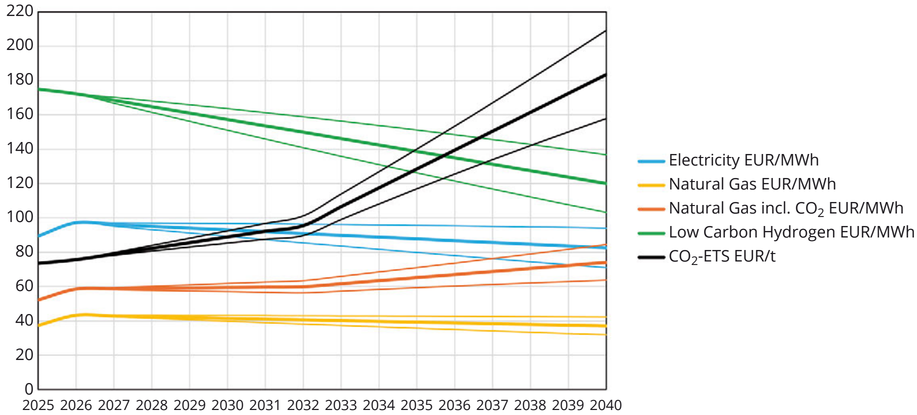

Fig. 8. Energy price scenario up to 2040 (annual base prices).

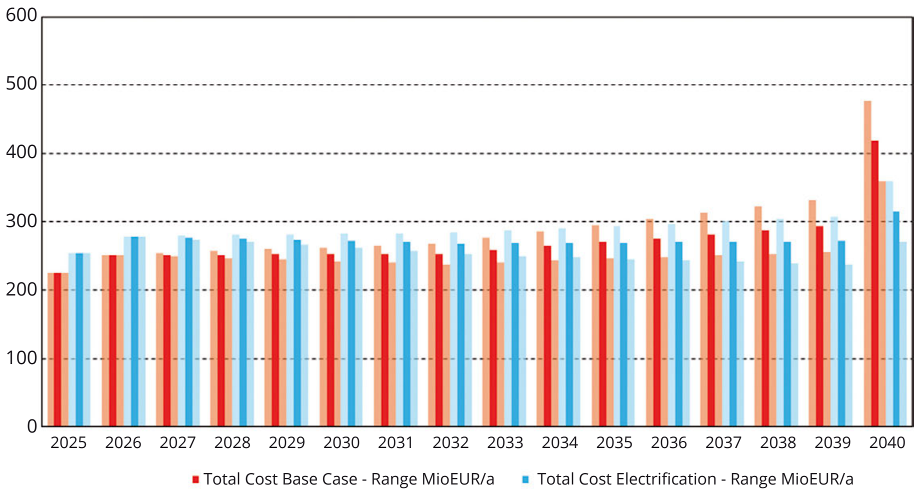

Fig. 9. Cost comparison between the current operation ("Base Case") and complete operation of the electrified system ("Electrification").

power plant system or exclusive operation of the electrified steam generation system, without switching between the two modes according to electricity market conditions.

The simplified analysis suggests that cost parity between the existing reference system and the fully electrified system can already be achieved from approximately 2035 onwards. This is mainly due to the expected decrease in electricity prices over time, while fuel costs continue to rise, particularly as a result of increasing CO_2 prices. In practice, however, such a transition would not take place abruptly but would be implemented gradually. Furthermore, it can be expected that both system configurations would be operated in parallel and optimised according to electricity market prices in order to minimise variable operating costs. Consequently, economic benefits compared with the reference system could be realised earlier than indicated by the simplified model. This aspect is the subject of ongoing investigations. For the year 2040, the model predicts a clear economic advantage for the electrified system. The principal reason is the requirement of the Heat Planning Act that 80 % of the heat supply must originate from renewable energy sources. Under the reference scenario, this would require a substantial proportion of renewable fuels, particularly hydrogen, to be used in the CCGT power plants. Even when assuming moderate hydrogen prices, this results in significant additional operating costs. The comparison therefore highlights the long-term economic advantages of electrifying steam generation. The following section discusses the implications for site planning and the resilience of the energy system.

Resilience of the site

Within the context of this study, resilience is understood as the ability of Marl Chemical Park, and of the infrastructure provider SYNEQT GmbH, to ensure the reliable, economical and adaptable supply of energy and infrastructure services under changing boundary and framework conditions. In particular, resilience comprises the continuous adaptation to regulatory requirements, funding schemes and market mechanisms, as well as the ability to respond flexibly to changes in customer structures, production requirements and supply chains. The objective is to maintain the long-term functionality and competitiveness of the site while ensuring that potential disruptions or market changes can be managed without significant impairment of the energy supply. In this study, the term resilience is used exclusively in the sense of technical, economic and organisational adaptability and robustness. It explicitly does not refer to military preparedness or defence-related aspects. One example is the sizing of the site's heat generation capacity, which is currently provided mainly by CCGT plants. These plants must be designed and operated with sufficient flexibility to respond resiliently to a wide range of changes occurring on different time scales.

On a minute-by-minute basis, fluctuations in customer demand must be balanced through flexible plant operation. On an hourly basis, electricity prices change continuously, requiring the market-connected CCGT plants to respond economically to these price movements. Both industrial demand and electricity market prices vary from day to day, making continuous adaptation of the plant portfolio within the day-ahead electricity market necessary. Seasonal variations require longer-term adjustments throughout the year. Long-term developments, such as the establishment of new production facilities or the closure of existing plants, can have a substantial impact on the economic viability of the site's infrastructure. Furthermore, the intended transformation pathway towards climate neutrality requires a gradual transition in heat generation technologies, ranging from electrification to the use of green hydrogen and other climate-friendly fuels. These developments must likewise be considered as an integral part of the site's resilience strategy. The resilience of the site is of central importance for the industrial competitiveness of the region, Germany and Europe as a whole [30] The long-term robustness of a chemical production site is strongly influenced by European policy. In particular, European instruments such as the Carbon Border Adjustment Mechanism (CBAM), together with its robust implementation, are of decisive importance. The ongoing transformation of the chemical industry's energy supply is driven primarily by climate protection rather than by cost optimisation. It is therefore the responsibility of both national and European policymakers not only to establish market-based instruments such as emissions trading (EU ETS) but also to protect domestic industry during the transformation process.

Summary and outlook

The defossilisation of the energy supply of the chemical industry represents a complex energy system transformation. In modern chemical parks, the system boundary is increasingly shifting. Whereas production facilities at a site were previously often operated by a single company, the various activities are increasingly being carried out by separate organisations. One example is the energy supply of an integrated industrial site being provided by an industrial park operator that does not itself operate production facilities.

The reason for this development is not primarily the creation of individual new business models, but rather the strategic focus of chemical companies on their core business. Infrastructure and energy supply activities are increasingly being organisationally separated, as limited investment resources are directed primarily towards core chemical production activities rather than towards maintaining or expanding site-wide infrastructure. A similar development can also be observed for commodity production plants within the chemical industry and at other industrial sites. A key requirement for successful transformation pathways is the ability to respond to changing boundary and framework conditions, such as evolving supply chains, changing regulatory requirements and the changing technology mix of fossil and renewable energy sources, while at the same time maintaining international competitiveness. This means making the right investment decisions at the right time.

A modern chemical park such as Marl Chemical Park can already be further developed using technologies that are commercially available today so that, in addition to fulfilling its existing supply functions, it can make a substantial contribution to the stabilisation and flexibilisation of the electricity system. The potential identified in this study indicates that, in the future, chemical parks can play an even more important role as the link between industrial production and the energy system.

In addition, further technical and economic options exist that could considerably expand the potential presented in this paper. Within the scope of this study, a possible transformation pathway for Marl Chemical Park has been outlined. In the next phase, this pathway must be developed further from a technical perspective, specified in greater detail and systematically compared with alternative options. This will require more detailed engineering work and further analyses. As a first step, the technical boundary conditions for further electrification must be examined and verified. These include, among other aspects, integration into the existing steam and utility networks, redundancy and security of supply requirements, and the impact on ongoing plant operation. In addition, future plant operation should be modelled using high-resolution hourly time-series simulations. On this basis, load profiles, flexibility potentials, operating strategies and opportunities for cost optimisation resulting from the interaction between the national electricity grid, the European electricity market and Marl Chemical Park can be assessed and quantified.

Furthermore, suitable locations for new plant components within the steam network must be identified. For these locations, technical integration concepts, operational safety concepts, as well as approval and inspection requirements must be developed and assessed by independent organisations. The results will provide the basis for a robust technical design and a more detailed cost assessment. On the basis of this detailed planning, a phased and economically viable investment plan can subsequently be developed. The transformation pathway is associated with considerable technical, organisational and economic challenges. At the same time, it represents an essential prerequisite for maintaining the site's long-term competitiveness, security of supply and climate neutrality.

Finally, the outlook also highlights the importance of reliable political and regulatory framework conditions. Significant costs are already incurred during the planning and engineering phase without directly creating added value. The benefits and robustness of such planning therefore depend to a large extent on energy, climate and industrial policy frameworks being designed to remain stable, consistent and supportive of investment over the long term. Only under these conditions can misguided developments be avoided and investment decisions for the successful transformation of industrial sites be made with confidence.

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Kurzfassung

Klimaneutrale Industriestandorte: Technologische Strategien für flexible, marktgetriebene und kohlenstoffarme Energiesysteme

Prozessindustriestandorte und Chemieparks wie der Chemiepark Marl stehen insbesondere in Bezug auf Energie- und Rohstoffpreise international im Wettbewerb. Gleichzeitig muss die Transformation hin zu nachhaltigen Industriestandorten im Einklang mit den EU-Klimazielen gelingen. Schon heute ermöglichen vielfältige Technologien die Nutzung fossiler Brennstoffe mit reduzierten Emissionen und die optimale Einbindung erneuerbarer fluktuierender Energien. Einige dieser Technologien haben bereits Serienreife erreicht und werden zu wettbewerbsfähigen Kosten eingesetzt. Andere befinden sich in der Präkommerzialisierungsphase oder noch im Entwicklungsstadium, besitzen jedoch ein hohes CO_2-Reduktionspotenzial. Ziel bei der Ausgestaltung des Technologiemixes ist die standortweite Optimierung des Energieverbunds sowie die Erhöhung der wirtschaftlichen Resilienz gegenüber externen Einflussfaktoren.

Am Standort liegt ein besonderes Augenmerk auf der Sektorenkopplung, also der Kopplung von Energiemärkten und produzierender Industrie. Der Einsatz bestehender Assets wie hochflexible Gas- und Dampfturbinenkraftwerke im Kraft-Wärme-Kopplungsbetrieb erweitert um elektrische Dampferzeugung wie z.B. Hochtemperaturwärmepumpen und damit der Nutzung hoher Abwärmepotenziale bietet die Möglichkeit, auf fluktuierende Strompreise optimal zu reagieren und trägt zur Reduzierung des Brennstoffeinsatzes bei. Weitere Standortsynergien entstehen durch die Nutzung produktbedingter Wärmequellen wie z.B. unvermeidbare Abwärme aus exothermen Reaktionen. Diese kann in angrenzende Wärmenetze überführt werden und ermöglicht somit ein systemweites Optimum inklusive Rückkopplung auf die Energiemärkte. Ebenso essenziell für ein Standortoptimum ist die betriebsübergreifende Optimierung sämtlicher Utilities abseits von Wärme (Kälte, Druckluft, Kühlwasser, u.a.). Zur vollständigen Defossilisierung von Standorten wie dem Chemiepark Marl bis Mitte der 2040er Jahre sind weitere innovative und disruptive Technologieschritte notwendig. Hierzu zählen der Einsatz alternativer Brennstoffe (Wasserstoff, HVO, biogenes Erdgas) oder die Abscheidung und Speicherung oder Nutzung von CO_2 (CCUS). In diesem Kontext bietet gerade die Rückführung von Kohlenstoff in die Wertschöpfungskette ein wirtschaftliches Potenzial für die Prozessindustrie und stellt einen essenziellen Schritt in Richtung Zirkularität als auch von Resilienz dar.