Modelling Sector-Coupled Local Renewable Energy Supply for Mixed Industrial Parks

Malte Höppner
Faculty of Management, Culture and Technology
University of Applied Sciences Osnabrueck
Lingen (Ems), Germany

Matthias Reckzügel
Faculty of Engineering and Computer Sciences
University of Applied Sciences Osnabrueck
Osnabrueck, Germany

Nils Karschuck
Faculty of Management, Culture and Technology
University of Applied Sciences Osnabrueck
Lingen (Ems), Germany

Tim Wawer
Faculty of Management, Culture and Technology
University of Applied Sciences Osnabrueck
Lingen (Ems), Germany

Abstract— **This paper gives recommendation to mixed industrial parks (MIP) to identify cost optimal investments for a short-term green transition by 2030 and a long term defossilization by 2045. Based on a sample of 44 MIPs with more than 3,000 companies in northwestern Germany we identify different types of MIP. We use a sector coupled energy model, to evaluate the economic optimal energy supply for each MIP across four scenarios. To prove the robustness of the obtained results for the design of the energy storage we use a Monte Carlo simulation. Key findings underscore the importance of considering heat demand structure in development of reliable energy transition concepts for MIPs. Electrification of heat supply and potential for local renewable energy emerge as crucial factors in achieving cost-effective energy supplies. The findings further reveal the significance of storage systems in managing energy flexibility in both ambitious and moderate energy transition strategies for MIPs, offering strategic insights to local planners.**

Index Terms-- **energy system modeling, energy costs, mixed industrial parks, renewable energy, SME**

I. INTRODUCTION

Electrification and sector coupling are essential components in the transition towards a low-carbon industrial production. At the same time energy costs are becoming increasingly critical for companies to stay competitive. For local authorities, sustainable and energy efficient industrial sites represent a decisive factor in ensuring the successful development of the regional economy. To reduce energy costs, ensure supply security, improve efficiency and facilitate the integration of decentralized renewable energy (RE) new collaborative efforts among established companies are needed. The cooperation can include district heating with waste heat utilization or joint electricity generation with electricity microgrids. The cooperative approach of companies within industrial parks bears similarity to the concept of energy communities (ECs). In this paper, the emphasis is placed on the investigation of feasible technical options for the collaborative optimization of the energy supply within mixed industrial parks (MIPs) in Germany. Compared to frequently studied industrial parks with large companies engaged in major industrial activities, MIPs are characterized by their reduced spatial extent and the prevalence of small and medium-sized enterprises (SMEs) [1]. Recent research highlights the significance of external facilitators, such as anchor tenants, local companies, the municipality or a park management, in the establishment of energy cooperation in industrial parks [2–4]. The results of our studies offer significant value to stakeholders that may assume such a role. Local planners can utilize these findings to draw develop steps for the decarbonization of MIPs within their municipalities. Hence, they serve as a starting point for developing detailed implementation initiatives at the local level. This is particularly relevant in the context of the 62,074 industrial and commercial estates in Germany [5] that require transformation. Leading to the research question: What can MIP do now to be prepared for a short-term green transition by 2030 and a long term defossilization by 2045?

II. BACKGROUND

A substantial body of literature has been published which investigates the potential advantages of energy cooperation for industrial production companies. An identified benefit is the reduction of energy costs. This is achieved by economies of scale in investment, installation and maintenance of generation units and infrastructures [6], improved energy efficiency via inter-company waste heat utilization [7], and the reduction of grid procurement costs [8]. In addition to economic benefits, [7, 9] also highlight ecological improvements in the form of reduced emissions. It is also noteworthy that the literature is predominantly focused on electricity, while thermal energy is given significantly less consideration [10, 11]. On the other hand, the majority of studies on ECs focus on residential units, with commercial and industrial energy cooperation being analyzed with less frequency [10]. Nevertheless, there is a broad field of research on eco-industrial parks (EIPs), to which [12–15] in particular have contributed significantly. Among other ecological criteria as material exchange and water

979-8-3503-8174-0/24/$31.00

treatment, the concept of EIPs typically encompasses RE supply, energy efficiency, and energy cooperation between the resident companies. However, the prevailing focus in the literature relates to expansive industrial estates, frequently encompassing areas of approximately 100 hectares, as in [2, 14, 16–19]. Large companies and major industrial activities are increasingly represented there. In contrast, [1] found that mixed industrial parks (MIPs) are poorly investigated. The research indicates that EIPs possess more favorable prerequisites for sustainable solutions than MIPs, largely due to their structural characteristics [1]. This represents a significant research gap that requires further investigation into the sustainable energy supply of MIPs. In Germany, industrial and commercial areas cover 6,338 square kilometers, which is equivalent to 18.7 percent of the country's total area [20]. Based on the number of 60,000 industrial and commercial estates in Germany, the average size of a park is approximately 10 hectares. This leads to the conclusion that the average park is much smaller than the EIPs that are mainly investigated in the literature.

III. METHODS

A. Classification of MIPs

For the purpose of this study, a random sample of 44 MIPs with more than 3,000 companies in north-west Germany was selected. For each company in this sample, we estimate the heat and electricity demand. The basis for the estimation are sector specific energy consumption factors per employee and revenue published in the literature. [21, 22] We classified the 3,000 companies according to the WZ 2008 system [23] and extracted the number of employees and the latest annual revenues from the MARKUS database and company websites. Additional information on company basis, including geographic information, was collected. This allows to estimate the industrial waste heat potential and the potential for photovoltaics (PV) for each company. A weighted average of the calculated energy consumption as a function of the number of employees and the revenue was determined. This estimated energy consumption and PV and waste heat potential were validated through a survey.

The calculated and validated input factors on a company level are aggregated for the 44 MIPs. Based on this data 44 parks are categorized into five types based on their energy demand structure. Figure 1. provides an overview of the types identified. We find, that the key determining factors are the relative proportions of electricity and heat demand split into four different heat levels. The first heat level is space heating and domestic hot water. Low process heat requires a temperature level of up to 100°C. Medium process heat is characterized by temperature levels between 100 and 500°C, and high temperature process heat is defined as greater than 500°C.

We denominate the first category 'Service Parks'. The predominant sectors include logistics, trade and office-related activities. The energy demand includes electricity, space heating and domestic hot water. These parks are characterized by the absence of industrial companies and therefore no demand for process heat.

'Industrial Parks' represent type three. These areas are characterized by a high concentration of industrial companies, resulting in a high demand for process heat at low and medium temperature levels. The demand for heating and hot water accounts for only 10% of the total energy demand in these parks.

The 'Hybrid Parks' represent a hybrid between both previous types. The typical composition includes service-oriented and a few manufacturing companies. Consequently, the heat demand is characterized by a large share for space heating and domestic hot water, complemented by a comparatively modest share for process heat.

The remaining two types have a considerably different electricity-heat ratio. In 'Power Parks', the electricity demand is significantly higher than the heat demand. This is due to electricity-intensive production processes such as, for example, the manufacturing of plastics, electronic products and electrical equipment, or the operation of cold stores with high cooling requirements.

In contrast, 'Thermo Parks' are parks with a share of more than 50 % of high-temperature process heat (>500 °C) in the total energy demand. The companies leading to this energy structure include glass production, the manufacture of basic metals, and the fabrication of metal products.

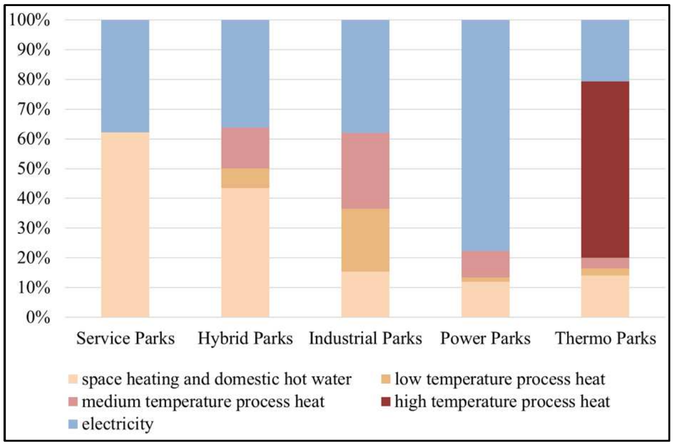

Figure 1. Types of MIP developed from the sample of 44 MIPs

B. Energy system modeling

Energy system modeling is frequently conducted to investigate the economic, ecological, and social effects of energy systems [10]. Most models concentrate on a single approach, with minimizing the costs being the primary focus. Objective functions are less frequently formulated on the basis of ecological, technical or social criteria, or even on multiple criteria from the aforementioned [10, 11].

We develop an energy system model with an hourly resolution using the Open Energy Modelling Framework (oemof). The objective is to minimize the annual cost of energy supply through the application of a mixed integer linear programming approach. The multi-energy system model incorporates both electricity and heat. The thermal energy requirement is divided into four distinct temperature levels: heating and domestic hot water, and the three process heat levels. The input data encompasses the companies' energy consumption estimates and their hourly load profiles as well as the estimated current costs and revenues for energy. In addition, investment and operating costs, efficiency and generation profiles and lifespan of various applicable technologies from a technology catalog are included.

In the status quo, it is assumed that the entire energy demand is met by grid supply of electricity and pipeline delivery of natural gas for gas boilers. This scenario is employed for comparative purposes, for example to evaluate annual energy costs.

Different scenarios are used to assess the overall uncertainty in model outputs due to uncertainties in input parameters, model assumptions, and model structure. We develop a long-term perspective for 2030 and 2045. The second main influencing factors is the local situation in the MIP. Here we make a distinction between favorable conditions and limited potential. For each of the resulting four scenarios different technologies are available. The technological options are illustrated in TABLE I. TABLE I.

TABLE I. MODELLING SCENARIOS

	Ready-for-30 limited potential	***Ready-for-30 favorable conditions***	***Fit-for-45 limited potential***	***Fit-for-45 favorable conditions***
Local RE-potential				
Rooftop-PV	X	X	X	X
Solar Thermal	X	X	X	X
Ground mounted PV		X		X
Wind turbines		X		X
Energy carriers				
Grid electricity	X	X	X	X
Hydrogen	X	X	X	X
Natural gas	X	X		
Biogas		X		X

In the Ready-for-30 scenarios, the objective is to ascertain the most cost-effective energy supply given the present circumstances. Hence, the use of natural gas is still considered an option within this strategy. In the Fit-for-45 scenarios we explore the most cost-effective energy supply that already today aligns with the future requirements. The imperative lies in aligning with the German 2045 targets through present investments, entailing a deliberate renouncement of natural gas.

In all scenarios, electricity from the grid remains available for use assuming it is only from renewable sources in the 2045 scenario. In addition, there is potential to import green hydrogen and to use waste heat for district heating or as input for heat pumps via waste heat recovery. The technology catalogue comprises the following technologies: photovoltaic (PV), wind turbines, engine-based combined heat and power plants (CHP), solar thermal, heat pumps, gas-, hydrogen- and electric boilers, electrolyzers, fuel cells, batteries and thermal storages. However, due to the varying availability of natural gas, biogas and RE between the scenarios, their use is limited in some cases.

As not all technologies can be implemented at all MIP sites a distinction is made between MIP with limited local potential and locations with favorable conditions. In our limited local potential scenarios, the potential for local electricity generation from RE at the site is limited to rooftop PV (RT-PV) and solar thermal and there is no biogas available. Furthermore, the implementation of biogas fired CHP is rendered unfeasible due to the absence of biogas in the Fit-for-45 with limited potential scenario.

Our favorable conditions scenarios include locations that have the same potential for rooftop PV and solar thermal as well as additional potential for local wind turbines, local ground-mounted PV (GM-PV) and the local availability of biogas.

In all scenarios, the model includes current investment decisions at current capital expenditures (CAPEX) and operating expenditures (OPEX). The objective in each scenario is therefore to minimize the annual costs of load overage.

IV. RESULTS

A. *Exemplary modeling results for MIP type 'Industrial Park'*

This section examines modelling results for the MIP-type 'Industrial Park'. We assume that a typical park in this category covers an area of 45 hectares and the annual energy demand amounts to 22 GWh of electricity and 40 GWh of natural gas. Resident companies are mostly from the manufacturing, retail and trade, logistics and office sectors.

TABLE II. DIMENSIONING OF TECHNOLOGIES PER SCENARIO

Technology	***Unit***	***Ready-for-30 limited potential***	***Ready-for-30 favorable conditions***	***Fit-for-45 limited potential***	***Fit-for-45 favorable conditions***
Rooftop-PV	[MWp]	3.9	3.9	3.9	3.9
Ground mounted PV	[MWp]	-	2.3	-	2.3
Wind turbines	[MW]	-	8.8	-	8.8
Natural gas fired CHP plant	[MWel]	3.3	2.0	-	-
Biogas fired CHP plant	[MWel]	-	-	-	1.2
Solar Thermal	[MWth]	-	-	-	-
Heat Pump	[MW]	0.5	2.0	3.8	2.2
Gas Boiler	[MW]	2.6	2.6	-	-
Hydrogen Boiler	[MW]	-	-	2.9	2.5
Electric Boiler	[MW]	-	1.4	-	2.6
Battery	[MWh]	2.9	2.3	0.1	2.3
Thermal storage	[MWh]	14.6	27.3	21.6	45.3
Electrolyzer	[MWel]	-	-	-	-
Fuel Cell	[MWel]	-	-	-	-
Grid Connection	[MW]	0.7	1.6	5.1	2.4

In TABLE II. the sizing of the technologies per scenario is summarized. Figure 2. and Figure 3. present the shares of the different technologies converging the annual electricity and heat demand. When interpreting the pie charts illustrating electricity demand coverage, it is important to note that the total electricity demand increases progressively in the sequence of scenarios due to the rising electrification of heat, whereas the heat demand remains constant across all scenarios.

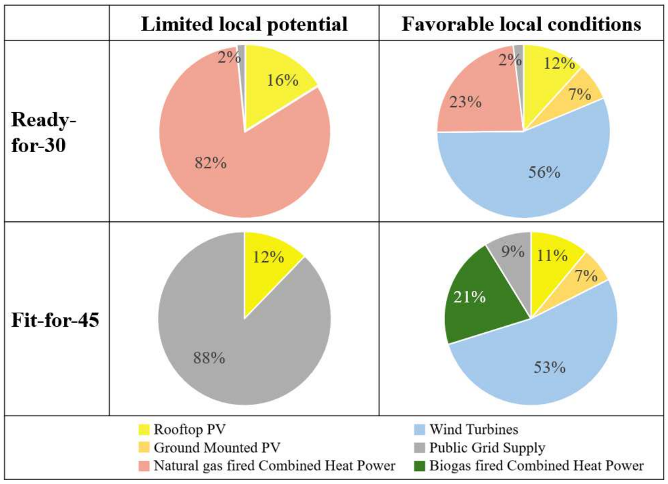

Figure 2. Annual electricity demand coverage per scenario

Although the entire usable roof area of the buildings is exploited for the installation of rooftop PV to a maximum capacity of 3.9 MW across all scenarios, this capacity is limited to covering 11-16 % of the annual electricity demand of the 'Industrial Park'. In the Ready-for-30 scenario with limited local potential, a large natural gas fired CHP plant with a capacity of 3.3 MW accounts for 82 % of the electricity demand as it is cheaper than electricity grid supply.

In the Fit-for-45 scenario with limited local potential the cost-efficient solution is to import 88 % of the electricity from the electricity grid, as the park lacks alternatives.

In scenarios with favorable local conditions wind turbines and ground mounted PV lead to a higher contribution of local generation to the optimal electricity supply. Local wind energy covers over 50 % of the total power demand. PV contributes approximately 20 %. Wind power and ground mounted PV are scaled up to their maximum capacity of 8.8 and 2.3 MW, respectively. This outcome is evident in both scenarios under favorable local conditions.

However, the Fit-for-45 scenario diverges from the Ready-for-30, as it incorporates the substitution of natural gas combined heat and power (CHP) with that of biogas. Moreover, it is observed that electricity grid consumption is comparatively higher in the Fit-for-45 scenario. The thorough examination of the power supply will now be followed by an investigation into the heat supply.

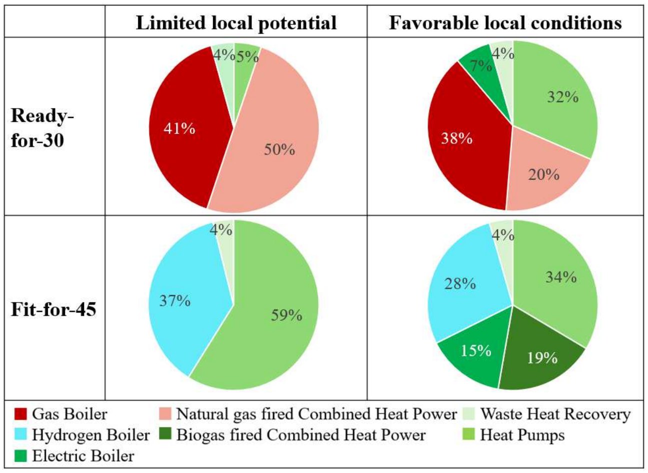

Figure 3. Annual heat demand coverage per scenario

First, it should be noted that waste heat recovery contributes approximately 4% of the total heat required across all scenarios.

In the Ready-for-30 scenario with limited local potential, most of the heat demand is met by natural gas fired sources. The CHP plant accounts for 50 % of the demand, while the gas boiler contributes 41 % with a maximum power of 2.6 MW.

Based on the restrictions of the Fit-for-45 scenario with limited local potential, natural gas is not available, and biogas cannot be used as a substitute. Consequently, 59 % of the heat requirement is met by heat pumps with a capacity of 3.8 MW, and 37 % by a 2.9 MW hydrogen boiler. The utilization of heat pumps is primarily for the purpose of meeting the space heating and domestic hot water demand as well as low process heat, while the hydrogen boiler is employed for medium process heat. Hence, it can be concluded that the hydrogen boiler is a substitute for the natural gas boiler and that heat pumps replace CHP plants.

In the Fit-for-45 scenario under favorable conditions, the 2.6 MW natural gas boiler is substituted by a composition of a hydrogen and an electrode boiler with a power of 2.5 MW each. The hydrogen boiler covers 28 % of the total heat demand, while the electrode boiler accounts for an additional 15 %. Additionally, as previously indicated in the context of electricity supply in the considered scenario, the conventional 2 MW CHP plant is substituted by a 1.2 MW biogas CHP plant.

As illustrated in Figure 3 the combination of technological solutions has results in a reduction of annual energy expenditures in three out of four scenarios. It is important to note that the costs include annuities for investments in new technologies.

To give an insight in the results we present load duration curves for heat and electricity for the Ready-for-30 scenario under favorable conditions in Figure 4. and Figure 5. The demand has been sorted in descending order, and the electricity or heat generation for each hour has been plotted. If generation exceeds demand within a given hour, the surplus energy is either stored or, in the case of electricity, sold to the grid. The white areas below the load curve are filled in the calculations by discharging storage, so that the load is always covered.

The optimal solution relies on a natural gas fired CHP plant. Although the 2 MW CHP plant satisfies 20% of the total heat demand, heat pumps with the same thermal power already cover a third of that same demand. Furthermore, the natural gas boiler provides a slightly lower proportion of the heat, with 7 % provided by an electrode boiler. As heat can be stored the load of the MIP is the highest, in hours with high production of renewable. Heat pumps and electric boilers operate to a maximum to take advantage of low electricity cost. The heat duration curve shows how the electric and the gas boiler are substitutes.

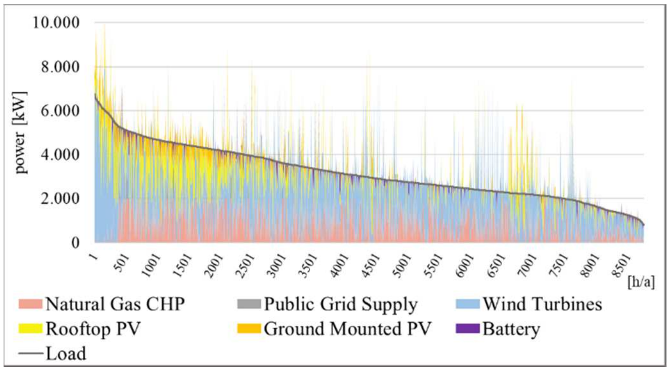

Figure 4. Duration curve for the electicity sector, scenario: "Ready-for-30" with favorable local conditions

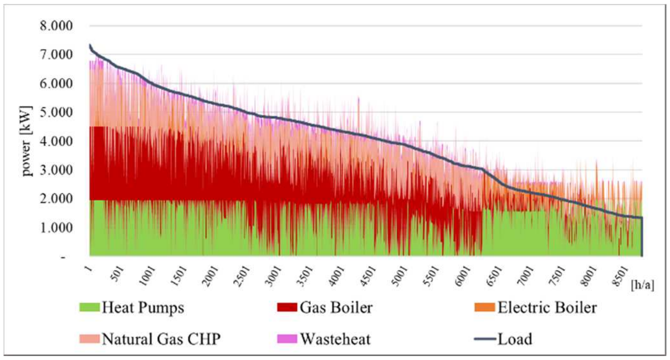

Figure 5. Duration curve for the heat sector, scenario: "Ready-for-30" with favorable local conditions

B. *Sensitivity analysis to identify storage capacity*

Our approach is suitable to derive strategic steps and identify no-regret investments, supporting informed decision-making amidst future uncertainties. To demonstrate the possible investment in storages (heat and electrical), we used a Monte Carlo simulation. This approach enhances the robustness and resilience of the results to uncertainties inherent in the input parameters. Utilizing a high-performance-cluster, we conduct multiple hundred optimizations with varying input parameters. This approach facilitates the estimation of the size range in which the technologies are likely to be dimensioned, as well as the likely range of investments and costs incurred for the industrial estates. Fluctuating prices of the energy sources electricity, natural gas, biogas and hydrogen are considered. The analysis accounts for the interdependencies of energy prices, such as the influence of natural gas prices on electricity prices, as well as the independent fluctuations of each energy carrier within specified price corridors. The main objective of this analysis is to determine whether price fluctuations have a significant impact on the design of the system components. The focus is particularly on the electricity and heat storage systems, which are examined in the four scenarios. This analysis provides information on how resistant our model is to market changes and serve as a basis for adapting the systems under changing conditions. Figure 6. illustrates the results of the Monte Carlo analysis for the storage systems.

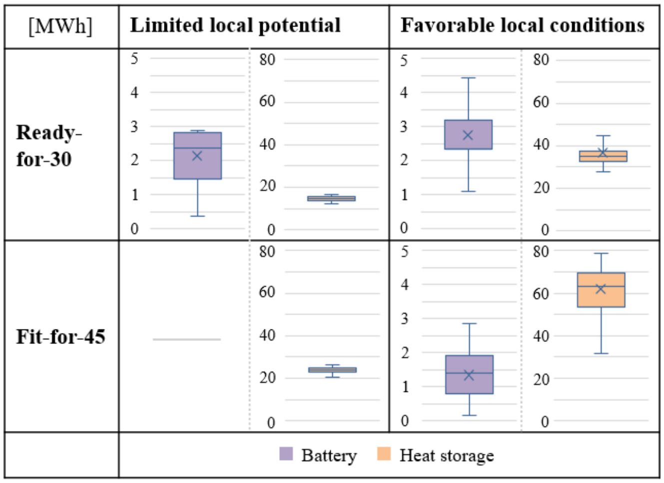

Figure 6. Results of the Monte Carlo Analysis for the Configuration of Storage Systems

In Fit-for-45 scenarios with limited local renewable energy potential, there is no electricity storage system required, as the amount of electricity drawn from the grid is high and offers sufficient flexibility. In the other three scenarios, the size of the electricity storage system varies between 1 and 3.5 MWh. In the scenarios with limited local renewable energy potential, the design of the heat storage system shows similar sizes of between around 17 and 22 MWh. Under favorable local conditions, much larger heat storage systems are used, with capacities ranging from around 35 MWh to 60 MWh and more.

V. CONCLUSION

In conclusion, our analysis shows that the structure of the heat demand is of particular significance in the context of energy transition concepts for MIPs. On the one hand, heat is the decisive characteristic for the typification, on the other hand, the electrification of heat plays an essential role in the transformation of MIPs.

The fundamental principle governing cost-effective electricity supply is the maximization of local electricity production in particular from wind and PV.

The study finds an escalating electrification of heat, with heat pumps proving effective in meeting space heating, domestic hot water and low-temperature process heat requirements. Furthermore, CHP systems remain vital due to their efficiency, especially in areas with limited local RE resources. When feasible, it is recommended that local biogas potential be utilized for CHP. Additionally, the feasibility of electrifying medium-temperature process heat depends on the competitiveness of electricity and hydrogen prices for electrode or hydrogen boilers. Moreover, it is noticeable that the local use of solar thermal, electrolyzers or fuel cells is not economically viable in any scenario.

As electrification of heat increases, maximizing local RE is crucial for cost reduction of both electricity and heat. Integration of wind power offers significant potential in this regard. The challenge of transforming locations with limited potential into areas with more favorable conditions offers significant opportunities for local stakeholders to establish more green MIPs with competitive energy prices.

As local RE systems become more prevalent and replace traditional energy sources, the need for substantial battery and heat storage systems becomes key to maintaining flexibility in the energy system. Notably, heat storage emerges as a more cost-effective solution compared to battery technology. As electrification and RE integration increase, the size of heat storage systems is projected to increase. Conversely, the size of battery storage systems is expected to decrease.

In sites characterized by favorable local conditions, the achievement of self-sufficiency levels approaching 50% occurs in economically optimal configurations. Consequently, electricity grid connections, with the exception of the grid dependent Fit-for-45 with limited potential scenario, can be significantly reduced.

ACKNOWLEDGMENT

This research is conducted within the AutaGE ('Energieautarke Gewerbegebiete') project funded by the Metropolregion Nordwest. The authors would like to thank all AutaGE project partners and associated partners for their support.

REFERENCES

[1] A. Lambert and F. Boons, "Eco-industrial parks: stimulating sustainable development in mixed industrial parks," *Technovation*, vol. 22, no. 8, pp. 471–484, 2002, doi: 10.1016/S0166-4972(01)00040-2.

[2] M. D. Mainar-Toledo *et al.,* "Accelerating sustainable and economic development via industrial energy cooperation and shared services – A case study for three European countries," *Renewable and Sustainable Energy Reviews*, vol. 153, p. 111737, 2022, doi: 10.1016/j.rser.2021.111737.

[3] V. Rodin and S. Moser, "From theory to practice: Supporting industrial decarbonization and energy cooperation in Austria," *Energy Research & Social Science*, vol. 94, p. 102863, 2022, doi: 10.1016/j.erss.2022.102863.

[4] K. Katana, B. Glaa, and M. Mirata, "Facilitator roles for knowledge sharing in industrial symbiosis networks during emergence," *Bus Strat Env*, vol. 33, no. 8, pp. 8540–8558, 2024, doi: 10.1002/bse.3923.

[5] Deutscher Bundestag Drucksache 19/11357, "Antwort der Bundesregierung auf die Kleine Anfrage der Abgeordneten Daniela Kluckert, Frank Antwort der Bundesregierung auf die kleine Anfrage der Abgeordneten Daniela Kluckert, Frank Sitta, Grigorios Aggelidis, weiterer Abgeordneter und der Fraktion der FDP," Accessed: Jan. 9, 2025. [Online]. Available: https://dserver.bundestag.de/btd/19/113/1911357.pdf

[6] T. Maes *et al.,* "Energy management on industrial parks in Flanders," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 4, pp. 1988–2005, 2011, doi: 10.1016/j.rser.2010.11.053.

[7] J.-N. Gerdes, M. Munder, and A. Sauer, "Evaluation of technical and economic potential of waste heat distribution networks in industrial sites," *Energy Reports*, vol. 9, pp. 219–226, 2023, doi: 10.1016/j.egyr.2022.12.112.

[8] B. Crowley, J. Kazempour, and L. Mitridati, "How Can Energy Communities Provide Grid Services? A Dynamic Pricing Mechanism with Budget Balance, Individual Rationality, and Fair Allocation," Sep. 2023. Accessed: Feb. 4, 2025. [Online]. Available: http://arxiv.org/pdf/2309.05363

[9] A. Neri, M. A. Butturi, F. Lolli, and R. Gamberini, "Inter-firm exchanges, distributed renewable energy generation, and battery energy storage system integration via microgrids for energy symbiosis," *Journal of Cleaner Production*, vol. 414, p. 137529, 2023, doi: 10.1016/j.jclepro.2023.137529.

[10] E. Barabino *et al.,* "Energy Communities: A review on trends, energy system modelling, business models, and optimisation objectives," *Sustainable Energy, Grids and Networks*, vol. 36, p. 101187, 2023, doi: 10.1016/j.segan.2023.101187.

[11] K. E. Lonergan, N. Suter, and G. Sansavini, "Energy systems modelling for just transitions," *Energy Policy*, vol. 183, p. 113791, 2023, doi: 10.1016/j.enpol.2023.113791.

[12] M. R. Chertow, "INDUSTRIAL SYMBIOSIS : Literature and Taxonomy," *Annu. Rev. Energy. Environ.*, vol. 25, no. 1, pp. 313–337, 2000, doi: 10.1146/annurev.energy.25.1.313.

[13] M. R. Chertow, "“Uncovering” Industrial Symbiosis," *J of Industrial Ecology*, vol. 11, no. 1, pp. 11–30, 2007, doi: 10.1162/jiec.2007.1110.

[14] M. Chertow and J. Ehrenfeld, "Organizing Self - Organizing Systems," *J of Industrial Ecology*, vol. 16, no. 1, pp. 13–27, 2012, doi: 10.1111/j.1530-9290.2011.00450.x.

[15] F. Boons, M. Chertow, J. Park, W. Spekkink, and H. Shi, "Industrial Symbiosis Dynamics and the Problem of Equivalence: Proposal for a Comparative Framework," *J of Industrial Ecology*, vol. 21, no. 4, pp. 938–952, 2017, doi: 10.1111/jiec.12468.

[16] N. B. Jacobsen, "Industrial Symbiosis in Kalundborg, Denmark: A Quantitative Assessment of Economic and Environmental Aspects," *J of Industrial Ecology*, vol. 10, 1-2, pp. 239–255, 2006, doi: 10.1162/108819806775545411.

[17] G. Massard, O. Jacquat, and D. Zürcher, "International survey on eco-innovation parks.: Learning from experiences on the spatial dimension of eco-innovation.," Bern, Rep. 1402, 2014. Accessed: Feb. 4, 2025. [Online]. Available: https://www.bafu.admin.ch/bafu/en/home/topics/education/publications-studies/

publications/international-survey-on-eco-innovation-parks.html

[18] J. Cerceau, N. Mat, G. Junqua, L. Lin, V. Laforest, and C. Gonzalez, "Implementing industrial ecology in port cities: international overview of case studies and cross-case analysis," *Journal of Cleaner Production*, vol. 74, pp. 1–16, 2014, doi: 10.1016/j.jclepro.2014.03.050.

[19] D. van Beers, K. Tyrkko, A. Flammini, C. Barahona, and C. Susan, "Results and Lessons Learned from Assessing 50 Industrial Parks in Eight Countries against the International Framework for Eco-Industrial Parks," *Sustainability*, vol. 12, no. 24, p. 10611, 2020, doi: 10.3390/su122410611.

[20] Statistisches Bundesamt. "Fläche für Siedlung nach Nutzungsarten in Deutschland." Accessed: Jan. 9, 2025. [Online]. Available: https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Flaechennutzung/Tabellen/siedlungsflaeche.html

[21] Fraunhofer ISI, IfE, GfK Retail and Technology GmbH, and IREES GmbH:, "Energieverbrauch des Sektors Gewerbe, Handel, Dienstleistungen (GHD) in Deutschland für die Jahre 2011 bis 2013: Schlussbericht an das BMWi," Karlsruhe, München, Nürnberg, 2015. Accessed: Feb. 4, 2025. [Online]. Available: https://www.isi.fraunhofer.de/de/competence-center/energiepolitik-energiemaerkte/projekte/ghd_314889.html#3

[22] J. Lässig, T. Schütte, and W. Riesner, *Energieeffizienz-Benchmark Industrie*. Wiesbaden: Springer Fachmedien Wiesbaden, 2022.

[23] Statistisches Bundesamt. "German Classification of Economic Activities, Edition 2008: English Version." Accessed: Jan. 13, 2025. [Online]. Available: https://www.destatis.de/DE/Methoden/Klassifikationen/Gueter-Wirtschaftsklassifikationen/Downloads/klassifikation-wz-2008-englisch.html