Deriving Functional Requirements for CPPS in Energy-Flexible Operations: A Systematic Review of Case Studies

Lasse M. Reinpold, Lukas P. Wagner, and Felix Gehlhoff
Institute of Automation Technology
Helmut Schmidt University Hamburg, Germany
Email:{lasse.reinpold, lukas.wagner, felix.gehlhoff}@hsu-hh.de

Alexander Fay
Chair of Automation
Ruhr University, Bochum, Germany
Email: alexander.fay@rub.de

***Abstract*—Many cyber-physical production systems (CPPSs) exhibit energy flexibility, which can be leveraged to promote the integration of variable renewable energy sources. Developing energy-flexible operating strategies for CPPSs requires substantial knowledge and human resources. This work supports the development of energy-flexible operating strategies by deriving general functional requirements for CPPSs. These requirements were identified through a systematic review of practical, scientific case studies documenting energy-flexible operating strategies in CPPSs. 33 practical case studies were identified and analyzed in relation to the structure of their CPPSs. A comparative analysis of these studies led to the identification of 100 functional requirements, which were mapped to 13 components of CPPSs. To enhance clarity, the applicability of requirements to specific use cases was also elaborated. The formulated requirements can serve as a knowledge base to provide practitioners and researchers with a framework to guide the development of energy-flexible operating strategies for ICPPS.**

***Index Terms*—Energy Flexibility, Industrial Cyber-Physical Production Systems, Systematic Review, Functional Requirements**

I. Introduction

The increasing energy generation from variable renewable energy sources necessitates energy flexibility on the demand side. Energy flexibility refers to the capability of resources to alter the energy consumption, generation, or storage in time. This can be leveraged to align energy consumption with the availability of renewable energy, thereby promoting the integration of variable renewable energy sources into the grid and addressing supply volatility from sources like wind and solar. The industrial sector offers significant potential for aligning energy use with renewable availability, reducing grid strain and advancing the energy transition [1].

Despite the significant potential of industrial energy flexibility, many companies fail to adopt it. Leinauer et al. [2] investigated obstacles to industrial demand response and they attribute the slow adoption of energy-flexible operation in part to knowledge gaps and resource constraints. They point out that developing energy-flexible operating strategies is often hindered by a lack of awareness about available technologies and economic benefits, as well as insufficient internal expertise to implement energy-flexible operating strategies effectively. The term operating strategy is used in this work to describe all technologies, actions, and interactions within an cyber-physical production system (CPPS) that enable an uninterrupted and profitable energy-flexible operation. According to Leinauer et al. [2], the addressed problems are compounded by a lack of dedicated human resources for managing the complexities of energy flexibility projects, which require both technical and regulatory understanding. Addressing these barriers is crucial to unlocking the untapped flexibility potential of industrial operations and thereby promoting the integration of renewable energy sources [2].

The goal of this work is to address the knowledge and resource barriers hindering the adoption of energy flexibility in industrial operations. By systematically analyzing real-world case studies, this work aims to identify best practices and thereby derive general functional requirements for CPPSs to enable energy-flexible operation. Thus, this study aims to answer which IT- and OT-functionalities must be present in CPPSs in order for energy-flexible operation to be possible and profitable. These requirements can serve as a practical knowledge base to simplify the development and implementation of energy-flexible operating strategies, thereby enabling industrial companies to better harness their flexibility potential and contribute to the integration of renewable energy sources.

The research question this study answers is: which functional requirements for CPPSs for energy-flexible operating strategies can be derived from existing case studies?

The research contributions of this work are:

- A set of general functional requirements for CPPSs for energy-flexible operating strategies
- A mapping of the requirements into 13 components of CPPSs
- Establishing the applicability of requirements to various use cases of industrial energy flexibility, where use cases are defined by the operated CPPS and the chosen operating strategy

This study was conducted within the research project OptiFlex, funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr. dtec.bw is funded by the European Union – NextGenerationEU.

The remainder of the paper is structured as follows: Sec. II provides an overview of relevant related works and establishes the research gap. Sec. III describes the systematic review process and the analysis of case studies. Sec. IV presents the results of the review by describing the resulting structure of requirements and explaining exemplary requirements. Sec. V discusses and concludes the paper and provides an outlook to future research.

II. Related Works

The analysis of related works will focus on other reviews in the field of industrial energy flexibility and works, investigating technological requirements for energy-flexible CPPSs.

A review of energy-flexibility in heavy industries has been conducted by Golmohamadi [3]. The focus of the review is on the analysis of flexibility potentials and available software tools and algorithms for modeling and optimization. Challenges regarding requirements for energy-flexible CPPSs are pointed out, but no detailed analysis of requirements is conducted. [3]

Ranaboldo et al. [4] present a review on energy flexibility in the European industry. They focus on various markets, scheduling approaches, aggregators' roles, and digitalization in the industry. Regarding the latter, they point out the importance of CPPSs, without performing a detailed analysis on requirements for energy-flexible CPPSs. [4]

Lashmar et al. [5] review barriers for the implementation of energy-flexible operating strategies in commercial and industrial energy consumers. While lack of knowledge and technological challenges are addressed, no requirements for CPPSs are derived.

A method to develop recommendations for realizing specific use cases of energy-flexible CPPSs is proposed by Kaymakci et al. [6]. The method proposes to ask stakeholders questions regarding the current state of the CPPS and, based on the answers of the stakeholder, identify deficits and make recommendations for required future actions. Specific questions or requirements for CPPSs are not derived in the study.

Stiphoudt et al. [7] present an IT-platform for managing energy-flexible production and communication with energy markets. The IT-platform aims to standardize IT-components, services, and interfaces for energy-flexible factories and is part of the VDI guideline 5207 on energy-flexible factories [8]. While the platform offers various services or components that can be solutions for requirements for energy-flexible CPPSs, no requirements are derived in the study. Therefore, knowledge barriers are only partially addressed by the study, as users unfamiliar with the topic of energy flexibility likely still need decision support to correctly choose the specific services required for their individual use case of energy-flexible production.

Some requirements for energy-flexible CPPSs are defined in a study by Fuhrländer-Völker et al. [9], who present an automation architecture to flexibly operate cleaning machines [9]. The requirements specified by Fuhrländer-Völker et al. [9] are not derived based on a systematic literature review, non-exhaustive, and focused on aspects of communication and interaction between machines and IT-systems. Therefore, many important components of energy-flexible CPPSs are not addressed.

Summarizing the related works discussed in this section, no previous study has conducted a systematic review of practical case studies to derive a set of functional requirements for energy-flexible CPPSs.

III. Methodology of Literature Review

A. Identification of Reports

The identification of industrial energy-flexibility related scientific case studies was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) 2020 statement [10]. The Scopus © database was accessed on August 8th 2024. The search term shown in Listing 1 was used to identify potentially eligible reports:

```
TITLE-ABS-KEY (
( energy OR power OR electric* OR heat* OR hydrogen OR cold
  OR cool* )
AND ( ( energy AND flexib* ) OR ( demand AND response ) OR
  ( demand AND management ) OR ancillary OR balanc* OR (
  load AND management ) )
AND ( industr* )
AND ( experiment* ) )
```

Listing 1. Scopus Search Term

The search term consists of four sub-terms representing the focus of this paper. In Listing 1, the four sub-terms are separated by the word 'AND' in the beginning of a line. The first sub-term represents the focus on various forms of energy. The second sub-term represents the focus on energy flexibility or related concepts. The third sub-term expresses the focus on industrial applications. The fourth sub-term highlights that practical experiments must be presented in the paper, representing the focus on applied case studies.

The identification of eligible reports was conducted in three stages: a screening of the titles of the reports, an analysis of the remaining reports' abstracts, and finally a full-text analysis.

B. Process for the Analysis of CPPSs in Case Studies

Requirements are rarely explicitly stated in a report. Therefore, instead of extracting requirements directly from a report, recurring IT and OT functionalities were identified and a list of these functionalities was created. This list was continuously refined throughout the literature analysis process, meaning new functionalities were described and existing descriptions of functionalities were updated. Additionally, the descriptions of functionalities were continuously enriched with examples of how the functionalities are applied in practice.

Based on the final list of functionalities, it was inferred which requirements each functionality was intended to fulfill. As it was only possible to identify functionalities instead of directly identifying requirements, all inferred requirements are functional requirements. The requirements were formulated in a solution-neutral manner. This approach aims to abstract from established terms such as supervisory control and data acquisition (SCADA) or process control system (PCS), focusing solely on describing the required functionalities rather than specifying how these functionalities should be implemented. It was also attempted to focus on requirements that are specific to energy-flexible operation. General requirements for engineering CPPSs were not considered.

Both functionalities and requirements are grouped into the same 13 components, which will be briefly described in the following:

1. Operational Planning[1] describes requirements for planning and dynamic re-planning of operations.

2. Planning Model describes required features of models of resources used for operational planning.[2]

3. Execution describes what is required to execute operating plans reliably in real CPPSs.

4. Forecast describes which use case requires which kind of forecasts.

5. Simulation describes which simulations are useful in energy-flexible operations.

6. Data and Information Management describes requirements for enterprise internal routing and processing of data.

7. Analytics describes what kind of evaluations of energy-flexible operations are required.

8. Human Machine Interface (HMI) describes which information should be presented to the user and which commands must be available.

9. External Interfaces describes which external parties communication interfaces should be established with.

10. Data Storage describes what data and information should be stored.

11. Control describes energy flexibility specific requirements for resource control programs.

12. Sensors describes which physical quantities must be measured.

13. Actuators describes energy flexibility specific requirements for actuators.

Not all requirements should be interpreted as mandatory for energy-flexible operation to be possible. Some requirements describe beneficial but not required features. The requirements are formulated accordingly. Likewise, not every requirement is applicable to every use case. Requirements that apply only to certain use cases are formulated accordingly.

IV. Results

A. Eligible Reports

The search term yielded 9,356 reports from the Scopus © database. In identifying the eligible reports, every paper that did not address all four focus topics described in Sec. III-A was excluded. 9,056 reports were excluded, because their titles showed a different focus. 240 reports were excluded because their abstracts revealed that at least one of the four focus topics was not addressed. 27 more reports were excluded because at least one of the four focus topics was not sufficiently addressed in the full-texts. 33 remaining eligible reports were included for the analysis of the CPPSs presented in the papers.

B. Overview of Case Studies

An overview of the 33 case studies of applied industrial energy flexibility is presented in Table I. For every case study, the purpose of the energy-flexible operation is listed. In most cases, the purpose is to reduce costs or generate additional revenue. In load management (LM), capacity charges can be reduced or energy supply equipment can be downsized. Energy savings (ES) reduce costs by reducing the energy consumption. Likewise, reacting to variable energy prices (VEP) can reduce costs. Providing ancillary services (AS) such as frequency reserves or other balancing services is a means to generate additional revenue. Maximizing the ratio of self-generated energy (SGM) can reduce costs and increase renewable energy integration. The industrial system that is operated flexibly is also listed in Table I. Finally, the flexibility measures leveraged in the case studies are stated. Flexibility measures have been evaluated according the VDI guideline 5207, where detailed definitions of the flexibility measures can be found [11].

Table I
Overview of reviewed case studies.

Study	Purpose	System	Measure
[12]	LM	Mining Shovel	SE
[13]	ES	Refrigerator	IS
[14]	AS	Electrolyzer	APP, IP
[15]	VEP	Manufacturing line	IP, SJS
[16]	VEP	Industry Energy Supply	SE, APP
[9]	VEP	Cleaning Machine	IS, APP
[17]	VEP	Factory Heat Supply	SE, APP
[18]	VEP	Extrusion Blow Molding	SJS
[19]	LM	Air Separation Unit	IP
[20]	VEP	Air Condition	SE, APP
[21]	LM	Data Center	SR
[22]	ES	Steel Plant	SE
[23]	LM	Mine (Various Machines)	IP
[24]	LM	Bacteria Plant	APP
[25]	ES	Conveyor	IP
[26]	AS	Electrolysis, Steel Plant	APP
[27]	AS	Electrolyzer	APP
[28]	AS	Cooling Supply	APP, IP
[29]	VEP	Distillation Column	IP
[30]	VEP	Industry Energy Supply	SE, BES
[31]	LM	Factory (unspecified)	SJS
[32]	AS	Various Industries	APP
[33]	LM	Mine (Crusher)	APP, IP
[34]	VEP	Machining Center	IP, SJO
[35]	LM, ES	CNC Machine	APP, SJO
[36]	LM	Industry Energy Supply	APP
[37]	ES	Wood Pellets Production	IP
[38]	LM	Manufacturing line	SJO, SR
[39]	VEP	CNC Machine, Annealing	SJO, SJS
[40]	VEP	Electrolysis (Zinc)	APP
[41]	ES	Pumpjack	IS, APP
[42]	SG	Electrolyzer	SE, APP, IP

Purpose abbreviations: LM - load management, ES - energy savings, AS - ancillary services, VEP - variable energy prices, SGM - self generation

Measure abbreviations: SE - store energy, IS - inherent storage, APP - adjust process parameters, IP - interrupt process, SJS - shift job start, SJO - shift job order, BES - bivalent energy supply, SR - switch resources

[1]The term operational planning subsumes production planning as well as planning of the operation of energy supply and storage systems.

[2]The term resource is generally used to refer to all machines, storage systems and other technical elements in a production system.

Interestingly, all flexibility measures can be located on the manufacturing level and the manufacturing control level [11]. No flexibility measures from the enterprise control level have been found. The analyzed case studies exhibit a wide range of systems from industrial energy supply systems [16] to logistics [25], discrete manufacturing [34], and process manufacturing [19]. The most common purposes of energy-flexible operation are load management and reacting to variable energy prices. It should be noted though, that all case studies reacting to variable energy prices did so in a hypothetical way, i.e., real energy market prices were utilized but no energy was traded at real markets.

C. Presentation of Requirements

By analyzing the full-texts of the 33 eligible reports, 100 functional requirements for energy-flexible CPPSs were derived. The requirements are grouped into the 13 components presented in Sec. III-B. Due to a limited number of pages, not all requirements can be presented and discussed. Instead the 16 requirements derived for the 'Analytics' component are presented exemplary. The complete list of requirements is openly available in the supplementary materials on Github[3]. The supplementary materials further include the IT and OT functionalities extracted from the 33 analyzed reports, as described in Sec. III-B, along with examples of how the respective functions are implemented in the practical case studies. The supplementary materials also contain a glossary of specific technical terms used in the requirements definition. All supplementary materials can be found on Github.

Some excerpts from the glossary relevant to understanding the presented requirements are the following:

Proactive Approach: An approach that plans ahead the operation of resources. Proactive approaches frequently leverage optimization techniques. The opposite is a reactive approach, where flexibility is only leveraged as a reaction to a signal.

High-Precision Use Case: A use case where temporary deviations from the operating plan can entail high financial losses. Any use case participating in wholesale energy markets is a high-precision use case. Likewise, use cases with strict, short-term production goals or strong logistic dependencies can be high-precision use cases.

Process Quality Indicator: A state variable that must be maintained within a given margin. E.g., the temperature in a refrigerator, the pressure in a pressurized air supply duct, or the concentration of impurities in a product.

The chosen exemplary CPPS component is '7. Analytics' (see Sec. III-B), which has the purpose of analyzing the quality of energy-flexible operating strategies. The analytics component is chosen because it is rarely the focus of reports, meaning that no best practices have been explicitly established so far. However, the analysis of reports revealed that many authors perform similar analyses regarding the quality of their energy-flexible operating strategies. From these common analyses, 16 general functional requirements were derived and are presented here.

[3] github.com/lreinpold...

Requirements for Analytics of Energy-Flexible Operating Strategies in CPPSs

7.1 In proactive approaches, analytics must assess how accurately resources can execute operating plans by comparing plans to actual measurements

7.1.1 The planned operation of resources must be compared to actual measurements to assess how accurately operating plans can be executed.

7.1.1.1 The planned **energy consumption** of resources must be compared to the measured energy consumption to assess how accurately operating plans can be executed.

7.1.1.2 In use cases with self-generation, the planned **energy generation** of resources must be compared to the measured energy generation to assess how accurately generation can be predicted.

7.1.1.3 The planned **production volume** of resources must be compared to the measured production volume to assess how accurately operating plans can be executed.

7.1.1.4 The planned **process quality indicators** of resources must be compared to the measured process quality indicators to assess how accurately operating plans can be executed.

7.1.2 Deviations between operating plans and actual measurements must be detected to potentially trigger a reaction during operation and to identify deficiencies in the operating strategy and enable long-term performance tracking.

7.1.2.1 Deviations between operating plans and actual measurements must be detected **in time to enable corrective actions**. The time available for detection depends on the use case. In high-precision use-cases analytics must be conducted in real-time.

7.1.2.2 If deviations between the operating plan and actual measurements are detected by analytics, a notification must be sent to the operator to enable the operator to trigger an appropriate reaction.

7.2 The analytics must quantify the benefits and drawbacks of energy-flexible operation to communicate them to the responsible parties.

7.2.1 The analytics must quantify the financial benefits of energy-flexible operation in comparison to conventional operation. Suitable metrics for this are the cost per unit produced or the cost per time, depending on the analyzed resources.

7.2.1.1 The analytics must quantify the cost of energy incurred during energy-flexible operation. This includes both energy rate and capacity charge as well as any other financial implications of energy-flexible operations.

7.2.1.2 The analytics must quantify the production volume achieved in energy-flexible operation, to assure that energy-flexible operation does not negatively impact productivity and to be able to calculate production volume-specific energy cost and consumption.

7.2.1.3 The analytics must quantify all other cost factors affected by energy-flexible operation, e.g., maintenance costs or salaries. Cost factors that deviate from conventional operation must be considered in the quantification of the benefits of energy-flexible operations.

7.2.2 The analytics should quantify the ecological benefits of energy-flexible operation in comparison to conventional operation. Suitable metrics for this may be the greenhouse gas emissions per unit produced per time or the energy consumed per unit produced or per unit time depending on the analyzed resources.

7.2.3 If several alternative operating plans are created, the analytics must compare alternative operating plans regarding the relevant KPIs to provide a solid decision basis for plant operators.

The requirements are ordered into different levels within each component, as can be seen in the gray text box. Requirements on lower levels specify certain aspects of requirements on higher levels. On the first level of requirements for the analytics component, shown in the gray text box, two requirements are derived. Requirement 7.1 deals with analyzing the quality of the operating strategy from a planning perspective, i.e., it specifies how well the actual operation of resources conforms to the previously created operating plan. This is important to identify deficiencies in the operating strategy, e.g., inaccuracies in optimization models or forecast components. Requirement 7.2 specifies that the benefits and drawbacks of energy-flexible operation must be quantified. This is important to provide a reliable information base to make strategic decisions regarding energy-flexible operations, i.e., the extra efforts for energy-flexible operations must always be outweighed by corresponding financial or environmental benefits.

Requirements on lower hierarchy levels specify certain aspects of requirements on higher hierarchy levels. In this way, Requirement 7.1.2, stating that deviations between operating plans and actual measurements must be detected, is refined by Requirement 7.1.2.1, stating in which time frame deviations must be detected.

The applicability of requirements to certain use cases is addressed explicitly by specifying the corresponding use cases. An example of this is Requirement 7.1.2.1, specifying that real-time analytics are only mandatory for high-precision use-cases.

The requirements are formulated to reflect that certain aspects of requirements are not mandatory but likely beneficial. An example of this is Requirement 7.2.2 stating that ecological benefits of energy-flexible operation **should** be quantified, implying that the quantification of ecological benefits is not strictly required in an operating strategy. This reflects that, while ecological considerations might be an important motivation for establishing energy-flexible operation, the main motivation for most stakeholders are financial merits [5]. This is why the financial effects of energy-flexible operation **must** be quantified. All requirements stating that something **must** be done are considered as mandatory to maintain a functional and profitable operating strategy.

Overall, it was attempted to formulate all requirements in a technology-agnostic manner, i.e., no specific technologies are recommended that can be leveraged to fulfill a given requirement. For example, while many approaches exist to forecast energy prices, no recommendations regarding specific forecasting technologies are made in the requirements.

V. Discussion and Conclusion

This work presents the results of a systematic literature review to derive functional requirements for CPPSs. In the review process, 33 practical, industrial case studies on energy-flexible operation were identified and analyzed. Recurring functions of CPPSs were extracted from the analyzed case studies and refined into a set of 100 general, functional requirements. This set of requirements can assist engineers in developing energy-flexible operating strategies by presenting considerations they might not have identified independently. The requirements can also serve as a foundational checklist to ensure relevant aspects are addressed, and to enable evaluation to avoid unnecessary complexity or over-engineering in proposed solutions.

While the literature review was conducted systematically, the 33 analyzed case studies are still a relatively small sample size. This means that the presented requirements should not be interpreted as exhaustive. Energy flexible operation of CPPSs is still a relatively new field, and this study shows that applicable practical case studies are still rare. As more case studies are published, new functionalities and requirements will likely be identified. Publishing the requirements on Github enables the entire community to contribute to refining the requirements derived in this study. Exemplary requirements that were not derived based on the analyzed case studies but that might become relevant are requirements regarding integration of energy-flexible production planning with manufacturing execution systems and enterprise resource management systems, which were not addressed in any of the analyzed case studies.

Generally, the requirements derived within this study are all functional requirements. This is because it is feasible to identify functions such as forecasting energy prices directly in reports or infer their presence from graphs, tables or other descriptions. Non-functional requirements were not derived, in part because of the small sample size. Deriving non-functional requirements would, in many cases, require statistical analyses to derive threshold values that energy-flexible CPPSs must conform to, e.g., the frequency at which sensor values must be recorded, or the time interval of optimization or planning models. Such statistical analyses could not be performed reliably with the limited data available. Other non-functional requirements regarding scalability or security of energy-flexible CPPSs were also not considered because these aspects were too rarely addressed in the analyzed case studies.

Future research regarding requirements for energy-flexible CPPSs could focus on deriving requirements for the previously mentioned aspects of scalability and security. Practical case studies considering these aspects would be highly beneficial for deriving a solid set of requirements.

As this work focused only on deriving requirements, and all requirements were formulated without proposing any technological solutions, future works should develop solutions in the form of design patterns to address the requirements derived within this study. Design patterns are tested solutions for different problems, describing the problems they address as well as the solution to the problem. Having a set of design patterns to address the requirements specified in this study could simplify the development of energy-flexible operating strategies. It should be noted that some design patterns for the derived requirements already exist. Wagner et al. [43] propose design patterns for planning models of flexible energy resources. Likewise, the IT-Platform proposed by Stiphoudt et al. [7] could be developed into a design pattern.

Finally, the requirements derived in this study could be made more easily accessible by developing a workflow guiding the user through the requirements, pre-filtering relevant requirements for the respective use case and making suggestions for solutions to fulfill requirements.

References

[1] A. Sauer, H. U. Buhl, A. Mitsos *et al.*, *ENERGIEFLEXIBILITÄT IN DER DEUTSCHEN INDUSTRIE: Band 2: Markt- und Stromsystem, Managementsysteme und Technologien energieflexibler Fabriken*, 2022.

[2] C. Leinauer, P. Schott, G. Fridgen *et al.*, "Obstacles to demand response: Why industrial companies do not adapt their power consumption to volatile power generation," *Energy Policy*, vol. 165, p. 112876, 2022.

[3] H. Golmohamadi, "Demand-side management in industrial sector: A review of heavy industries," *Renewable and Sustainable Energy Reviews*, vol. 156, p. 111963, 2022.

[4] M. Ranaboldo, M. Aragüés-Peñalba, E. Arica *et al.*, "A comprehensive overview of industrial demand response status in Europe," *Renewable and Sustainable Energy Reviews*, vol. 203, p. 114797, 2024.

[5] N. Lashmar, B. Wade, L. Molyneaux *et al.*, "Motivations, barriers, and enablers for demand response programs: A commercial and industrial consumer perspective," *Energy Research & Social Science*, vol. 90, p. 102667, 2022.

[6] C. Kaymakci, D. Bauer, A. Sauer *et al.*, "Eine strukturierte Methode zur IT-Systemanalyse für Energieflexibilität in der Industrie," *Zeitschrift für Energiewirtschaft*, vol. 47, no. 1, pp. 38–53, 2023.

[7] C. Stiphoudt, S. Menci, C. Kaymakci *et al.*, "Energy Synchronization Platform Concept to Enable and Streamline Automated Industrial Demand Response," *Energy Proceedings*, 2024.

[8] VDI - Production and Logistics, "Energieflexible Fabrik: IT-Infrastructure for the Operation of Energy-Flexible Factories," Berlin, 01.09.23.

[9] D. Fuhrländer-Völker, J. Magin, and M. Weigold, "Automation architecture for harnessing the demand response potential of aqueous parts cleaning machines," *Production Engineering*, vol. 17, no. 6, pp. 785–803, 2023.

[10] M. J. Page, J. E. McKenzie, P. M. Bossuyt *et al.*, "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews," *BMJ (Clinical research ed.)*, vol. 372, p. n71, 2021.

[11] "VDI 5207 Sheet 1:2020-07, Energy-flexible factory Fundamentals," Berlin.

[12] O. Abdel-Baqi, P. Miller, and A. Nasiri, "Energy management for an 8000HP hybrid hydraulic mining shovel," in *2015 IEEE Transportation Electrification Conference and Expo (ITEC)*. IEEE, 14.06.2015 - 17.06.2015, pp. 1–8.

[13] J. Cirera, J. A. Carino, D. Zurita *et al.*, "Improving the Energy Efficiency of Industrial Refrigeration Systems by Means of Data-Driven Load Management," *Processes*, vol. 8, no. 9, p. 1106, 2020.

[14] E. Crespi, G. Guandalini, L. Mastropasqua *et al.*, "Experimental and theoretical evaluation of a 60 kW PEM electrolysis system for flexible dynamic operation," *Energy Conversion and Management*, vol. 277, p. 116622, 2023.

[15] S. Emec, M. Kuschke, M. Chemnitz *et al.*, "Potential for demand side management in automotive manufacturing," in *IEEE PES ISGT Europe 2013*. IEEE, 2013, pp. 1–5.

[16] L. Ferrari, F. Esposito, M. Becciani *et al.*, "Development of an optimization algorithm for the energy management of an industrial Smart User," *Applied Energy*, vol. 208, pp. 1468–1486, 2017.

[17] F. Fuhrmann, B. Windholz, A. Schirrer *et al.*, "Energy management for thermal batch processes with temporarily available energy sources– Laboratory experiments," *Case Studies in Thermal Engineering*, vol. 39, p. 102473, 2022.

[18] X. Gong, Y. Liu, N. Lohse *et al.*, "Energy- and Labor-Aware Production Scheduling for Industrial Demand Response Using Adaptive Multiobjective Memetic Algorithm," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 2, pp. 942–953, 2019.

[19] Z. Han, J. Zhao, W. Wang *et al.*, "A two-stage method for predicting and scheduling energy in an oxygen/nitrogen system of the steel industry," *Control Engineering Practice*, vol. 52, pp. 35–45, 2016.

[20] A. von Hayn, J. Wendt, N. Lieberth *et al.*, "Development of Energy Flexible and Sustainable Operation Strategies of Air Conditioning Systems for Industrial Production Environments," *Procedia CIRP*, vol. 116, pp. 155–160, 2023.

[21] C.-H. Hsu, Q. Deng, J. Mars *et al.*, "SmoothOperator," in *Proceedings of the Twenty-Third International Conference on Architectural Support for Programming Languages and Operating Systems*, X. Shen, J. Tuck, R. Bianchini *et al.*, Eds. New York, NY, USA: ACM, 2018, pp. 535–548.

[22] L. Kasper, P. Schwarzmayr, F. Birkelbach *et al.*, "A digital twin-based adaptive optimization approach applied to waste heat recovery in green steel production: Development and experimental investigation," *Applied Energy*, vol. 353, p. 122192, 2024.

[23] O. Laayati, M. Bouzi, and A. Chebak, "Smart Energy Management System: Design of a Monitoring and Peak Load Forecasting System for an Experimental Open-Pit Mine," *Applied System Innovation*, vol. 5, no. 1, p. 18, 2022.

[24] I.-H. Lu, "Research on Energy-Saving Efficiency of the Air-Conditioning Host in Agricultural Plant Bacteria Room," in *2022 IEEE 5th Eurasian Conference on Educational Innovation (ECEI)*. IEEE, 2022, pp. 384–387.

[25] S. Mechs, S. Grimm, D. Beyer *et al.*, "Evaluation of prediction accuracy for energy-efficient switching of automation facilities," in *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*. IEEE, 2013, pp. 6928–6933.

[26] E. Perroy, D. Lucas, and V. Debusschere, "Provision of Frequency Containment Reserve Through Large Industrial End-Users Pooling," *IEEE Transactions on Smart Grid*, vol. 11, no. 1, pp. 26–36, 2020.

[27] Y. Qiu, B. Zhou, T. Zang *et al.*, "Extended Load Flexibility of Industrial P2H Plants: A Process Constraint-Aware Scheduling Approach," in *2022 IEEE 5th International Electrical and Energy Conference (CIEEC)*, pp. 3344–3349.

[28] S. Rahnama, T. Green, C. H. Lyhne *et al.*, "Industrial Demand Management Providing Ancillary Services to the Distribution Grid: Experimental Verification," *IEEE Transactions on Control Systems Technology*, vol. 25, no. 2, pp. 485–495, 2017.

[29] L. M. Reinpold, L. P. Wagner, L.-T. Reiche *et al.*, "Experimental Setup for the Evaluation of Optimization Strategies for Flexible Energy Resources," in *2023 IEEE 2nd Industrial Electronics Society Annual On-Line Conference (ONCON)*. IEEE, 2023, pp. 1–6.

[30] Sandro Magnani, Piero Danti, and Giovanni Cauchi, "Experimental results of the optimized management of an EMS-equipped small-size prosumer," *2019 UK/ China Emerging Technologies (UCET)*, 2018.

[31] M. Sawczuk, A. Stawowy, O. Okrzesik *et al.*, "Managing Costs of the Capacity Charge through Real-Time Adjustment of the Demand Pattern," *Energies*, vol. 17, no. 8, p. 1911, 2024.

[32] F. Silletti, L. Orru, M. Di Serafino *et al.*, "H2020 OSMOSE PROJECT: Final results of the experimentation phase of industrial Demand Response (DR)," in *2022 AEIT International Annual Conference (AEIT)*. IEEE, 2022, pp. 1–6.

[33] M. A. Sokolovsky and V. S. Klimash, "Power Management of a Continuous Mining Process," in *2019 International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon)*. IEEE, 2019, pp. 1–3.

[34] X. Sun, X. Wang, J. Wu *et al.*, "Prediction-based manufacturing center self-adaptive demand side energy optimization in cyber physical systems," *Chinese Journal of Mechanical Engineering*, vol. 27, no. 3, pp. 488–495, 2014.

[35] H. Suwa and T. Samukawa, "A New Framework of Energy-efficient Manufacturing Systems Based on Energy Load Profiles," *Procedia CIRP*, vol. 41, pp. 313–317, 2016.

[36] J. Tian, Z. Liu, J. Shu *et al.*, "Base on the ultra–short term power prediction and feed–forward control of energy management for microgrid system applied in industrial park," *IET Generation, Transmission & Distribution*, vol. 10, no. 9, pp. 2259–2266, 2016.

[37] H. Vigants, D. Blumberga, and I. Veidenbergs, "Demand Side Management in Pellet Production: Internal and External Factors," *Environmental and Climate Technologies*, vol. 14, no. 1, pp. 30–35, 2014.

[38] J. Wan, B. Chen, S. Wang *et al.*, "Fog Computing for Energy-Aware Load Balancing and Scheduling in Smart Factory," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 10, pp. 4548–4556, 2018.

[39] H. Wicaksono, M. Trat, A. Bashyal *et al.*, "Artificial-intelligence-enabled dynamic demand response system for maximizing the use of renewable electricity in production processes," *The International Journal of Advanced Manufacturing Technology*, 2024.

[40] C. Yang, G. Deconinck, W. Gui *et al.*, "An optimal power-dispatching system using neural networks for the electrochemical process of zinc depending on varying prices of electricity," *IEEE transactions on neural networks*, vol. 13, no. 1, pp. 229–236, 2002.

[41] H. Zhao, Z. Wang, Y. Wang *et al.*, "Electromechanical Based Energy Saving Control Strategy for Beam Pumping Motor Systems in Oil Production Industry," in *2021 IEEE Industry Applications Society Annual Meeting (IAS)*. IEEE, 2021, pp. 1–8.

[42] C. Ziogou, D. Ipsakis, P. Seferlis *et al.*, "Optimal production of renewable hydrogen based on an efficient energy management strategy," *Energy*, vol. 55, pp. 58–67, 2013.

[43] L. P. Wagner, L. M. Reinpold, and A. Fay, "Design Patterns for Optimization Models of Flexible Energy Resources," in *2023 IEEE 2nd Industrial Electronics Society Annual On-Line Conference (ONCON)*. IEEE, 2023, pp. 1–6.