Generic Model Structure for the Representation of Flexible Energy Resources and Their Joint Optimization

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Abstract – **Modeling energy resources is essential to benefit from their inherent energy flexibility. This paper describes a generic model structure to model flexible energy resources. Based on the presented generic model structure, an electrolyzer connected with a hydrogen storage system is modeled and its operation is subsequently optimized to minimize operational expenses. Within the case study the participation of the modeled system in the intra-day market for electric energy is analyzed. The results of the analysis illustrate the potential of energy flexibility by optimally responding to external signals, e.g., prices for electric energy.**

Keywords* – *Energy flexibility, Generic Model, Energy resource, Optimization

NOMENCLATURE

c_{el} in EUR/MWh	Cost of electric energy
$C_{Storage}$ in kWh	Capacity of the energy storage
EUR	Euro
H in kWh	Hydrogen production target
h_i in kW	Hydrogen power output in i
i	Index for time interval
$\eta(x)$	Efficiency in dependence on x
P in kW	Power
SOC	State of charge
$t, \Delta t$	Time, Time interval
Ω	Generic factor

I. INTRODUCTION

According to the Paris Agreement, many countries aim to achieve a carbon neutral economy by 2050. This implies that, among other things, the renewable energy generation capacity needs to be massively expanded within the coming decades [1]. Major renewable energy resources like wind and solar power entail the challenge of intermittent availability.

This has an impact on both spot market electricity pricing and power grid stability. A possible approach to tackle these challenges is to leverage the flexibility of individual components of the power system's components [2]. This can be accomplished using storage systems like batteries and material buffers or by shifting the electricity demand towards times when renewable energy is abundant.

Flexibility is defined as a capability of a system able to execute different paths of action at given occasions. Systems providing energy flexibility are able to temporally decouple energy demand from its supply [3]. This ability can be classified into demand-side and supply-side flexibility, as well as the flexibility of energy storage systems. This study considers the latter as it has the greatest flexibility potential. Zhao *et al.* show that making use of energy flexibility can result in lower operational expenses [4]. For minimizing the costs, mathematical modeling of energy resources with a subsequent optimization of their operation is commonly applied. To simplify this engineering process and to provide consistent models, a generic model structure to represent flexible energy resources is presented here.

Several previous publications deal with the topic of generic mathematical model structures which are used to optimize the operation of flexible energy resources. A review for the modeling approaches and the optimization of integration of renewable energy resources is provided by Wagh and Kulkarni [5]. Schott *et al.* present a descriptive data model for industrial flexibility with respect to power consumption which was developed in the *Kopernikus* project *SynErgie* [6]. Khatri *et al.* develop a generic modeling approach which is used to consider the active participation of industrial enterprises in electricity markets [7]. Whereas Corsetti *et al.* deal with the modeling and deployment of multi-energy flexibility as an energy lattice framework [8].

Energy hubs provide the possibility to model complex energy systems with multiple conversions and multiple energy flows [9]. This concept serves as a foundation for a generic framework for the modeling of energy systems that include numerous energy carriers presented by Krause *et al.* [10]. It can also be applied in combination with the power nodes modeling framework which focusses on modeling energy storage systems [11]. Both concepts enable the user to conduct detailed, system level investigations. To model one energy resource without multiple energy carriers, the authors formulate the hypothesis that a simplified approach can be used. The detailed analysis of current research in energy resource modeling results in the awareness that a generic model structure is needed which is described in this paper. Therefore, the main contribution of this paper is a generic model structure for energy resources with an appropriate level of detail for the optimization and its application to a use case.

The generic model structure is intended to represent a wide variety of flexible energy resources from energy converters like electrolyzers or diesel engines over storage systems like batteries or material buffers to production machines and processes or household appliances. The mathematical representations of these energy resources allow their use in optimization models which can determine the most economic or the most climate-friendly operation schedule.

To demonstrate the applicability of the presented model structure, it is applied to model a hydrogen production facility consisting of an electrolyzer and a hydrogen storage system. To illustrate the benefit of flexible energy resources, a comparison of static operation with a fixed operation point and variable operation, optimizing the participation at the intra-day market is carried out.

This paper is structured as follows: Sec. II describes the methodology applied in modeling and optimization. The case study in Sec. III analyzes the energy flexibility inherent to the hydrogen production facility. A critical reflection and conclusion is given in Sec. IV.

II. GENERIC MODEL FOR FLEXIBLE ENERGY RESOURCES

Based on the state of the art outlined in Sec. I, this section presents the methodology applied to build models for energy flexibility. First a generic model structure is presented (Sec. II -A). The methodology for the optimization is presented in Sec. II -B.

A. *Generic Model for Energy Flexibility*

The analysis of different mathematical models shows that a lot of different models representing energy resources exist. However, to ensure that every model of different energy resources provides the same structure, a generic model structure is built and presented in the following.

TABLE 1: SELECTED MATHEMATICAL MODEL OF FLEXIBLE ENERGY RESOURCES.

Energy Resource	***Relevant Equations***
Electrolyzer [12–18]	$P(t)_{out} = P(t)_{in} \cdot \eta(P_{in}(t))$ $\mathrm{P(t)}_{in} \leq \mathrm{P}_{\mathrm{max}}$
BESS [19–21]	$\mathrm{SOC}(t+\Delta t) = \mathrm{SOC}(t) + \frac{P_{charge} \cdot \eta_{charge} \cdot \Delta t}{C} - \frac{P_{dis} \cdot \Delta t}{C \cdot \eta_{dis}}$ $SOC_{min} \leq SOC(t) \leq SOC_{max}$
Wind Turbine [22–24]	$\mathrm{P}(\omega(t)) = \begin{cases} P^{u}_{rated} & \omega_{min} \leq \omega(t) \leq \omega_u \\ x(\omega(t)) \cdot P_{rated} & \omega_u \leq \omega(t) \leq \omega_{max} \\ 0 & \omega(t) \leq \omega_{min} \; or \; \omega_{max} \geq \omega(t) \end{cases}$ x is a factor representing throtteling at higher windspeeds.
Solar PV [25–27]	$P_{out}(t) = P_{installed} \cdot \eta \cdot x(t)$ x is a factor representing solar irradiation

The equations listed in TABLE 1 determine the power output of the respective system. For energy resources generating electrical energy of renewable resources, the calculation is conducted by multiplying the maximum or rated power by an operation point or other influencing factors such as wind speed. In addition, energy resources which convert one energy carrier into another and are controllable are modeled somehow different. An electrolyzer, for example, converts electric energy into chemically bonded energy in the form of hydrogen. The conversion depends on the power input and always causes power losses. As stated in Eq. 1, it is possible to model this energy resource and its dependencies. An energy resource's power output P_{out} can be calculated from its power input P_{in} and – if applicable – the corresponding efficiency $\eta(P_{in})$. η also represents influencing factors in case of renewable generation. To represent the energy resource as accurately as possible, a minimum $P_{in,min}$ and maximum input power $P_{in,max}$ can also be set as model constraints.

$$P_{out}(P_{in}) = \begin{cases} P_{in} \cdot \eta(P_{in}), & P_{in,min} \leq P_{in} \leq P_{in,max} \\ 0, & P_{in} < P_{in,min} \end{cases} \tag{1}$$

This generic model structure can be extended to represent the dynamic behavior of energy resources such as the response to a change in the operating set point or a change of its environment, i.e., its boundary conditions. Further limitations can be imposed on the permissive operating conditions, e.g., regarding operating hours or dependencies to other systems.

The generic model description shown in Eq. 1 is also applicable to energy storage systems. The power input P_{in} can be coupled to the power output of another system, as shown in Eq. 2. The state of charge (SOC) of the storage is calculated by an energy balance (Eq. 3). The SOC of a given time step $(t_i + \Delta t)$ depends on the SOC of the previous time step (t_i) as well as the power input P_{in} and output P_{out} of the storage during the time step Δt divided by the storage's capacity $\mathrm{C}_{Storage}$ and the efficiency of (dis-) charging $\eta(P_i)$. Further, the energy generation target per interval and desired power output can be defined according to the system configuration and the modeler's needs.

$$P_{in,Sys2} = P_{out,Sys1} \tag{2}$$

$$\mathrm{SOC}(t_i + \Delta t) = \mathrm{SOC}(t_i) + \frac{|P_{in}| \cdot \eta_{in}(P_{in}) \cdot \Delta t}{C_{Storage}} - \frac{|P_{out}| \cdot \Delta t}{C_{Storage} \cdot \eta_{out}(P_{out})} \tag{3}$$

The time resolution of the model can be adapted to fit the needs of the researcher. Guidelines for a suitable time-resolution of a model of flexible energy resources are provided by Cao and Sirén [28]. Often an interval of 15 minutes is selected if an analysis aims at intraday power market participation.

To instantiate the generic model, data about the energy resource's system characteristics, the maximum or rated power, and possible limits of the operational point need to be known. In addition, the capacity and efficiencies (if applicable) of the storage is also needed.

B. *Optimization*

To optimize the use of the energy flexibility described by the instantiated generic model, an optimization problem must be formulated. To implement unified models of energy resources, the optimization problem is based on the presented generic model approach. In addition, an objective function and operational constraints must be established.

The optimization problem can realize the maximization or minimization of the objective function according to Eq. (*4*) depending on the power, as well as possible generic factors Ω_i, which represent for example the current energy prices.

$$\min/\max objective = \sum_{i=0}^{t_{max}} P_i \cdot \Delta t \cdot \Omega_i \tag{4}$$

On the basis of this objective function, which satisfies the criteria of a linear optimization problem according to , Unger and Dempe [29], the function can be optimized in dependency on the decision variable (Eq. 4: P_i).

Furthermore, constraints need to be set and considered, which can be deduced from the mathematical description of the generic model. For example, constraining the power input of the system so that the power neither falls below a defined minimum value nor exceeds a defined maximum value (see Eq. 5). This constraint can be derived from Eq. 1. Additional constraints might be set for, e.g., energy production within the interval.

$$P_{in,min} \leq P_{in} \leq P_{in,max} \tag{5}$$

If multiple systems are coupled together, it is also necessary to ensure that the input power of system 2 is equal to the output power of system 1 (see Eq. 2).

III. CASE STUDY

Within this case study, the generic model is instantiated for an electrolyzer and a hydrogen storage system. After demonstrating the applicability of the approach, the model is used to optimize the electric energy to hydrogen conversion against a historic prices for electric energy traded in the intra-day market provided by EPEX SPOT [30].

As an exemplary energy resource, the electrolyzer Siemens *Silyzer 200* with a rated electric power of 6,000 kW is modeled using the characteristics derived from real operation. As a modeling environment, the *Energy Option Model* [31] is used in combination with the solver IBM CPLEX [32].

Eqs. 7-9 describe the electrolyzer and its storage system by instantiating the generic model developed in Sec. II. The objective function (Eq. (*6*)) describes the minimization of the costs of electric energy through power consumption.

$$\min objective = \sum_{i=0}^{t_{max}} P_{el,i} \cdot \Delta t \cdot c_{el,i} \tag{6}$$

Eq. 7 instantiates the generic model described in Sec. III using the characteristics of the electrolyzer.

$$\mathrm{P}_{hydrogen} = P_{el} \cdot \eta(P_{el}) \tag{7}$$

Equations 8-11 represent constraints for the operation: Eq. 8 limits the electric power (see TABLE 2), Eq. 9 represents the storage and constrains the operation to not overfill the storage.

$$P_{el,\,min} \leq P_{el} \leq P_{el,\,max} \tag{8}$$

$$0 \leq SOC(t_i) \leq 1 \quad \forall t \tag{9}$$

Apart from Eq.3, which is applied as a constraint to represent the energy balance in the hydrogen storage system, Eqs. 10 & 11further define the operation by setting targets for the hydrogen production in the interval H and the power output of the storage (or of the electrolyzer directly) h_i. h_i can also be interpreted as the hydrogen demand of a consumer.

$$\sum_{i=0}^{t_{max}} P_{Hydrogen,\,i} \cdot \Delta t = \mathrm{H} \tag{10}$$

$$P_{out,Storage,\,i} = h_i \tag{11}$$

Two operation modes of the electrolyzer are compared: Inflexible operation with a fixed operation point and flexible operation with the ability of the process to modulate its power input between $P_{el,min}$ and $P_{el,max}$. Due to its operation mode, no hydrogen storage system is necessary to operate the energy resource in the inflexible mode. In both cases the constraints described in Eqs. 10 & 11 are satisfied and the total amount of hydrogen produced is the same. The selected time interval for the case study is August 12th until August 21st, 2022. Values for all key parameters are shown in TABLE 2.

TABLE 2: KEY PARAMETERS AND RESULTS OF THE COMPARISON.

Parameter	***Flexible***	***Inflexible***
Cost of electric energy	398,207 EUR	430,140 EUR
Hydrogen production H	599 MWh	599 MWh
Hydrogen demand h_i	2,500 kW	2,500 kW
Hydrogen output electrolyzer	900 … 3,700 kW	2,500 kW
Storage size $C_{Storage}$	10,000 kWh	0 kWh
Electric power P_{el} of electrolyzer	1,200 … 6,000 kW	4,000 kW

The analysis shows that reacting to prices of electric energy at the intra-day market yields 7 % lower costs compared to the inflexible operation. The grey curve in FIGURE 1 shows the difference between the hydrogen output of the hydrogen production system between the flexible and the inflexible operation modes over an exemplary timespan of 30 hours. To achieve the previously stated savings, the hydrogen output power of the electrolyzer alternates between the maximum and minimum permissible operating point, deviating from the average hydrogen demand h_i by more than ± 1 MW as shown in FIGURE 1.

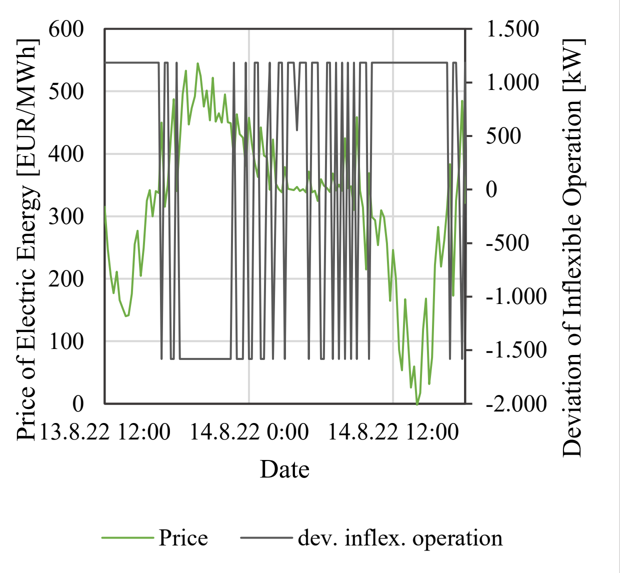

FIGURE 1: PRICE OF ELECTRIC ENERGY (GREEN) [30] AND DEVIATION OF THE FLEXIBLE OPERATION FROM INFLEXIBLE OPERATION (HYDROGEN OUTPUT, GREY).

FIGURE 2 shows the corresponding state of charge in the same representative time interval. The grey curve in FIGURE 2 demonstrates that the hydrogen storage system is charged during the hours exhibiting the lowest electricity prices. Correspondingly, the hydrogen storage system is discharged during the hours exhibiting the highest electricity prices.

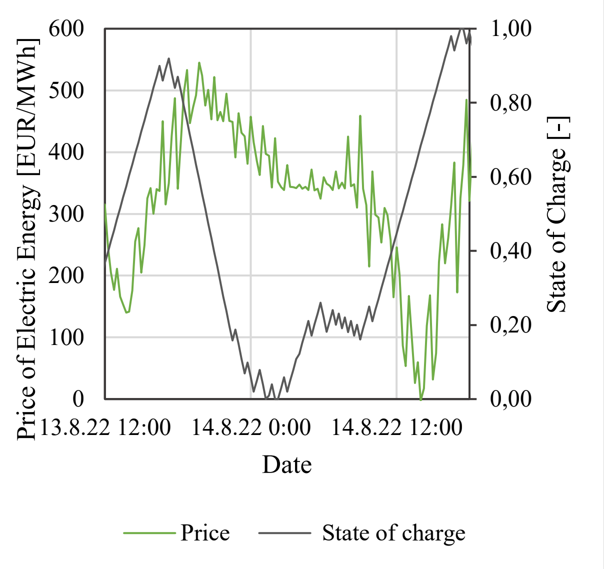

FIGURE 2: PRICE OF ELECTRIC ENERGY (GREEN) [30] AND SOC (FLEXIBLE OPERATION, GREY).

The analysis shows that a flexible operation of the electrolyzer is favorable compared to a static operation with a fixed operation point in terms of cost savings achieved through real-time pricing.

IV. DISCUSSION AND CONCLUSION

This paper presents a generic model structure to represent flexible energy resources and to optimize their operation. The model structure is derived from multiple energy resource models of different energy resources found in other publications. The applicability is demonstrated in a case study where the generic model is instantiated to model an electrolyzer and a hydrogen storage system. Subsequent optimization based on the model, including respective constraints, shows financial benefits of energy flexibility compared to inflexible operation.

While the applicability of the generic model structure is demonstrated in this case study, several assumptions are made that might not be applicable to other case studies. To simplify the case study, it was assumed that the production capacity of the electrolyzer and the storage capacity of the hydrogen storage system are fixed values. Future case studies can extend this optimization to include the capacities of the two energy resources as optimization variables to solve the resulting component sizing problem. This entails the need to include other important cost factors such as the capital expenditure of both systems in the optimization problem or other operational expenses, such as costs for rapidly changing the operational point which can lead to increased degradation of the electrolyzer, even though it has been shown in [33] that this impact is negligible. Moreover, successive projects should aim to more precisely reflect the real technical behavior of implemented units, e.g., by implementing ramping constraints. To include additional factors of the energy price course such as lower PV production in winter, a longer timespan than the 10 days considered in this study is desirable.

Another challenge to be addressed in future works are the uncertainties regarding the energy prices on the EPEX SPOT markets which need to be considered in forecasted flexibility scheduling. Today, prices for intraday energy trading are only available for a certain day from 3 pm on the previous day and even these prices are subject to changes up until five minutes before power delivery is due. This means that an optimization of the operation schedule beyond the next day is subject to major uncertainties. While methods exist to predict prices for different power markets, future works should consider the statistical uncertainty in price predictions and implement it in the modeling approach. An existing approach to address this uncertainty is statistical programming, which will be implemented on top of the existing methods in future works.

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REFERENCES

[1] European Commission, *Going climate-neutral by 2050: A strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy*. Luxembourg: Publications Office of the European Union, 2019.
[2] Emil Hillberg *et al.*, “Flexibility needs in the future power system,” 2019.
[3] N. Lehmann, E. Kraft, C. Duepmeier, I. Mauser, K. Förderer, and D. Sauer, “Definition von Flexibilität in einem zellulär geprägten Energiesystem,” 2019.
[4] J. Zhao, T. Zheng, and E. Litvinov, “A Unified Framework for Defining and Measuring Flexibility in Power System,” *IEEE Trans. Power Syst.*, vol. 31, no. 1, pp. 339–347, 2016, doi: 10.1109/TPWRS.2015.2390038.

[5] M. M. Wagh and V. V. Kulkarni, “Modeling and Optimization of Integration of Renewable Energy Resources (RER) for Minimum Energy Cost, Minimum CO2 Emissions and Sustainable Development, in Recent Years: A Review,” *Materials Today: Proceedings*, vol. 5, no. 1, pp. 11–21, 2018, doi: 10.1016/j.matpr.2017.11.047.

[6] P. Schott, J. Sedlmeir, N. Strobel, T. Weber, G. Fridgen, and E. Abele, “A Generic Data Model for Describing Flexibility in Power Markets,” *Energies*, vol. 12, no. 10, p. 1893, 2019, doi: 10.3390/en12101893.

[7] R. Khatri, M. Schmidt, and R. Gasper, “Active participation of industrial enterprises in electricity markets - a generic modeling approach,” *Energy Inform*, vol. 4, S3, 2021, doi: 10.1186/s42162-021-00173-5.

[8] E. Corsetti, S. Riaz, M. Riello, and P. Mancarella, “Modelling and deploying multi-energy flexibility: The energy lattice framework,” *Advances in Applied Energy*, vol. 2, p. 100030, 2021, doi: 10.1016/j.adapen.2021.100030.

[9] M. Geidl and G. Andersson, “A modeling and optimization approach for multiple energy carrier power flow,” in *2005 IEEE Russia Power Tech*, St. Petersburg, Russia, 2005, pp. 1–7.

[10] T. Krause, G. Andersson, K. Fröhlich, and A. Vaccaro, “Multiple-Energy Carriers: Modeling of Production, Delivery, and Consumption,” *Proc. IEEE*, vol. 99, no. 1, pp. 15–27, 2011, doi: 10.1109/JPROC.2010.2083610.

[11] K. Heussen, S. Koch, A. Ulbig, and G. Andersson, “Energy storage in power system operation: The power nodes modeling framework,” in *2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*, Gothenburg, Sweden, 2010, pp. 1–8.

[12] F. R. Albogamy *et al.,* “Efficient Energy Optimization Day-Ahead Energy Forecasting in Smart Grid Considering Demand Response and Microgrids,” *Sustainability*, vol. 13, no. 20, p. 11429, 2021, doi: 10.3390/su132011429.

[13] M. Brennenstuhl, D. Lust, D. Pietruschka, and D. Schneider, “Demand Side Management Based Power-to-Heat and Power-to-Gas Optimization Strategies for PV and Wind Self-Consumption in a Residential Building Cluster,” *Energies*, vol. 14, no. 20, p. 6712, 2021, doi: 10.3390/en14206712.

[14] M. Kopp, “Strommarktseitige Optimierung des Betriebs einer PEM-Elektrolyseanlage,” Dissertation, Universität Kassel, Kassel, 2018.

[15] M. Majidi, S. Nojavan, and K. Zare, “Multi-Objective Optimization Framework for Electricity and Natural Gas Energy Hubs Under Hydrogen Storage System and Demand Response Program,” in *Operation, Planning, and Analysis of Energy Storage Systems in Smart Energy Hubs*, B. Mohammadi-Ivatloo and F. Jabari, Eds., Cham: Springer International Publishing, 2018, pp. 425–446.

[16] F. Najibi, T. Niknam, and A. Kavousi-Fard, “Optimal stochastic management of renewable MG (micro-grids) considering electro-thermal model of PV (photovoltaic),” *Energy*, vol. 97, pp. 444–459, 2016, doi: 10.1016/j.energy.2015.12.122.

[17] D. Wang *et al.,* “An energy-constrained state priority list model using deferrable electrolyzers as a load management mechanism,” *Applied Energy*, vol. 167, pp. 201–210, 2016, doi: 10.1016/j.apenergy.2015.10.129.

[18] F. Zhu, J. Fu, P. Zhao, and Da Xie, “Robust energy hub optimization with cross‐vector demand response,” *Int Trans Electr Energ Syst*, vol. 30, no. 10, 2020, doi: 10.1002/2050-7038.12559.

[19] W. Li, T. Zhang, and R. Wang, “Energy Management Model of Charging Station Micro-Grid Considering Random Arrival of Electric Vehicles,” in *2018 IEEE International Conference on Energy Internet (ICEI)*, Beijing, China, 2018, pp. 29–34.

[20] G. Lorenzi and C. A. S. Silva, “Comparing demand response and battery storage to optimize self-consumption in PV systems,” *Applied Energy*, vol. 180, pp. 524–535, 2016, doi: 10.1016/j.apenergy.2016.07.103.

[21] Y. Shen, W. Hu, M. Liu, F. Yang, and X. Kong, “Energy storage optimization method for microgrid considering multi-energy coupling demand response,” *Journal of Energy Storage*, vol. 45, p. 103521, 2022, doi: 10.1016/j.est.2021.103521.

[22] S. A. F. Asl, L. Bagherzadeh, S. Pirouzi, M. Norouzi, and M. Lehtonen, “A new two-layer model for energy management in the smart distribution network containing flexi-renewable virtual power plant,” *Electric Power Systems Research*, vol. 194, p. 107085, 2021, doi: 10.1016/j.epsr.2021.107085.

[23] C. Li, X. Jia, Y. Zhou, and X. Li, “A microgrids energy management model based on multi-agent system using adaptive weight and chaotic search particle swarm optimization considering demand response,” *Journal of Cleaner Production*, vol. 262, p. 121247, 2020, doi: 10.1016/j.jclepro.2020.121247.

[24] J. Mikkola and P. D. Lund, “Modeling flexibility and optimal use of existing power plants with large-scale variable renewable power schemes,” *Energy*, vol. 112, pp. 364–375, 2016, doi: 10.1016/j.energy.2016.06.082.

[25] P. Bakhshaei, A. Askarzadeh, and R. Arababadi, “Operation optimization of a grid-connected photovoltaic/pumped hydro storage considering demand response program by an improved crow search algorithm,” *Journal of Energy Storage*, vol. 44, p. 103326, 2021, doi: 10.1016/j.est.2021.103326.

[26] D. Rakipour and H. Barati, “Probabilistic optimization in operation of energy hub with participation of renewable energy resources and demand response,” *Energy*, vol. 173, pp. 384–399, 2019, doi: 10.1016/j.energy.2019.02.021.

[27] A. Rinaldi, M. C. Soini, K. Streicher, M. K. Patel, and D. Parra, “Decarbonising heat with optimal PV and storage investments: A detailed sector coupling modelling framework with flexible heat pump operation,” *Applied Energy*, vol. 282, B, p. 116110, 2021, doi: 10.1016/j.apenergy.2020.116110.

[28] S. Cao and K. Sirén, “Impact of simulation time-resolution on the matching of PV production and household electric demand,” *Applied Energy*, vol. 128, pp. 192–208, 2014, doi: 10.1016/j.apenergy.2014.04.075.

[29] T. Unger and S. Dempe, *Lineare Optimierung*. Wiesbaden: Vieweg+Teubner, 2010.

[30] EPEX SPOT SE, Ed., “IntraDay Auction Prices for Germany,” Accessed: Aug. 23 2022. [Online]. Available: www.epexspot.com

[31] C. Derksen and R. Unland, “The EOM: An Adaptive Energy Option, State and Assessment Model for Open Hybrid Energy Systems,” in *Proceedings of the 2016 Federated Conference on Computer Science and Information Systems*, 2016, pp. 1507–1515.

[32] IBM Corporation, *IBM ILOG CPLEX Optimizer (V22.1.0).* [Online]. Available: https://www.ibm.com /academic/topic/data-science (accessed: Aug. 23 2022).

[33] D. Gusain, M. Cvetkovic, R. Bentvelsen, and P. Palensky, “Technical Assessment of Large Scale PEM Electrolyzers as Flexibility Service Providers,” in *2020 IEEE 29th International Symposium on Industrial Electronics (ISIE)*, Delft, Netherlands, 2020, pp. 1074–1078.