

# EaSimPower – a novel web-based tool for teaching the interplay between technologies and markets in future electricity systems

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**Abstract**—Future electricity markets will rely on a complex interplay between generation and storage technologies, demand-side flexibilities and dynamic price signals. This necessitates a deeper understanding of how techno-economic characteristics of technologies interact in optimized sustainable and efficient power systems. EaSimPower is a web-based educational tool designed to help students analyze these interdependencies, focusing on investment and dispatch modeling. It enables users to explore different energy technologies' complementarity and substitution effects within a single market zone. By modifying parameters such as technology mix, fuel prices, or CO<sub>2</sub> limits, students can observe impacts on system operation and optimization outcomes as well as on market prices. The open data EaSimPower tool integrates real-world datasets for realistic market scenarios. It supports learning across various academic levels, addressing educational barriers in energy economics through interactive, accessible, and practical learning.

**Index Terms**—Open educational resources, Optimization models, Power system economics, Power system modeling

## NOMENCLATURE

### Sets

$\mathcal{T}$	Set of time steps
$\mathcal{J}$	Set of technologies
$\mathcal{J}^{Sto}$	Set of storage technologies
$\mathcal{J}^{Conv}$	Set of conventional technologies
$\mathcal{J}^{PtG}$	Set of power-to-gas technologies
$\mathcal{J}^{Res}$	Set of renewable energy sources
$\mathcal{J}^{HyRes}$	Set of hydro reservoir technologies
$\mathcal{J}^{no\_inv}$	Set of technologies without investment

### Variables

$C^{tot}$	Total costs (objective function)
$C^{op}$	Operational costs
$C^{inv}$	Investment costs

$K_i$	Installed capacity of technology $i$
$y_{t,i}$	Electricity production of technology $i$ at time $t$
$y_{t,i}^{ch}$	Electricity consumption for charging storage of technology $i$ at time $t$
$l_{t,i}$	Storage filling level of technology $i$ at time $t$
$y_{t,i}^{curt}$	Curtailment of renewable energy for technology $i$ at time $t$
$y_{t,i}^{h2}$	Hydrogen production for power-to-gas technology $i$ at time $t$

### Parameters

$D_t$	Energy demand at time $t$
$p^{h2}$	Market price hydrogen
$c_i^{fuel}$	Fuel cost for technology $i$
$c_i^{other}$	Other operational costs for technology $i$
$c_i^{inv}$	Investment cost for technology $i$
$a_i$	Annuity factor for technology $i$
$\eta_i$	Efficiency of technology $i$
$K_{0,i}$	Installed capacity for technology $i$ at $t = 0$
$\chi_i^{CO_2}$	CO <sub>2</sub> emissions factor for technology $i$
$L^{CO_2}$	CO <sub>2</sub> emissions limit
$\gamma_i^{Sto}$	Energy-to-power ratio for storage technology $i$
$s_{t,r,i}$	Renewable supply at time $t$ for renewable technology $i$
$h_{t,i}$	Inflow for hydro reservoir

## I. INTRODUCTION

The transition to future energy systems requires the integration of various technical components and economic mechanisms to enable sustainable, efficient, and cost-effective solutions. In particular, the shift towards decarbonized electricity systems requires a deep understanding of the

interactions between renewable energy sources, storage systems, controllable generation, and dynamic market mechanisms. A comprehensive education in this field is essential to prepare the next generation of professionals for the complexities of modern energy systems.

EaSimPower has been developed to facilitate students' and professionals' access to these complex interdependencies while also highlighting key features of primal and dual solutions to energy system models based on linear optimization. As a web-based learning platform, the tool enables interactive analyses of energy systems, allowing users to adjust parameters such as technology mix, capacities, fuel prices, or CO<sub>2</sub> constraints. The platform provides immediate visual feedback on the impacts of these changes on investment and dispatch decisions as well as resulting prices, fostering an intuitive understanding of optimization models. Moreover, the tool introduces users to the basic concepts of optimization, enabling them to analyze key trade-offs and constraints in energy systems, as represented in optimization results [1] [2] [3].

The key contribution of the tool is bridging the gap between the properties of theoretical models and their practical application by providing an intuitive, interactive platform that lowers the entry barrier for learners. Multiple tools exist for energy system analysis, including e.g. TIMES [4], Calliope [5], PyPSA [6] and EHDO [7], each with strengths but limited suitability for broad educational use. TIMES enables comprehensive energy sector optimization with environmental policies but demands detailed data and technical expertise. Calliope excels in high-resolution spatial and temporal modeling from urban to continental scales, yet its reliance on programming limits accessibility. PyPSA provides versatile tools for power flow analysis and investment optimization, which are suitable for research but challenging for non-experts. Closest to teaching requirements, EHDO supports advanced system modeling for Master's-level courses but is complex and requires extensive user input.

EaSimPower, by contrast, is designed to address these challenges with features like real-time feedback, modularity for different academic levels, and integration of real-world datasets. Combining hands-on application with theoretical grounding, EaSimPower offers an innovative approach to analyzing energy systems' technological, economic, and regulatory aspects. This conference paper introduces the functionalities, highlights its educational value, and discusses the challenges of implementing such tools in academic practice.

## II. INTERACTIVITY AND MULTI-DIMENSIONALITY IN ENERGY EDUCATION

Teaching the long-term development of energy markets as represented energy system models requires connecting various economic and engineering concepts, including short-run and long-run marginal cost, energy and market balances, merit order, peak load pricing, shadow prices of storage and CO<sub>2</sub> constraints, long-term equilibria and capacity investment. [1] These concepts are foundational in energy economics. Being already difficult to grasp separately, the multi-dimensional interactions of the concepts complicate learning. For instance, the merit order illustrates how power plants with the lowest

marginal costs are dispatched first, which relates to short-term market operations yet influences long-term investment decisions. Similarly, peak load pricing highlights the necessity of balancing supply and demand during periods of high consumption, a concept critical for understanding both operational and investment strategies in power systems. Moreover, long-term market equilibrium requires learners to simultaneously consider technical aspects, such as generation technology characteristics, and economic principles, like cost recovery and market pricing mechanisms. These interdependencies are further complicated by policy instruments such as CO<sub>2</sub> pricing or budgeting, fuel cost variations, and capacity expansion constraints. As described in [1] and [2], integrating these dimensions into a coherent framework is essential for a comprehensive understanding of sustainable energy systems.

Traditional teaching methods often rely on static models or simplified case studies, which may be weak to capture these interactions. EaSimPower addresses these limitations by allowing students to explore and manipulate system parameters actively, enabling them to observe the immediate effects of adjustments as key outcomes, such as generation mix, cost, and investments. The tool highlights the underlying mathematics of cost minimization and constraint satisfaction by jointly visualizing outcomes. Instead of theoretical concepts, students interact with dynamic outputs. It thereby builds on other examples of integrating OR methods into higher education using integrative tools. Notably [8] [9] describe a cross-university project, which develops practice-oriented case studies for sustainable energy systems. Students, for instance, analyze the impact of flexibility options on power systems using optimization models [10] or apply portfolio optimization to evaluate optimal power plants based on economic and technical criteria [11]. These examples illustrate how interactive OR tools can effectively convey complex decision-making processes in a practical and accessible way, yet they are less dedicated to the long-term evolution of national energy systems in a decarbonization perspective.

## III. EASIMPOWER

### A. Optimization model for Investment

EaSimPower is a Python-based investment tool that implements a long-term equilibrium model for energy system analysis. The model optimizes capacity investments and operational dispatch under user-defined parameters, providing insights into the interplay between technologies and markets in electricity systems. The model calculates optimal capacity investments making use of demand time series and fluctuating renewable energy input profiles for Germany from 2023 [12]. Technological parameters such as emission factors, efficiencies, investment and fuel costs, and typical lifespans are pre-loaded from [12] [13] [14] [15] but can be customized for greater flexibility – also the time series input may be adjusted. Standard technologies for investments include lignite, fossil gas (OCGT and CCGT), hard coal, oil, PV, wind (onshore and offshore), hydrogen, pumped hydro storage, battery storage, and electrolyzers, with additional options like biomass, run-of-river, hydro reservoirs, and nuclear. The optimization results include total costs, CO<sub>2</sub> price, newly installed capacities, time-

series outputs for generation by technology, curtailment rates, electricity prices, storage operation, and more.

The model is formulated as a linear program including the following objective function and constraints.

$$\text{minimize! } C^{tot} = C^{op} + C^{inv} \quad (1)$$

$$C^{op} = \sum_i y_{t,i} \cdot (c_i^{fuel}/\eta_i + c_i^{other}) \cdot \Delta t - \sum_{i \in \mathcal{J}^{PtG}} y_{t,i}^{h2} \cdot p^{h2} \cdot \Delta t \quad (2)$$

$$C^{inv} = \sum_i a_i \cdot K_i \cdot c_i^{inv} \quad (3)$$

$$s. t. \left( \sum_i y_{t,i} - \sum_{i \in \mathcal{J}^{Sto}} y_{t,i}^{ch} \right) \cdot \Delta t = D_t \cdot \Delta t, \quad \forall t \quad (4)$$

$$y_{t,i} - K_i \leq K_{0,i}, \quad \forall i \in \mathcal{J} \quad (5)$$

$$y_{t,i} + y_{t,i}^{ch} - K_i \leq K_{0,i}, \quad \forall i \in \mathcal{J}^{Sto} \quad (6)$$

$$y_{t,i}^{ch} - K_i \leq K_{0,i}, \quad \forall i \in \mathcal{J}^{PtG} \quad (7)$$

$$y_{t,i}^{ch} \cdot \eta_i = y_{t,i}^{h2}, \quad \forall i \in \mathcal{J}^{PtG} \quad (8)$$

$$y_{t,i} + y_{t,i}^{curt} = s_{t,r,i} \cdot (K_{0,i} + K_i), \quad \forall i \in \mathcal{J}^{Res} \quad (9)$$

$$l_{t,i} \leq (K_{0,i} + K_i) \cdot \gamma_i^{Sto}, \quad \forall i \in \mathcal{J}^{Sto} \quad (10)$$

$$l_{t+1,i} = l_{t,i} - (y_{t,i}/\eta_i - y_{t,i}^{ch} \eta_i) \cdot \Delta t, \quad \forall i \in \mathcal{J}^{Sto} \quad (11)$$

$$l_{t+1,i} = l_{t,i} + (h_{t,i} - y_{t,i}) \cdot \Delta t, \quad \forall i \in \mathcal{J}^{HyRes} \quad (12)$$

$$\sum_t \sum_i y_{t,i}/\eta_i \cdot \chi_i^{CO2} \cdot \Delta t \leq L^{CO2} \quad (13)$$

The objective function (1) minimizes total costs, with the first summand consisting of operational costs minus revenue for produced hydrogen (2) and the second summand representing the annualized investment costs (3). The model is constrained by a load-serving constraint (4) and a maximum capacity constraint (5). Further constraints ensure that capacity investments are restricted to the preselected technologies and that Power-to-Gas (PtG) is prevented from producing power. The maximum storage charging and discharging constraint is

formulated in (6), and the maximum electrolyzer capacity in (7). The PtG hydrogen production (8) is determined by the efficiency and the renewables infeed (9) by capacity factors. Filling level restrictions are formulated for storage power plants in (10) and (11) and for hydro reservoirs in (12). CO<sub>2</sub> emissions depend on the technologies' efficiencies and CO<sub>2</sub> intensities and are limited within the model (13).

## B. Web-based implementation and handling

EaSimPower is implemented as a browser-based tool, leveraging a client-server architecture to ensure seamless user experience and computational efficiency. Users select their desired parameters through a graphical user interface (GUI), after which the model optimizes on a server. This server-side computation ensures robust performance even for complex scenarios involving high-resolution time steps and multiple technologies. The tool is entirely Python-based, using linopy as the modeling language and the HiGHS solver for optimization. Unlike proprietary solutions, e.g. GAMS, EaSimPower adopts open-source libraries, making the tool more accessible and cost-effective. The GUI is developed with Streamlit and hosted on Huggingface, providing an intuitive and visually engaging platform [16].

The interface is structured into three main tabs: the first tab contains the model with its inputs and outputs, the second shows detailed documentation of all sets, variables, parameters, and the objective function with constraints, and the third provides background information about the research group, including its teaching and research focus. A language selection field in a fixed sidebar ensures usability for users with different backgrounds. User interactivity is central to EaSimPower, enabling real-time parameter exploration and immediate evaluation of their effects on energy system outcomes. The intuitive GUI (Figure 1) allows users to modify parameters such as CO<sub>2</sub> limits, hydrogen prices, fossil fuel prices, and investment options for various technologies. Users can set modeling resolutions (e.g., hourly or aggregated time steps) and upload customized datasets for specific study cases. The tool supports both predefined configurations with standard parameters and fully customizable scenarios, making it adaptable to a wide range of use cases. As the tool aims to provide an introductory approach to energy system analysis,

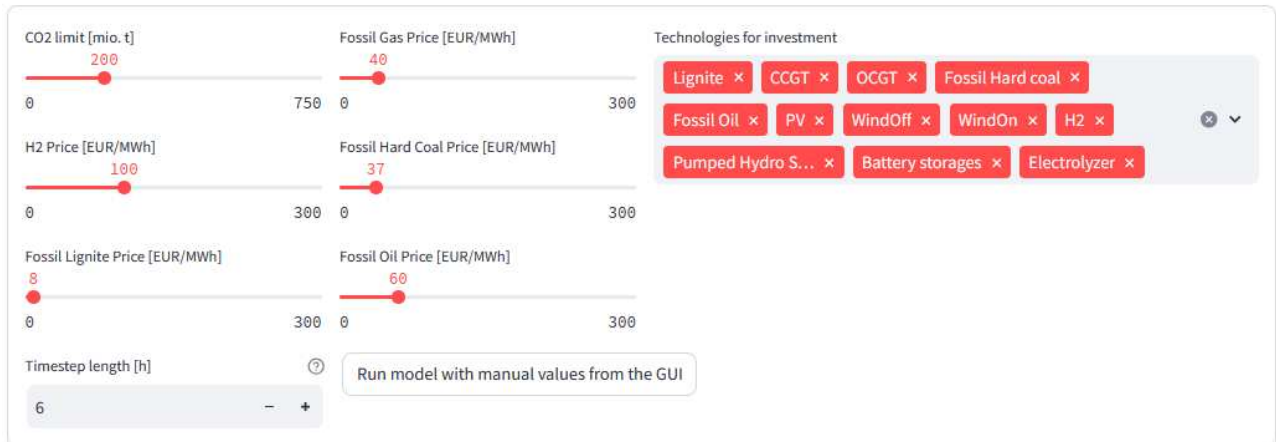


Figure 1: GUI for manual settings

EaSimPower can be tailored to different levels of undergraduate expertise, offering a simplified undergraduate and a more advanced graduate version. The Bachelor's version focuses on the transition from simple examples of graphically solved market equilibria to dynamic systems based on time series. This illustrates the power plant dispatch and the appearance of load and price peaks depending on different boundary conditions. However, it includes a reduced number of decision variables and options for energy conversion. The Master's version allows for a more detailed exploration of modern energy systems and their interdependencies, including additional complexities such as different storage technologies and sector coupling options.

Outputs are provided in visually engaging formats, including bar charts for new capacities, pie charts for the generation mix, time series of technology-specific generation, curtailment levels, electricity prices, residual load duration, and price duration curves. Additionally, all results can be downloaded as Excel files for further analysis. Generally, the interactive, user-focused design fosters learners and professionals to intuitively grasp complex system interactions and refine their scenarios based on dynamic feedback.

C. Exemplary case studies

The following case studies illustrate how EaSimPower enables users to explore key aspects of energy system modeling, including the impact of CO<sub>2</sub> budgets, price drivers and temporal resolution. These examples demonstrate the tool's ability to reveal complex interdependencies and support decision-making in energy system planning.

1) Effects of reduced emission budget

Solving the model with the described standard setting (cf. Figure 1) leads to approximately 90 GW of installed wind and PV capacity. Yet nearly one-third of electricity generation still stems from lignite plants, with a significant share also being supplied by gas-fired units. The corresponding residual load duration curve, with stacked electricity production, is depicted in the left part of Figure 3.

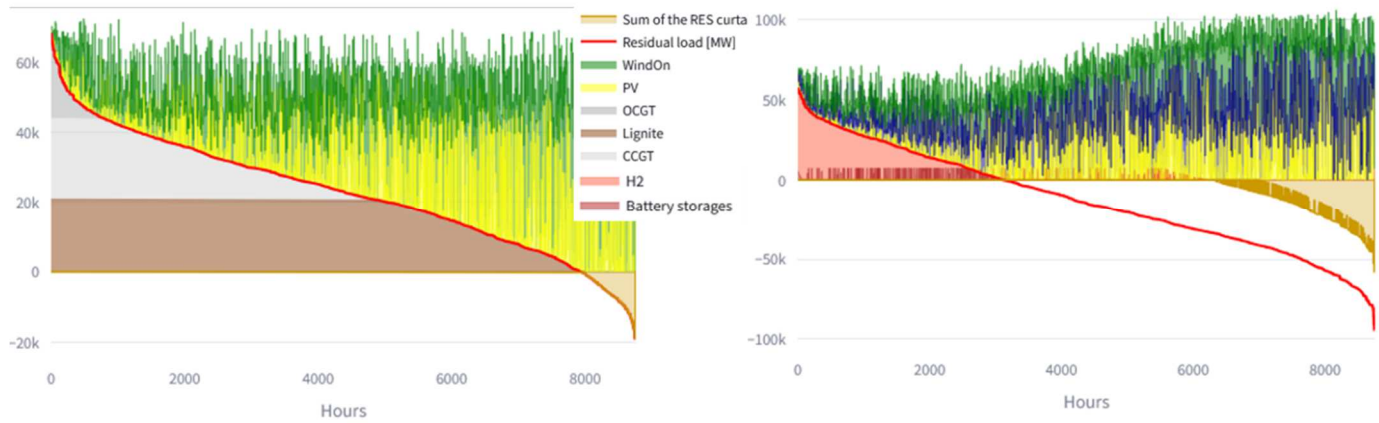


Figure 3: Load duration curve in standard settings with emission limit of 200 Mt (left) and zero (right)



Figure 2: Electricity prices in EUR/MWh, emission limit 50 Mt

Reducing the emission limit from 200 million tons to zero, fossil technologies are excluded from the energy mix. In this zero-emission scenario, there is a strong increase in investments in renewable energy technologies, along with the deployment of hydrogen power plants, storage capacities, and electrolyzers. This transition results in a markedly different residual load duration curve, which falls into negative after less hours of the year. Storage systems and electrolyzers are crucial in managing this shift, creating a “gap” between negative residual load and the total curtailment of renewable energy generation, see the right part of Figure 3. The total system costs rise from €30.19 bn. in the standard scenario to €50.86 bn. in the zero-emission scenario, highlighting the additional investments required to achieve a fully decarbonized energy system. These changes underline the economic and operational challenges of transitioning to a zero-emission power sector.

2) Price peaks in long-term deterministic models

Prices in equilibrium are derived based on long-term marginal costs, containing variable costs and annualized investment costs. Marginal costs above variable costs only occur in hours when capacity is scarce and additional generation is needed to satisfy the demand. In a deterministic model without uncertainty, there is one period of maximal residual demand where marginal costs are extremely high (cf. Figure 2) [1]. Using the provided inputs and outputs, students are now equipped to exemplify that every power plant (type)

recovers its full costs in equilibrium. OCGT, with the lowest investment costs but high variable costs, emerges as the peak technology. Table 1 illustrates how the cost recovery can be computed.

On the cost side, annualized capital costs per unit are determined using the data inputs and an annuity factor. This is multiplied by the optimized capacity for the respective technology. For the revenue side, students must extract the production and the price during the peak period from the output file. Variable costs are calculated based on fuel costs, efficiency, emission factor (all model inputs), and the CO<sub>2</sub> price (a model output). The difference between the peak price and the variable costs, multiplied by the production output, yields the revenue. Multiplying this by the modeling timestep length equals the annual capital costs.

This exercise illustrates the economic concept of equilibrium prices and provides practical insights into the details of cost recovery for different power plant technologies in the context of energy system modeling.

### 3) Increase of the temporal granularity

Students may also gain more methodical insights by varying the timestep length in optimization models. Taking the standard setting plus a CO<sub>2</sub> budget of 50 million tons as starting point, students may reduce the timestep length from, e.g., 6 to 2 hours. This induces changes in the results: storage technologies become operational, and total system costs increase.

Table 1: Full cost recovery of peak technology (standard setting with CO<sub>2</sub> limit of 50 Mt)

Description	Value	Source/Comment
<b>Investment costs</b>		
Investment costs p.u.	575 €/kW	Input file
Lifetime	30 years	Input file
Annuity factor (AF)	0.08059	$\frac{0.07 \cdot (1.07)^{40}}{(1.07)^{40} - 1}$
Annual capital costs p.u.	46,337 €/MW/a	AF · 1000 · investment costs
Capacity	21,108 MW	Output file
Annual capital costs	978,085,238 €	Capacity · ann. inv. costs p.u.
<b>Contribution margin</b>		
Production	21,108.32 MWh	Join production and prices in output file and sort (desc). Peak technology only recovers its costs during peak price period
Maximum Price	7,908.20 €/MWh	
Variable costs	185.33 €/MWh	Use fuel costs, efficiency, emission factor (inputs) and CO <sub>2</sub> price (output)
Difference	7,722.86 €	Price minus variable costs
Revenue	163,016,691 €	Production · difference
Total revenue	978,100,147 €	Revenue · Δt

The student can then be invited to identify the relevant causes: First, shorter timesteps reveal demand and supply fluctuations that are smoothed out in longer intervals, making intra-day variability more visible. Second, this variability induces more versatile prices creating economic incentives for storage technologies to operate by charging during low-price periods and discharging during high-price periods. Third, variations within short timescales are obscured when using coarser temporal resolutions, while they contribute to making storage profitable in fine temporal granularity.

## IV. DISCUSSION

EaSimPower is designed to strike the balance between simple didactic examples and a fully realistic model. It could be expanded to enhance its scope and level of detail. A finer spatial resolution could be implemented to model multiple regions, enabling the analysis of cross-regional interactions and a representation of transmission constraints. Incorporating power flow modeling would further refine the tool by accounting for electrical load flow constraints, allowing a detailed understanding of system operation and bottlenecks. Differentiating technology classes by parameters such as costs and efficiencies would improve the granularity of the model and make it more reflective of real-world heterogeneity. Additionally, integrating stochastic scenarios across multiple years could provide a more robust framework for long-term energy system planning. Yet such extensions might hamper the understanding of more basic principles and students will grasp the implications of these advanced issues best if they learn based on their own implementation.

The tool obviously possesses limitations inherent to its design. It assumes perfect foresight, disregarding demand, fuel prices, or renewable generation uncertainties. The assumption of perfect coordination among all market participants oversimplifies real-world market dynamics and decision-making processes. The model also features a limited representation of technological heterogeneity and does not account for investor behavior heterogeneity. The focus is on a greenfield approach, disregarding existing infrastructure and legacy systems at least in the standard setting. Probably most importantly, the simplified treatment of market and policy interactions limits the model benefits when it comes to investigate and assess complex regulatory and economic scenarios.

## V. CONCLUSION

EaSimPower addresses the gap between theoretical models and practical applications in energy system education by offering an intuitive, web-based tool. Its multi-dimensional yet hands-on approach enables users to experiment with complex systems in a controlled environment, fostering a holistic understanding of long-term system perspectives. By lowering technical barriers and providing real-time feedback, EaSimPower equips learners with the skills needed to navigate the complexities of future electricity markets. This contribution demonstrates the potential of interactive tools to bridge the divide between research and education, making energy system modeling more accessible and impactful.

## REFERENCES

- [1] C. Weber, D. Möst and W. Fichtner, *Economics of power systems*, Essen: Springer Texts in Business and Economics, 2022.
- [2] M. Tanaka, A. J. Conejo and A. S. Siddiqui, *Economics of power systems*, Tokyo: International Series in Operations Research & Management Science, 2022.
- [3] D. Kirschen and G. Strbac, *Fundamentals of Power System Economics*, John Wiley & Sons, Ltd, 2004.
- [4] R. Loulou, U. Remne, A. Kanudia, A. Lehtila and G. Goldstein, "Documentation for the TIMES Model - PART I 1–78," 2005.
- [5] S. Pfenninger and B. Pickering, "Calliope: a multi-scale energy systems modelling framework," *Journal of Open Source Software*, vol. 3, no. 29, 2018.
- [6] T. Brown and J. S. D. Hörsch, "PyPSA: Python for Power System Analysis," *Journal of Open Research Software*, vol. 6, no. 1, 2018.
- [7] M. Wirtz, P. Remmen and D. Müller, "EHDO: A free and open-source webtool for designing and optimizing multi-energy systems based on MILP," *Computer Applications in Enigneering Education*, vol. 29, no. 5, pp. 983-993, 2020.
- [8] J. Geldermann and I. Wiemer, "Operations Research (OR) for Sustainability: Energy, Mobility, Industry," ORCA.nrw et al., 2024.
- [9] S. Pathe and V. Bertsch, "Teaching Operations Research for Energy System Research: Challenges and Real-Life Examples," in *International Conference on Operations Research - OR 2023*, Hamburg, 2023.
- [10] L. Plaga and V. Bertsch, "Case Study Novel flexibility options in the German electricity grid" CC-BY-SA (4.0), 2024. [Online]. Available: [moodle.ruhr-uni-bochum.de/course/view.php?id=62498](https://moodle.ruhr-uni-bochum.de/course/view.php?id=62498). [Accessed 31 1 2025].
- [11] R. Madlener, B. Glensk and Q. Yu, "Case study Selection of optimal power plant generation mix" CC-BY-SA (4.0), [Online]. Available: [moodle.ruhr-uni-bochum.de/course/view.php?id=62713](https://moodle.ruhr-uni-bochum.de/course/view.php?id=62713). [Accessed 31 1 2025].
- [12] ENTSO-E, "Transparency Platform," European Network of Transmission System Operators for Electricity, [Online]. Available: [transparency.entsoe.eu](https://transparency.entsoe.eu). [Accessed 23 12 2024].
- [13] C. Kost, P. Müller, J. S. Schweiger, V. Fluri and J. Thomsen, "Levelized Cost of Electricity – Renewable Energy Technologies," Freiburg, 2024.
- [14] Agora Industry; Agora Energiewende, "EU map of hydrogen production costs," Berlin, 2024.
- [15] EWI, "EWI Merit-Order Tool 2023 – Dokumentation," Köln, 2024.
- [16] Y. Pflugfelder, H. Kramer, C. Klüter, J. Radek, C. Jahns and C. Weber, "EaSimPower," Chair of Management Science and Energy Economics, House of Energy Markets and Finance, University of Duisburg-Essen, [Online]. Available: <https://huggingface.co/spaces/EWL/EaSimPower>. [Accessed 5 2 2025].