Dispatch Optimization of the Electricity and Heat of the Smart-Energy-Transform-Unit: A Residential Case Study

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***Abstract* – With the integration of renewable energy production into grids, hydrogen storage is an effective solution for coping with the fluctuating nature of the resources and reliably providing energy demands. Metal hydride storage is seen as a key technology due to its low operating pressure and temperatures near ambient, while it has a significant volumetric capacity (for room temperature hydrides: 50-110 kg/m^3) compared to pressurized (40 kg/m^3 under 700 bar and room temperature) or even liquified hydrogen (70 kg/m^3 at – 253 ºC and 1 bar). One potential application with metal hydride storage lies in the flexibilization of residential energy demand. Excess photovoltaic generation from a house can power an electrolyser to produce hydrogen, which is then stored in the metal hydride storage. When power and heat are needed in the building, the hydrogen is released into a fuel cell. This case study investigates the dispatch optimization of a metal hydride storage system within a residential household energy system. The interaction of the electrolyser, metal hydride storage, and fuel cell, all components of a container solution called Smart Energy Transform Unit, was studied during summer and winter. Results show that in an exemplary period in winter, from 21 December 2021 to 28 December 2021, the total electricity demand is 98% covered by supply from the grid due to the low photovoltaic generation, which also yields a low hydrogen production; the total heat demand is 90% covered by the heat pump and the thermal storage as a buffer. During an exemplary period in summer, from 20 June 2021 to 27 June 2021, the system is self-sufficient, as hydrogen was stored during the day due to the high yield of photovoltaic generation, and hydrogen is used in a fuel cell at night to provide energy demands. In addition, heat pump operation during summer is small due to the heat provided by the electrolyser, the fuel cell, and the thermal buffer storage. The PV system, together with the Smart Energy Transform Unit, covers 99% of the total electric demand during this period in summer, while for the total heat demand, a coverage of 85% is observed, and the heat pump covers 15%.**

Keywords – Sector integration, metal hydride storage, energy system modelling, optimization

NOMENCLATURE

Digi-HyPro	Digitalized Hydrogen Process Chain for the Energy Transition
MH	Metal hydride
PV	Photovoltaic
SET-Unit	Smart-Energy-Transform-Unit

I. Introduction

Hydrogen storage plays a key role in balancing fluctuations between energy production from renewable sources [1] and energy demands. It can provide reliable energy storage and a continuous power supply without the dependency on fossil fuels [2]. However, there are challenges associated with the storage of hydrogen. As hydrogen has a very low density of 0,089 kg/m^3 at a pressure of 1 atm and a temperature of 0 °C (Standard Test Conditions) [1], storing large amounts under these conditions is challenging. High pressures of 350 and 700 bar are usually used for compressed hydrogen storage, which is then employed in mobility applications [3]. It can also be stored in cryogenic liquid form which requires a temperature of – 253 °C, but around one-third of the hydrogen energy content is required for liquefaction [4]. An alternative for hydrogen storage is based on chemically bonding the hydrogen to a powdered metal, forming a metal hydride (MH). In the MH, hydrogen absorption is an exothermic reaction, i.e. it releases heat. The desorption process, hydrogen discharge, is endothermic, i.e. it requires heat. This type of storage in MHs can operate at much lower pressures (e.g. 10 bar), and the volumetric capacity in terms of hydrogen atoms per cubic meter of material can be four times higher than compressed hydrogen and twice that for cryogenic hydrogen [5].

In the context of the project Digi-HyPro (Digitalized Hydrogen Process Chain for the Energy Transition), the goal is to develop a container solution where hydrogen is stored in a MH tank, and released when needed to supply energy demands [6]. This container solution, called Smart-Energy-Transform-Unit (SET-Unit), allows a flexible transformation of energy where hydrogen is the main energy carrier, thereby allowing the coupling of electricity, gas, heat, and mobility grid. One potential application of the SET-Unit is to provide electricity and heat for a household in form of a backup power generation unit or to increase self-consumption of renewable energies.

In this paper, the dispatch optimization of the SET-Unit for a residential energy system will be presented. This application is depicted in Figure 1 for a single-family household. Excess electricity from the solar PV system can drive the electrolyser for the production of hydrogen, which can be stored in the MH-storage. The electricity demand can be supplied by providing the hydrogen to a fuel cell. Any electricity needed can also be supplied from the grid at a defined cost. Also, excess electricity from the PV system can be sold to the grid at a certain feed-in tariff. For heat supply and heat storage, a heat pump and a thermal storage are present, respectively. In addition, heat is produced during operation of the electrolyser, the fuel cell, and during the flow of hydrogen into the MH-storage (absorption process). On the other hand, heat is consumed during the release of hydrogen from the MH-storage (desorption process) and in the household.

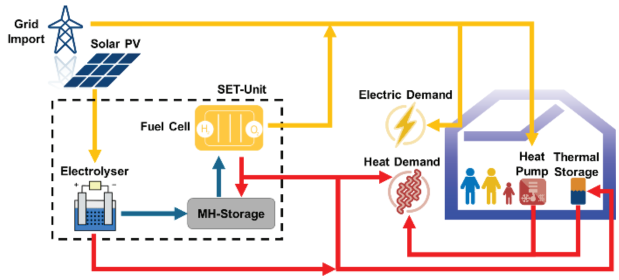

FIGURE 1. COMPONENTS OF THE SMART ENERGY TRANSFORM (SET)-UNIT IN A RESIDENTIAL APPLICATION. THE COLOURED ARROWS INDICATE ELECTRICITY (YELLOW), HYDROGEN (BLUE), AND HEAT (RED) FLOW

As there are multiple components and multiple flows (electricity, heat, and hydrogen) in the residential energy system shown in Figure 1, there are multiple paths to operate the system with the aim to supply the heat and electricity demands. Considering the boundary conditions of the residential energy system, there is a need to find an optimal dispatch strategy with the minimum operating cost. So, the main research question of this case study is: what is the optimal dispatch strategy of the SET-Unit to provide electricity and heat demands for a residential household during seven days in an exemplary winter and summer period?

The subsequent sections of this investigation are structured as follows. Method (Section II) defines all data required and steps taken to model the SET-Unit for a residential energy system. Results and Discussion (Section III) presents the main findings of the optimized dispatch strategy during summer and winter. Conclusion (Section IV) provides a summary of the relevant findings of this investigation, as well as future research topics.

II. METHOD

An energy system model that considers the SET-Unit components interacting with the household was first built. For this purpose, the python package oemof.solph from the Open Energy Modelling Framework (oemof) was employed [7]. oemof is an open-source framework that is used to model energy systems. It is used to perform dispatch optimization, i.e. to supply the energy demands at the minimum cost by optimizing the use of the resources. It has been used in multiple investigations, including the modelling of the Italian energy system [8], a fuel cell electric vehicle providing electricity and heat to a neighbourhood [9], and designing a district heating system in a sub-urban region in northern Germany [10].

The energy system model in oemof.solph can be seen in Figure 2. Five main classes were employed: bus, sink, source, transformer, and generic storage. Sources were used to import electricity from the grid and from the PV system. Sinks were employed to supply the electricity and heat demands, and if there was excess electricity from PV. This excess PV generation can be sent to the excess electricity sink at a defined feed-in tariff for PV. An electricity bus, heat bus, and hydrogen buses had been implemented as well. Transformers, which convert one type of energy to another, were employed for the electrolyser, MH absorption process (storing hydrogen and releasing heat), MH desorption process (releasing hydrogen and need of heat), fuel cell, and heat pump. The MH and thermal storage were modelled using the generic storage class.

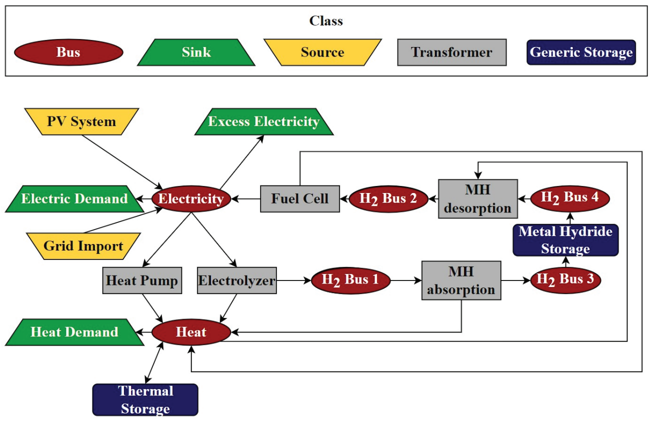

FIGURE 2. ENERGY SYSTEM MODEL IN OEMOF CONSIDERING THE SET-UNIT

The following values were used in the model. They are designed to be as close as possible to the hardware used to build the SET-Unit in the project Digi-HyPro.

A. *Electrolyser and Fuel Cell*

It was assumed that the electrolyser has 9,6 kW of nominal power consumption, 62% efficiency, and 30% of waste heat utilization capacity. For the fuel cell, 5 kW of installed electrical capacity, 40% efficiency, and 60% waste heat utilization capacity were assumed. No operating costs for the electrolyser and the fuel cell were considered.

B. *MH Storage*

A total of 2 kg hydrogen capacity in the MH storage was modelled. Additional details on the material used in the project Digi-HyPro can be found in [6]. The amount of heat required during absorption was assumed to be the same as that produced during desorption, with a value of 0,445 kWh of heat per kWh of hydrogen. The initial state of charge was assumed to be zero.

C. *Thermal Storage*

Stratified thermal storage was modelled with a nominal storage capacity of 35 kWh (3 m^3 of water). A hot water temperature of 60 °C and a cold-water temperature of 30 °C was assumed. The initial state of charge was assumed to be 100%.

D. *Heat Pump*

A heat pump with a heat production capacity of 4 kW was considered. The Coefficient of Performance (COP) was assumed to be 3.

E. *Costs and Incentives*

An electricity cost of 0,4627 EUR/kWh was assumed for obtaining electricity from the grid. On the other hand, excess PV generation can be sold as an incentive with a feed-in tariff of 0,086 EUR/kWh.

F. *PV Supply and Household Demands*

The PV system had a nominal capacity of 10 kW_{peak}, with an hourly profile extracted from the Photovoltaic Geographical Information System (PVGIS) [11]. A typical German single-family house of three members was assumed with an annual heat demand of 21,4 MWh and an electricity demand of 5 MWh [12]. From these demands, hourly load profiles were generated using the demandlib package from oemof [13].

The previous boundary conditions were applied to the energy system model. Minimum operating loads for the electrolyser, fuel cell and heat pump were excluded. A total of seven days during winter and seven days during summer were analysed, with an hourly time resolution. The simulation objective is to find an optimal dispatch strategy that satisfies the energy demands of the household with the minimum operating cost.

III. RESULTS AND DISCUSSION

A. *Winter Dispatch*

The electricity and heat dispatch of the residential energy system during seven days of winter can be seen in Figure 3 and Figure 4, respectively, ranging from 21 December 2021 to 28 December 2021. Figure 3 shows the electric power in the y-axis (left). A convention was defined so that an electric power value greater than zero represents consumed electricity, which is true for the electric demand (cyan), heat pump (blue), electrolyser (red), and excess electricity (green). Electric power provided by the PV system (orange), grid import (purple), and fuel cell (brown) is considered electricity produced and it has a negative value. The state of charge of the MH storage can be seen in grey, ranging from zero to one, in the secondary y-axis (right).

In Figure 4 the y-axis (left) depicts the heat power. Similar to the power convention, the heat convention was defined so that if the heat power value is greater than zero is considered heat consumed which is the case for the heat demand (magenta) and desorption process (pink). A negative heat power value is considered heat supply which applies for the heat pump (olive), fuel cell (brown), electrolyser (red), and absorption process (blue). The secondary y-axis (right) depicts the state of charge of the thermal storage in grey and it is scaling from zero to one.

In Figure 3 it can be seen that on 22 December, PV generation reached 4 kW, which was sufficient to operate the electrolyser, and hydrogen was stored in the MH storage. Again, on 26 December, a significant PV generation reaching 5 kW enable the electrolyser to produce hydrogen, which then increased the state of charge of the MH storage to 0,15. On 27 December, the strategy was to release all the hydrogen stored into the fuel cell for electricity production. Electricity from the grid was mainly needed during the seven days due to the low PV generation. Because of that, there was also no excess PV supply to the grid. 98% of the total electricity demand in the seven days in winter was covered by electricity from the grid.

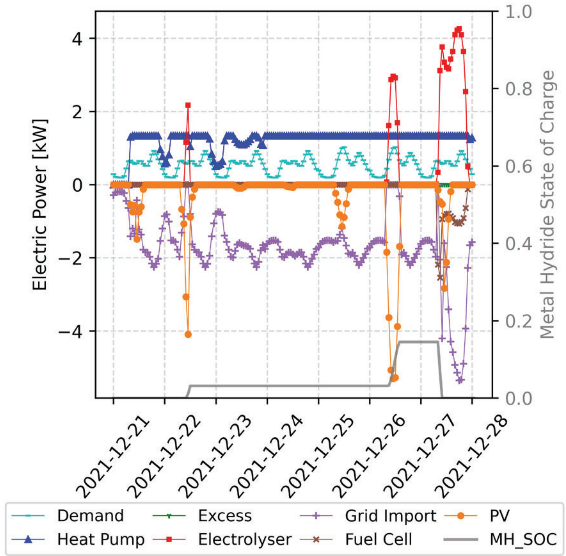

FIGURE 3. ELECTRICITY DISPATCH DURING SEVEN DAYS IN WINTER

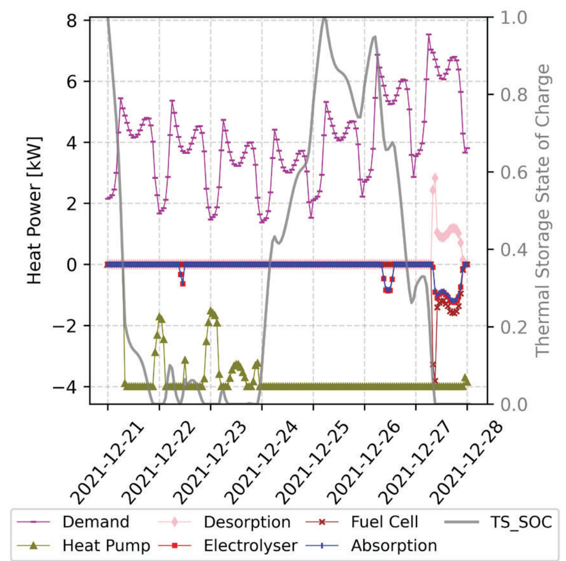

FIGURE 4. HEAT DISPATCH DURING SEVEN DAYS IN WINTER

In terms of heat, shown in Figure 4, the energy stored in the thermal storage was enough to cover the heat demand without operating the heat pump for the first twelve hours; after that, the heat pump started operating. The heat pump operated most of the given period at nominal capacity (4 kW) to provide the heat demand. As the heat demand was seen to increase after 25 December and reaching a maximum of almost

8 kW between 27 December and 28 December, the resulting strategy was to operate the heat pump at nominal capacity to supply the heat demand as well as to charge the thermal storage before the maximum peak. With this strategy, both the thermal storage and heat pump cope with the expected increase in demand. The thermal storage was fully charged between 25 December and 26 December and reached a state of charge of 90% (0,9) between 26 December and 27 December. Afterwards, it supplied part of the heat demand until it was fully discharged between 27 December and 28 December. During this period, as the heat pump capacity was insufficient to provide the heat, the resulting strategy was to provide additional heat by operating the MH's electrolyser, fuel cell, and absorption process. In addition, the desorption process also required additional heat. This simultaneous operation of the electrical devices to provide heat is why in Figure 3 during this period there is electricity grid import to satisfy the electrolyser consumption, and on the other hand, electricity production from the fuel cell while consuming hydrogen. In reality, it might not be feasible to operate the electrolyser and fuel cell at the same time, as well as simultaneously charging and discharging the MH storage. However, with the given boundary conditions, there was no other way for meeting the household heat demand during this simulation for the optimizer. During these seven days in winter, the heat pump and thermal storage covered 90% of the total heat demand.

B. *Summer Dispatch*

Figure 5 and Figure 6 show the heat and electricity dispatch, respectively, during summer from 20 June 2021 to 27 June 2021. The aforementioned conventions regarding the positive and negative values of the electricity and heat flows are also applied.

A much higher PV generation compared to winter results in a longer operational time of the electrolyser, which can be seen in Figure 5. In addition, some of the excess PV generation (green) was sold to the grid. On 20 June it can be observed that part of the PV generation supplies the electrolyser, which produces hydrogen, and it is absorbed in the MH storage (increase in the state of charge). The remaining PV generation supplies the electric demand and is additionally sold as excess to the grid. At night, when there is no PV generation, the fuel cell supplies the electric demand by consuming the hydrogen coming from the MH desorption process. This operational pattern during day and night of the SET-Unit is also seen for the rest of the days. This results in an oscillating behaviour of the state of charge of the MH storage, i.e. absorption of hydrogen during day and desorption of hydrogen during night. To add, there was a small grid import and heat pump consumption, which makes the SET-Unit practically self-sufficient during summer. 99% of the total electric demand during these seven days in summer was covered by the PV system and the SET-Unit. Because the optimization period for this model is only seven days, no hydrogen is stored for longer self-sufficiency (e.g. winter). Therefore, the electrolyser was not operated at full load as seen in Figure 5. As a consequence, the optimization strategy was to sell excess PV generation to the grid with the aim of reducing operating costs. To see seasonal energy shifting, longer time periods have to be simulated.

The heat dispatch in summer shown in Figure 6 depicts small operation times of the heat pump during the seven days. The reason is due to the low heat demand together with heat provided by other components. When the electrolyser was operated during the day, the heat from it and the heat from the absorption process covered the heat demand and some heat increased the state of charge of the thermal storage. During the fuel cell operation at night, the desorption heat required was covered by the heat produced from the fuel cell, while the thermal storage covered the heat demand. As in the electric dispatch curve in Figure 5, the SET-Unit showed a self-sufficient behaviour to cover the heat demand. 85% of the total heat demand was provided by the heat from the SET-Unit and the thermal storage, and the heat pump supplied 15%.

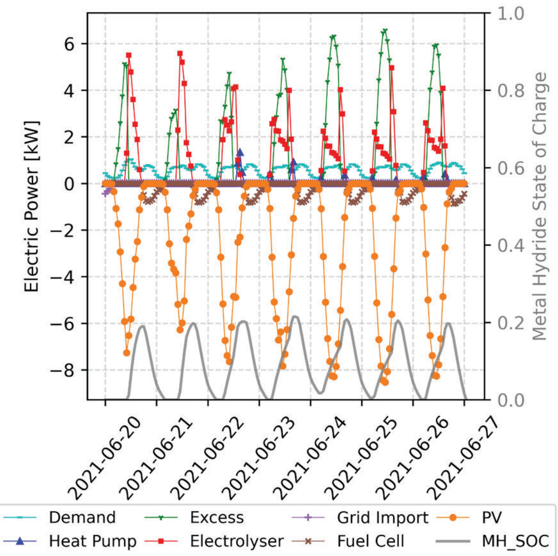

FIGURE 5. ELECTRICITY DISPATCH DURING SEVEN DAYS IN SUMMER

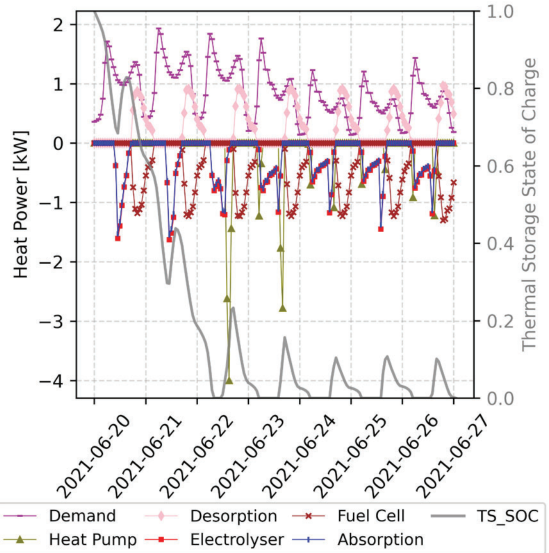

FIGURE 6. HEAT DISPATCH DURING SEVEN DAYS IN SUMMER

IV. CONCLUSION

This case study aimed to investigate the integration of the Smart-Energy-Transform-Unit (SET-Unit) of the Digi-HyPro project into a residential household. A heat pump and thermal storage are considered to be provided in a single-family house. In this application, surplus electricity from a residential PV system powers an electrolyser, and the hydrogen produced is stored in a metal hydride storage. Then, hydrogen can be converted to electrical power by a fuel cell when power is needed.

The coverage of the residential electricity and heat demands using the SET-Unit and the interaction of the different components in summer and winter are also investigated. The main research question was: what is the optimal dispatch strategy of the SET-Unit to provide electricity and heat demands for a residential household for seven days at a stretch in winter and summer?

Results show that hydrogen production (and storage) are low during winter due to the low generation of PV. Running the electrolyser and storing hydrogen is feasible when the PV generation is larger than 4 kW. Electricity from the grid is also needed during the seven days of winter to supply the electric demand. Regarding the heat demand, the heat pump is seen to operate at full load most of the time, and as the heat demand towards the end of the seven days is expected to increase, the strategy was to operate the heat pump at full load towards the end and charge the thermal storage as much as possible. On the seventh day, as the heat pump and thermal storage capacity were insufficient to cover the high heat demand, the strategy was to obtain heat from the electrolyser and fuel cell by operating these components.

Furthermore, the results show that the SET-Unit serves as a daily buffer for the energy system during summer. During the day, hydrogen is stored due to high PV generation, and at night, hydrogen is released for electricity production. In addition, the heat produced in the electrolyser and fuel cell, and heat stored in the thermal storage is enough to cope with most of the heat demand. This results in a small heat pump operational time and small electric grid import. The residential energy system including the SET-Unit is shown to be practically self-sufficient during summer.

The framework of oemof for modelling and optimizing an energy system with the SET-Unit has the potential to aid in the investigation of further research topics. One topic involves seasonal shifting, where energy is stored in summer and in winter it can be used. A similar shift was seen in this investigation when during summer the metal hydride storage was charged during the day and discharged during night, but this shift was rather intraday. Therefore, investigating a seasonal period will involve finding an optimal size of the metal hydride storage and performing a full year dispatch optimization. Another topic is the price competitiveness of the SET-Unit relative to other components and systems. For this latter topic, capital expenditures and operating expenditures of different alternatives to metal hydride storage will be evaluated.

In addition, this case study excluded to model the detailed thermodynamics that are taking place in every component and the resultant temperature profiles. These considerations are included in current investigations of the Digi-HyPro project, specifically in the building of digital twins for system simulation.

Acknowledgement

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References

[1] T. Amirthan and M. Perera, "The role of storage systems in hydrogen economy: A review," *Journal of Natural Gas Science and Engineering*, vol. 108, p. 104843, 2022, doi: 10.1016/j.jngse.2022.104843.

[2] C. Tarhan and M. A. Çil, "A study on hydrogen, the clean energy of the future: Hydrogen storage methods," *Journal of Energy Storage*, vol. 40, p. 102676, 2021, doi: 10.1016/j.est.2021.102676.

[3] E. Rivard, M. Trudeau, and K. Zaghib, "Hydrogen Storage for Mobility: A Review," *Materials (Basel, Switzerland)*, vol. 12, no. 12, 2019, doi: 10.3390/ma12121973.

[4] A. T. Wijayanta, T. Oda, C. W. Purnomo, T. Kashiwagi, and M. Aziz, "Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review," *International Journal of Hydrogen Energy*, vol. 44, no. 29, pp. 15026–15044, 2019, doi: 10.1016/j.ijhydene.2019.04.112.

[5] Fraunhofer IFAM Dresden, "Applications of Metal Hydrides: Comparison of volumetric hydrogen storage densities," 2024. Accessed: Apr. 3 2024. [Online]. Available: https://www.ifam.fraunhofer.de/en/Aboutus/Locations/Dresden/HydrogenTechnology/hydrides/applications-of-metal-hydrides.html

[6] J. Puszkiel *et al.,* "Hydrogen in stationary applications: Coupling the electricity, gas and mobility sectors (Digi-HyPro)," 2022.

[7] U. Krien, P. Schönfeldt, J. Launer, S. Hilpert, C. Kaldemeyer, and G. Pleßmann, "oemof.solph—A model generator for linear and mixed-integer linear optimisation of energy systems," *Software Impacts*, vol. 6, p. 100028, 2020, doi: 10.1016/j.simpa.2020.100028.

[8] M. G. Prina *et al.,* "Multi-objective investment optimization for energy system models in high temporal and spatial resolution," *Applied Energy*, vol. 264, p. 114728, 2020, doi: 10.1016/j.apenergy.2020.114728.

[9] T. Tiedemann *et al.,* "Supplying electricity and heat to low-energy residential buildings by experimentally integrating a fuel cell electric vehicle with a docking station prototype," *Applied Energy*, vol. 362, p. 122525, 2024, doi: 10.1016/j.apenergy.2023.122525.

[10] M. Kersten, M. Bachmann, T. Guo, and M. Kriegel, "Methodology to design district heating systems with respect to local energy potentials, CO_2-emission restrictions, and federal subsidies using oemof," 2021, doi: 10.5278/ijsepm.6323.

[11] T. Huld, R. Müller, and A. Gambardella, "A new solar radiation database for estimating PV performance in Europe and Africa," *Solar Energy*, vol. 86, no. 6, pp. 1803–1815, 2012, doi: 10.1016/j.solener.2012.03.006.

[12] Statistisches Bundesamt (Destatis), "Umweltökonomische Gesamtrechnungen: Private Haushalte und Umwelt," 2021. Accessed: Oct. 27 2022. [Online]. Available: https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/UGR/private-haushalte/Publikationen/Downloads/haushalte-umwelt-pdf-5851319.html

[13] U. Krien, "demandlib," Release 0.1.9, Open Energy Modelling Framework (oemof), Mar. 2023. Accessed: Mar. 27 2024. [Online]. Available: https://demandlib.readthedocs.io/_/downloads/en/stable/pdf/