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Model-based techno-economic evaluation of power-to-hydrogen-to-power for the electrification of isolated African off-grid communities

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ABSTRACT

Mini-grids are expected to be the least cost option to electrify more than half a billion people living predominantly in isolated communities in sub-Saharan Africa. Providing a high reliability of power supply to satisfy paying customers is vital for the challenging business case of mini-grid owners. Therefore, renewable-based mini-grids of the third generation commonly include either diesel generators or battery storage for backup power supply.

Power-to-hydrogen-to-power (P2H2P) is a promising alternative to overcome technical, financial, and social shortcomings of diesel generators and batteries. Previous research highlights the challenging economic competitiveness of P2H2P in specific case studies only. Here, we conduct a model-based techno-economic analysis on an archetypal representative mini-grid to compare the economic performance of P2H2P against the diesel generator and battery storage. We identify key parameters decisive for the competitiveness of P2H2P via sensitivity analysis.

Under today´s conditions, P2H2P is financially viable in 100% decarbonized mini-grid systems. Ongoing trends of increased fuel price and P2H2P technology improvements must continue to achieve economic advantages of P2H2P over the diesel generator. However, P2H2P is competitive in locations in which the diesel price is higher than 2.6 USD/l or when P2H2P investment costs drop by more than 50%, which is expected beyond 2040. Sensitivity analysis shows that increasing P2H2P system efficiency can substantially benefit the economic performance. Seasonal variations on the African continent are insufficient to create exploitable advantages of P2H2P against the short-term storage of batteries.

The results suggest especially larger future PV mini-grids to combine battery storage and P2H2P rather than including common diesel generators or only including batteries when trends toward cheaper and more efficient technologies continue and diesel prices increase. Future work should investigate economic effects of the unique multi-usability of hydrogen on the mini-grid system, such as the usage as clean cooking fuel.

KEYWORDS

Access-to-electricity, off-grid electrification, isolated mini-grid, decentralized hydrogen, techno-economic analysis, power-to-hydrogen-to-power.

INTRODUCTION

1.1 Background and motivation

Eight years before the completion of the Sustainable Development Goal (SDG) period the goal of universal electrification outlined in SDG 7 is still at significant distance. 600 million people lack access to electricity in sub-Saharan Africa (SSA) only (International Energy Agency, 2019). Especially affected is the rural population. Three out of ten people living in rural areas had no reliable access to electricity in 2020 (World Bank, 2021). Isolated small scale grids – hereinafter referred to as mini-grids – are a promising pathway to electrify rural communities in addition to Solar Home Systems and grid extension (Morrissey, 2017). Recording rapid cost-decline of components and a politically incentivized establishment of a competitive private sector market in many African countries, mini-grids have become increasingly popular (IRENA, 2015; Se4all, 2020) and economically competitive (Africa Process Panel, 2016) for rural electrification in the recent past. As a consequence, mini-grids are expected to be the most suitable electrification pathway for more than half a billion people in future (ESMAP, 2019).

However, mini-grids pose significant economic challenges to the owner and operator. Revenues and profit margin in rural mini-grids are often small (Peters, Sievert, & Toman, 2019). When not designed conscientious towards economic threads, mini-grid projects end up being business failures (Palit & Sarangi, 2014; Sovacool, 2013). Regular and reliable payments are indispensable for the owner, in order not to endanger the economic profitability. Therefore, the reliability of power supply, evidently a major driver for customer satisfaction impacting the ability and willingness to pay for electricity of customers (Robert, Sisodia, & Gopalan, 2019) is one fundamental pillar of a financially sustainable mini-grid project. Especially costumers with higher income and demand, e.g., entrepreneurs, who

require a reliable supply, may either stop paying their bills or invest in individual supply systems when facing frequent power outages (Schnitzer et al., 2014). Therefore, mini-grids of the third generation – powered by volatile renewable energies of unpredictable nature – commonly include diesel generators (DGs) or battery storage as backup technologies to increase the reliability of power supply. Duran et al. report that 94 out of 104 analyzed mini-grids (90%) include a DG as a backup generator (Duran & Sahinyasa, 2020). Such DGs, however, are not in line with global efforts towards decarbonization and environmental protection. Further, DGs jeopardize self-sufficiency of communities but create dependencies on diesel imports. In rural areas, diesel imports can be challenging and costly, while the price of such oil derivates fluctuates with market movements on global stock exchange. Considering decreasing resources of crude oil, a long-term trend of increasing diesel prices may be likely (U.S. Energy Information Administration, 2021).
An alternative solution to provide backup power is electricity storage. Storage technologies store electricity produced in excess by renewable energies. When demand exceeds the production, i.e. during the night, the storage discharges to satisfy the loads. The most common and mature technology for such electricity storage in mini-grids are batteries. In the past, significant advances have been made especially for lithium-ion batteries (IRENA, 2016). Nevertheless, batteries still have technical limitations and physical boundaries that restrict the optimal fields of application. Such limitations include the property of self-discharge, which limits the application for longer-term storage. With this, the battery may fail to serve power during extended cloudy days (considering PV primary production) or during maintenance of the primary power generation unit. Also, cyclic loading and operation over the entire charging capacity can harm the lifetime of batteries. To still exploit sufficient energy capacity to mitigate daily or weekly variability phenomena, oversizing of battery storage systems would be required. This in return leads to reduced average utilization and thereby increased average costs (ESMAP & World Bank Group, 2020). Thus, the optimal field of application of batteries is still seen in short-term storage of up to a few hours (ESMAP & World Bank Group, 2020).

Facing the limitations of these two common backup technologies – DG and battery –, mini-grid developers are looking for alternative solutions to increase the reliability of power supply. A recently discussed technology is power-to-hydrogen-to-power (P2H2P). In P2H2P, excess electricity is converted to gaseous hydrogen (and oxygen) via electrolysis and stored in (pressurized gas) tanks. The stored hydrogen is reconverted into electricity (and water) through a fuel cell (FC). P2H2P may overcome the obstacles of the aforementioned backup systems:

- Environmental protection: P2H2P does not emit any harmful local emissions when noise emissions are avoided through correct shelter.
- Self-sufficiency: Decentralized hydrogen production via renewable energies avoids any dependency on external supply during system operation (Notably, we consider water resources are available for at least small-scale hydrogen production according to the H_2-Atlas in most African countries (H2 Atlas consortium, 2022))
- Storability: Hydrogen storage allows for long-term energy storage without significant losses. This allows to cover for seasonal variations of renewable energy generation or longer disruptions in the primary supply of electricity.
- Multi-usability: In addition to power supply, hydrogen can also be used as a clean cooking fuel (Topriska, Kolokotroni, Dehouche, Novieto, & Wilson, 2016; Topriska, Kolokotroni, Dehouche, & Wilson, 2015), mobility fuel, or for other productive uses, e.g., in fertilizer production, which might unlock synergies to other sectors (ESMAP & World Bank Group, 2020).

Reflecting on this potential, P2H2P is expected to become a competitive option for power supply in remote mini-grids in future (Duran & Sahinyasa, 2020; Schöne, de Rochette, & Heinz, 2021). However, today, the P2H2P technologies are in an early stage of entering the electrification sector. Besides technical challenges, economic competitiveness against other backup technologies may not yet be achieved. It remains a challenge for research to identify economic use-cases, barriers, and chances to financially viable P2H2P integration in isolated mini-grids.
Previous literature has proposed P2H2P for rural electricity supply systems (Al-Sharafi, Sahin, Ayar, & Yilbas, 2017; Ayodele, Mosetlhe, Yusuff, & A.S.O., 2021; Barzola-Monteses & Espinoza-Andaluz, 2019; Ghenai, Salameh, & Merabet, 2018; Hailu Kebede & Bekele Beyene, 2018; Khemariya, Mittalb,

Baredarb, & Singh, 2017; Pal & Mukherjee, 2021) and small island systems (Cozzolino, Tribioli, & Bella, 2016; Groppi, Garcia, Basso, Cumo, & De Santoli, 2018; Marocco, Ferrero, Martelli, Santarelli, & Lanzini, 2021; Marocco, Ferrero, Lanzini, & Santarelli, 2022). Only a few research has explored the techno-economic competitiveness of P2H2P against DGs, battery storage, or both. Silva et al. (Silva, Severino, & de Oliveira, 2013) (2013) compared the economic performance of P2H2P to battery storage in a PV-powered mini-grid installed in rural Brazil, applying the Hybrid Optimization Model for Electric Renewables (HOMER) (HOMER Energy, 2018). Based on the real costs of the pilot project, the optimization indicates the FC integration to be not viable against a system including a battery as storage only (Silva et al., 2013). Brenna et al. (Brenna, Foiadelli, Longo, & Abegaz, 2016) (2016) applied HOMER to detect the optimal energy system configuration for a rural community in Ethiopia, considering DG, battery storage, and P2H2P. With costs derived from literature, the study finds a system including hydrogen to have only 0.1% higher initial costs – but 0.1% lower operational costs – compared to the optimal solution integrating only a DG and battery storage (Brenna et al., 2016). Das et al. (Das, Tan, Yatim, & Lau, 2017) find battery storage to be economically advantageous against a DG or P2H2P for a village longhouse located in rural Malaysia (Das et al., 2017). In contrast, the results of an optimization applying a multi-objective crow search algorithm applied by Jamshidi et al. (Jamshidi & Askarzadeh, 2018), propose P2H2P to be economically advantageous against a diesel-powered electricity supply for a rural off-grid community in Kerman, south Iran (Jamshidi & Askarzadeh, 2018).

1.2 Ambition and contribution to research

The review of previous literature reveals significant gaps in the economic assessment of P2H2P in rural mini-grids.

Existing techno-economic analyses are limited to case studies in specific considered settings. While this approach may provide a sophisticated answer for the specific case and setting of investigation, the transferability of findings is limited. Due to the high complexity of the considered systems and the variety of parameters influencing the result, estimating the impact of changes in parameters on the result is difficult. Thereby, transferability of the results is jeopardized. Further, the case studies consult latest economic and technical data, but miss to include potential future development of parameters. This paper aims to overcome these limitations and produce transferable results in a techno-economic comparison of P2H2P against DGs and batteries. Therefore, the paper will apply an opposite approach to previous work, by creating a linear problem-based energy system model of a representative archetypal mini-grid. The paper will investigate the impact of several technical and economic parameters on the competitiveness of P2H2P against the DG and battery in supplying power to the mini-grid. Selected parameters will be varied within a sensitivity analysis according to their potential development or variation on the African continent. This allows transferring the findings of the study to any other context on the continent. The parameters considered during sensitivity analysis are:

- Parameters influencing investment of a single technology: specific electrolyzer (EL) investment costs, specific FC investment costs, specific battery investment costs, specific DG investment costs, P2H2P efficiency (influencing the required size of the components)
- Parameters influencing the operation of a single technology: Diesel fuel price, P2H2P efficiency (influencing the required energy throughput), battery depth of discharge (DoD),
- Parameters influencing all present technologies: Load profile shape, seasonality of PV irradiation, weighted average costs of capital (WACC).

The paper follows a materials and methods section, which includes a description of the energy system model, components of the energy system considered, and parameters applied. Section 3 presents the results, which are discussed and interpreted in Section 4. The paper closes with a conclusion and summary of findings.

2. MATERIAL AND METHODS

This section covers the materials used and methodology applied to evaluate the economic competitiveness of P2H2P for supplying backup power to an isolated African community. Section 2.1

describes the considered mini-grid and its components. Section 2.2 describes the applied methodology to define an optimal solution to the research question.

2.1 Integration of P2H2P in the mini-grid

Figure 1 presents the set-up of the mini-grid topology when including all options of backup power supply technologies. The P2H2P system is connected to the direct current (DC) bus, while the EL converts DC electricity to hydrogen and the FC reverts the process to satisfy electricity demands. A detailed description of P2H2P integration in isolated small-scale systems is given in (Akinyele, Olabode, & Amole, 2020). Notably, our considerations in this study are limited to electricity and exclude the potential usage of waste heat released by any component, such as the fuel cell. Further, the usage of electrolysis by-product O_2 is neglected. While in other settings with local O_2 demand the use of the byproduct has shown to improve the economic P2H2P system performance (Roeben, Schöne, & Bau, 2021), the local use of O_2 in mini-grids may be context-specific and must be explored in further research.

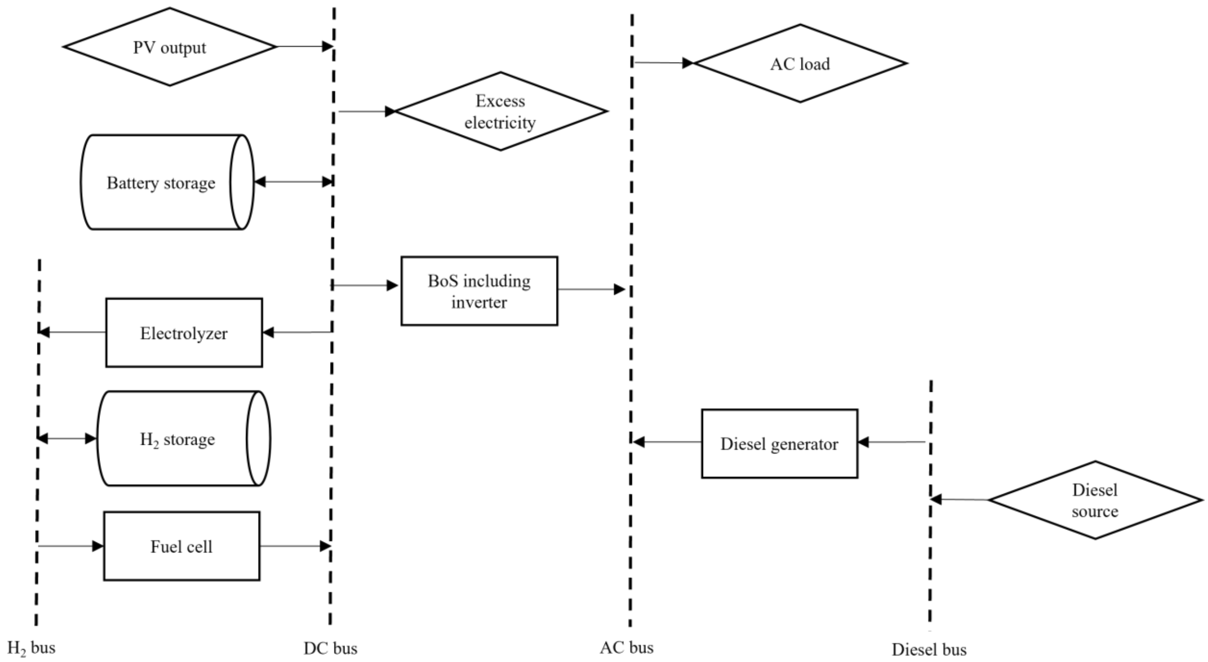

Figure 1: Energy system topology considering the three backup technologies to be compared during our analysis.

The following subsections will detail the function of the distinct energy system components. Assumptions made for in analysis are discussed on the background of recent literature.

2.1.1 Load

We consider a common alternating current (AC) load in the analysis. As of limited seasonality in electricity demand behavior, load profiles for African mini-grids in the literature are usually reported as single-day resolution, rather than annual profiles (Lorenzoni et al., 2020). A common attempt in defining the load profile is to specify distinct load profiles for categories of loads (i.e. residential load, business loads, community loads, and productive use loads) by either measurement or survey. However, this bottom-up approach – accurate for the individual mini-grid – is questionable to serve as a representative mini-grid profile, as it contains the specific socio-demographic, tariff, and climate influencing parameters of the case studied. For our representative mini-grid, we follow Lorenzoni et al. (Lorenzoni et al., 2020), who, in a top-down approach, defined distinct archetypal load profiles for mini-grid clustered according to socio-demographic and other parameters (Lorenzoni et al., 2020). The generated archetypal load profiles show a trend with the two extreme profiles being a *peak* profile –

that is a profile with a significantly increased load during the evening period – and a *flat* profile, showing a more homogeneous consumption during day and night. As the *flat* profile covers the widest spectrum of operator models (including utility, community, private and hybrid), size, level of energy and peak consumption per connection, measurement age, and geographical distribution, the normalized average *flat* profile serves as the base-case profile in our considered analysis. To investigate the effect of load distribution on techno-economic performance of P2H2P, sensitivity analysis will approximate the *peak* profile while maintaining the total energy supply. Figure A.1 of the Appendix shows the gradual transformation of the normalized *flat*-profile towards a *peak*-profile. Peak consumption (kW) of the energy system is scaled on a mini-grid located in Kenya, which is representative according to customer base and Tier-level (Lorenzoni et al., 2020). Applying the *flat* and *peak* load profiles to the peak load of this reference system results in peak loads of 75 kW and 199 kW respectively.
No energy shortage is considered in our analysis for the following reasons: Firstly, this analysis compares different power backup technologies, which aim to maximize the reliability of supply. Thus, the maximum possible reliability should serve as a maxim. Secondly, perceived acceptable shortages are known to be different for distinct customer groups (Robert et al., 2019). As the analysis explicitly avoids the differentiation of different costumer groups, only a global shortage could be introduced to the system, which would conflict with the recommendations from previous work (Robert et al., 2019). Thirdly, P2H2P systems may supply base load energy, considering comparatively high specific investment costs. Conventional peak clipping would not reduce the contribution by the P2H2P system, while we do not consider energy shortage on base load devices, as these might be critical to the user.

2.1.2 Primary power supply

The mini-grid considered does not foresee any connection to an external (main) grid. Local renewable energy resources and imported diesel fuel are the only options for primary power supply.

2.1.2.1 Renewable energy

Solar PV is the only renewable energy source considered in this analysis, as i) previous work from Moner-Girona et al. applying a spatial electrification model to Kenya detected PV as the least-cost option for the considered region of the reference system (Moner-Girona et al., 2019) and ii) access to alternative renewable energies might be of more local nature.
As input data for a time series in hourly resolution, we choose the MERRA-2 dataset with the reference year 2019 (Pfenninger & Staffell, 2016), at the location of Latitude 2.4924 Longitude 39.5669, which fit´s the location of the mini-grid consulted to define the peak-load (Kenya, Eldas region). Data was accessed via (renewables.ninja). System losses including e.g. array mismatch, dirt, and shading are assumed to be 10% (Pfenninger & Staffell, 2016). A PV panel tilt of 10° is suggested by (Jacobson & Jadhav, 2018).
Based on the yearly PV output data, the PV seasonality index of our yearly solar data set – defined as the ratio between the highest and the lowest of monthly long-term PV output per kW averages (ESMAP, 2020) –calculates to 1.24. Notably, our calculation violates the defined procedure of calculating the seasonality index over a time span of several years and can therefore only be used as an approximation. The seasonality index given by (ESMAP, 2020) for Kenya is 1.33 (ESMAP, 2020). Only Lesotho (1.17), Mauritania (1.20), Namibia (1.17), Rwanda (1.21) and South Africa (1.23) have slightly lower seasonality indices, while most African countries face a higher seasonality (ESMAP, 2020). The highest seasonality index reported in the African continent is in Tunisia, with an average of 1.48. To analyze the effects of such variation in PV seasonal output on our energy system model, we artificially increase the distance from the annual average in the monthly PV outputs of our data set as reported in the original source (ESMAP, 2020) in steps of 10% up to 100% deviation. The maximum seasonality index achieved via this procedure is 1.54. Notably, during the procedure we maintain the total amount of annual solar irradiation. The resulting seasonal PV production profiles are illustrated in Figure A.2 of the Appendix.
PV production costs have been rapidly declining over the course of the past decade (Jäger-Waldau, 2019). However, the purchase costs significantly vary across countries and regions in rural Africa (ESMAP, 2019; Jäger-Waldau, 2019). We assume 1,000 USD/kW investment costs – notably excluding the inverter – which is in line with field data obtained by Moner-Girona for SSA Africa

(930 USD/kW) (Moner-Girona et al., 2018), data obtained by a survey of the Energy Sector Management Assistance Program (ESMAP) for 2019 in Kenya (994 USD/kW/module and 283 USD/kW for PV racks) (ESMAP, 2019), and a global market study by Jäger et al. (700 USD/kW module costs, excluding any taxes and administration costs) (Jäger-Waldau, 2019). Operation and maintenance costs are assumed to be constant throughout the project lifetime at 15 USD/kW/year (scaled to considered investment costs according to (Jäger-Waldau, 2019)). The financial lifetime of the PV system is assumed to be 20 years (Jäger-Waldau, 2019; Moner-Girona et al., 2019).

2.1.2.2 Diesel supply

At the time period of the latest available evidence (November 2021 – December 2021) the average diesel price at pump in Kenya – including all taxes and fees – was 1.13 USD/l, with rural stations tending towards the maximum of 1,24 USD/l (Energy and Petroleum Regulatory Authority, 2022). However, the diesel fuel price varies significantly with the region and African countries (GlobalPetrolPrices, 2022). In addition, as petrol is a limited fossil commodity traded on global markets, the price for diesel is highly variable and predicted to increase in the long run (U.S. Energy Information Administration, 2021).

Concluding on this argumentation, we assume a diesel price of 1 USD/l, plus 0.1 USD/l to include logistics of fuel delivery via truck (Agenbroad, Carlin, Ernst, & Doig, 2018) for the base case of our study.

2.1.3 Backup technologies

The study considers three different types of backup technologies to maximize the reliability of supply: a DG, battery storage and P2H2P.

2.1.3.1 Diesel generator

DGs remain the most common option chosen as backup technology in rural mini-grids (Duran & Sahinyasa, 2020), with a variety of types and manufacturers available in Africa. Evidence on investment costs of DGs shows a wide spectrum from 400 USD/kW (Tim Reber, Samuel Booth, Dylan Cutler, Xiangkun Li, & Salasovich, 2018) to 1,050 USD/kW for a DG including housing (Agenbroad et al., 2018). We choose a conservative assumption of 500 USD/kW investment costs, which is in line with an extensive study from Moner-Girona in 2018 (Moner-Girona et al., 2018). However, a sensitivity analysis of the parameter will be conducted during our analysis. Fixed operation and maintenance costs are assumed to be 25 USD/kW/y (Tim Reber et al., 2018). The financial lifetime is assumed to be 10 years (Tim Reber et al., 2018). We assume a fuel conversion efficiency of 33% (Al-Hammad, Becker, Bode, Gupta, & Kreibiehl, 2015). To reduce the mathematical optimization problem, we neglect a minimum operating capacity, as it conflicts with linear equations.

2.1.3.2 Battery storage

Common lead-acid batteries dominate the African market for stationary storage applications (Se4all, 2020). However, recent developments in alternative battery technologies, especially lithium-ion batteries, may suggest an increased use of such alternative battery technologies in new mini-grids in future (Se4all, 2020). Notably, the term “lithium-ion” battery in this paper refers to a battery including lithium at the positive electrode, while not further distinguishing the anode material.

The main technical characteristics of batteries to consider for the application in rural mini-grids are the maximum DoD, rate of discharge (or charge) compared to the capacity of the storage (C-rate), round-trip efficiency, and self-discharge. Each of these parameters is strictly linked to the economic performance of the battery. As the costs of a battery increase proportionally with the storable energy, i.e. USD/kWh, the amount of usable energy to satisfy the load curve is critical. Given this relationship, a high DoD or low C-rate may have to be compensated with larger installed capacity of the battery. Additionally, the expected lifetime of a battery impacts the economic performance of the technology considered over the financial period of a project. The lifetime of batteries is subject to numerous influencing chemical mechanisms (e.g. side reactions) and physical mechanisms (e.g. thermal stress and mechanical stress), impacting both the calendar lifetime and cycle lifetime (Hu, Xu, Lin, & Pecht, 2020). Calendar aging occurs when a battery is not being used, therefore being impacted by

temperature and state of charge (SOC). Cycle aging instead occurs when the battery is under charge or discharge current, being additionally impacted by the total charge throughput over battery lifetime and the current (Dufo-López, Cortés-Arcos, Artal-Sevil, & Bernal-Agustín, 2021). Previous research indicates charge and discharge rates, charge (Ah) throughput, the time between full charge, time at a low SOC, and partial cycling to be the main aging influencers for lead-acid battery lifetime (Dufo-López et al., 2021; Lujano-Rojas et al., 2016). Lithium-ion batteries are mostly affected by temperature, charge and discharge rates, and the DOD (Dufo-López et al., 2021). For an extensive review of degradation mechanisms of lithium-ion batteries see Han et al.(Han et al., 2019). As cyclic aging mechanisms are sensitive to operational treatment, hardly possible to depicture in the level of detail of our analysis, we exclude cyclic aging here.
Table 1 provides an overview of selected technical and economic parameter of batteries as assumed in our analysis.

Table 1: Assumptions on technical and economic parameters of the battery.

Parameter	Lead-acid	Lithium-ion
Costs [USD/kWh]	175 (Moner-Girona et al., 2018) 150 – 500 (Spataru & Bouffaron, 2016)	500 – 1,500 (Spataru & Bouffaron, 2016)
O&M costs USD/kW/y	15 (Ghandi & Srinivasan, 2020)	5 (Ghandi & Srinivasan, 2020)
C-rate [h^{-1}]	0.1 (Sen, 2018)	0.5 (Spataru & Bouffaron, 2016) 1 – 2 (Huld, Moner-Girona, & Kriston, 2017)
DoD [%]	60 (Moner-Girona et al., 2018)	80
Roundtrip efficiency [%]	70 – 90 (Spataru & Bouffaron, 2016)	85 – 95 (Spataru & Bouffaron, 2016)
Calendar lifetime [y]	5 (Agenbroad et al., 2018; Spataru & Bouffaron, 2016)	10-15 (Spataru & Bouffaron, 2016)
Self-discharge rate %/months	2 (Spataru & Bouffaron, 2016)	5 (Spataru & Bouffaron, 2016)

2.1.3.3 P2H2P System

To evaluate the techno-economic performance of the P2H2P system, we discuss the included components in the following.

Water electrolysis system

We consider three types of water EL technologies to be suitable for the application in rural SSA mini-grids as of today: alkaline electrolysis (AEL), anion exchange membrane electrolysis (AEMEL), and polymer electrolyte membrane electrolysis (PEMEL). Solid oxide electrolysis (SOEL) may offer high efficiencies when integrating high-temperature heat from external processes (Buttler & Spliethoff, 2018) but the technology still is at a low maturity.
AEL is the most mature EL technology with currently the lowest investment cost and largest application (Buttler & Spliethoff, 2018; ESMAP & World Bank Group, 2020). However, stagnation in efficiency improvement and cost reduction as well as limitations in dynamic behavior has motivated to search for technology redesign and technology alternatives (Grigoriev, Fateev, Bessarabov, & Millet, 2020). The PEMEL has gained increasing attention during the last recent years, as favorable dynamic behavior allows for applications requiring an intermittent operation, such as short-term electricity markets and ancillary grid services (Kopp et al., 2017). AEMEL is the least mature technology amongst the three considered. However, AEMEL does not contain any noble metals as a catalyst, which may promise cost advantages in the future (Shirvanian, Loh, Sluijter, & Li, 2021). The AEMEL promises to offer similar efficiencies as the AEL and capability for flexible operation as a PEMEL (Li & Baek, 2021; Shirvanian et al., 2021). For a comprehensive overview of AEMEL see Li and Baek (Li & Baek, 2021). Table 2 presents the technical characteristics and selected parameters of the three technologies according to recent literature. It must be noted that the presented parameter might influence each other, and trade-offs must be found in system design (e.g. decreasing start-up times might negatively affect the stack lifetime). The values indicated in the table therefore must only be seen as indicative.

For our study, we base parameters in alignment with AEL systems, as this is the most mature technology. We assume conservative 1,000 USD/kW investment costs, with 3% annual operation and maintenance costs, while the specific investment costs will be included in the sensitivity analysis. Notably, the EL may produce hydrogen at elevated pressures as indicated in Table 2. Such pressurized operation is beneficial when considering pressurized storage subsequently, as external compression can be reduced. However, due to uncertainty of such pressurized operation in projects we neglect this opportunity. Further assumptions are discussed below:

- Efficiency: we consider the system efficiency against the lower heating value (LHV) rather than stack efficiencies, to include losses occurring in auxiliary devices. While the efficiency of EL systems is known to be a non-linear function depending on the utilization (Kopp et al., 2017), the efficiency deviates only slightly across a wide range of installed capacity (Kopp et al., 2017). Hence, we simplify for a constant electrolysis efficiency of 60% (Buttler & Spliethoff, 2018) for the purpose of our study.

Table 2: Technical characteristics and selected parameter of AEL, AEMEL and PEMEL technology from recent literature.
*Notably, significant scale effects are expected for large scale systems (IRENA, 2020a).
**Defined below 50 °C temperature.
***Notably, system efficiency of PEMEL is known to be a non-linear function of the power input. Included values may refer to regarding the efficiency reference power depending on the source consulted.

Parameter	Unit	AEL	AEMEL	PEMEL
CAPEX*	USD/kW	850 – 1,600 USD/kW (Buttler & Spliethoff, 2018) 800 USD/kW (ESMAP & World Bank Group, 2020) 825USD/kW (Danish Energy Agency, 2022)	/	1.500 – 2.200 USD/kW (Buttler & Spliethoff, 2018) 1,100 USD/kW (ESMAP & World Bank Group, 2020) 1,000 USD/kW (Danish Energy Agency, 2022)
OPEX	% of invest/y	2 – 3 (Buttler & Spliethoff, 2018) 5% (Danish Energy Agency, 2022)	/	3-5 (Buttler & Spliethoff, 2018) 7 (Danish Energy Agency, 2022)
Efficiency* (System, LHV)**	%	51 – 60 (Buttler & Spliethoff, 2018) 42 – 66 (IRENA, 2020a)	74.7% cell efficiency (Li & Baek, 2021)	46 – 60 (Buttler & Spliethoff, 2018) 40 – 66 (IRENA, 2020a)
Lifetime stack		8-15 y (Buttler & Spliethoff, 2018) 55,000 – 96,000 h (Felgenhauer, Hamacher, & 2015, 2015)	5,000 h (ESMAP & World Bank Group, 2020)	60.000 – 100.000h (Buttler & Spliethoff, 2018) 80,000 h (ESMAP & World Bank Group, 2020)]
Lifetime system		30-50 y (Pewinksi, 2015)	20 (Motealleha et al., 2021)	20 y (Buttler & Spliethoff, 2018) 20 y (ESMAP & World Bank Group, 2020)
Min. part-load	%	20 (Buttler & Spliethoff, 2018))	5 (ESMAP & World Bank Group, 2020)	0 (Buttler & Spliethoff, 2018) 5 (Smolinka et al., 2011)
Start-up time (cold/warm)**		1-2 h / 1 – 5 min (Buttler & Spliethoff, 2018)	<20 min/<<20 min (ESMAP & World Bank Group, 2020)	5 – 10 min/>10 s (Buttler & Spliethoff, 2018)
		Technical properties		
Electrolyte	/	10-30% KOH (Li & Baek, 2021)	Quaternary ammonia polysulfide or optional dilute caustic solution (Li & Baek, 2021)	Perfluoro sulfonic acid (Li & Baek, 2021)
Operating temperature	°C	65 – 100 (Li & Baek, 2021)	50 – 70 (Li & Baek, 2021)	70 – 90 (Li & Baek, 2021)
Operating pressure	Bar	1 – 200 (Grigoriev et al., 2020); <30 (ESMAP & World Bank Group, 2020)	<35 (ESMAP & World Bank Group, 2020)	1 – 350 (Grigoriev et al., 2020) < 70 (ESMAP & World Bank Group, 2020)
Catalyst material	/	Ni/Fe based species (Li & Baek, 2021)	Ni-based materials (Li & Baek, 2021)	Platinum groups (Li & Baek, 2021)
Bipolar plate material	/	Ni plate (Li & Baek, 2021)	Ni plate (Li & Baek, 2021)	Titanium plate (Li & Baek, 2021)
Current density	mA cm^{-2}	200 – 500 (Li & Baek, 2021)	100 – 500 (Li & Baek, 2021) 200 – 2000 (ESMAP & World Bank Group, 2020)	800 – 2.300 (Li & Baek, 2021) 2.200 (Danish Energy Agency, 2022)
Developing status	/	Mature technology (Li & Baek, 2021)	Under development(Li & Baek, 2021)	Mature technology for small scale (Li & Baek, 2021)

- Lifetime: Literature distinguishes between the lifetime of the stack/cell and system (Buttler & Spliethoff, 2018; T. Smolinka et al., 2018). The stack/cell lifetime is influenced by electrochemical and mechanical processes during system operation, thereby significantly lower than the system lifetime. Mechanical stress caused by high current densities, catalyst reduction as a consequence of start-stop protocols and catalyst dissolution due to overpotential are drivers for aging in PEMEL stacks (Babic, Tarik, Schmidt, & Gubler, 2020). In addition to these, AEL systems are object to degradation by the corrosive alkaline environment (Symes, Al-Duri, Bujalski, & Dhir, 2015). As the stack accounts for 45% (IRENA, 2020a; T. Smolinka et al., 2018) of the total investment costs, our analysis foresees a partial reinvest of 45% of the total investment costs after 10 years to account for the stack exchange.

- Minimum part-load: While the minimum operational capacity is determined by auxiliary components in the example of a PEMEL (Smolinka, Günther, & Garche, 2011), the conductivity of the diaphragm leading to critical gas concentrations restricts the minimum part load of AEL (Mergel, Carmo, & Fritz, 2013). However, both overload and part-load behavior are neglected in our analysis as the energy system modeling framework does not allow for component optimization while maintaining a minimum operation constraint. The assumption might be reasonable, however, as flexible operation is proven (Kopp et al., 2017) but conflicts with degradation in the lifetime (Babic et al., 2020) and poses quasi-de-facto constraints when tied to warranties of manufacturers.
- Start-up time: AEL operate at temperatures above 50 °C, as indicated in Table 2. To reduce any mechanical stress of the material, start-up times may be considered to heat up to operational temperature. As we consider an hourly resolution during system optimization, we neglect start-up times because of their negligible influence on the result.

Pressurized hydrogen storage

A hydrogen storage system is required to buffer the surplus of hydrogen produced via electrolysis and decouple the EL and FC operation. While there are different hydrogen storage technologies commercially available on the market – i.e. liquefied hydrogen carrier, and hydride storage – a pressurized storage tank remains the most common option due to the low costs (Danish Energy Agency, 2018). We assume a Type 1 seamless steel or aluminum tank storage, which allows for pressures up to 250 bar, which is commonly used for stationary application. Standby losses are negligible due to the low permeability of the tank (Danish Energy Agency, 2018). To simplify our model, we integrate the compression required to compress the hydrogen produced by the EL to storage pressure into our storage component. Therefore, the roundtrip efficiency of the storage considers operational losses due to compression, and such losses caused by the pressure losses in valves and tubes during filling and retrieving. With assuming the energy consumed by the compressor for compression of 1 kg hydrogen up to 200 bar being 4 kWh/kg, we can assume a roundtrip efficiency of the hydrogen storage of 88% (Danish Energy Agency, 2018). The investment costs of the system are considered to be 20USD/kWh for the storage tank (Danish Energy Agency, 2018), which is in line with the wide span found in recent literature (6 USD/kWh – 30 USD/kWh) (van Leeuwen & Mulder, 2018). Additional investment costs for the compressor are neglected in this paper, as costs significantly depend on the configuration of the plant (e.g. output pressure of the EL, storage pressure, flow) and the estimates in the literature vary widely between 160 USD/kW – 20,350 USD/kW (van Leeuwen & Mulder, 2018). Fixed operating costs of the storage are assumed with 1.5% of the investment costs (Parra, Valverde, Pino, & Patel, 2019). System lifetime is expected to be 25 years (Danish Energy Agency, 2018). As no significant improvements are expected for Type 1 tanks within the upcoming years (Danish Energy Agency, 2018), the hydrogen storage tank is not further considered for sensitivity analysis.

Hydrogen fuel cell

A variety of FC technologies are commercially available as of today, including PEM FCs (PEMFCs), Alkaline FCs (AFCs), molten carbonate FCs (MCFCs), solid oxide FCs (SOFCs) and phosphoric acid FCs (PAFCs) (Akinyele et al., 2020; ESMAP & World Bank Group, 2020). While PEMFCs and AFCs typically operate at temperatures below 80°C, MCFCs and SOFCs are classified as high-temperature FCs operating above 650°C and 800°C respectively (Akinyele et al., 2020). While these high temperatures make the systems suitable for combined heat and power applications, it limits their dynamic and cyclic capabilities and poses material and corrosion challenges (Akinyele et al., 2020), which is why we do not consider the systems for the purpose to supply power in rural SSA mini-grids today. The PAFC in contrast may be classified as medium-temperature FC, with a typical operating temperature between 150°C and 220°C (Akinyele et al., 2020). By today, PAFCs make a significant share of FCs in stationary applications. However, almost all units run on natural gas as feedstock

(ESMAP & World Bank Group, 2020). Table 3 presents selected technical and economic characteristics of AFCs, PEMFCs, and PAFCs from recent literature. For a comprehensive overview of the discussed technologies and their integration in African microgrids, see (Akinyele et al., 2020). In principle, the similar advantages and restrictions that are discussed for water electrolysis are applicable for the reverse reaction with a FC. Inter alia due to its advantageous dynamic performance and therefore suitability in mobility applications, the PEMFCs have recorded most sales by today, and remarkable production facility capabilities (ESMAP & World Bank Group, 2020). According to the ESMAP, manufacturing capacities for PEMFCs exceeded 1,100 MW in 2020, which at that time was more than ten times higher than the manufacturing capacities of competitive technologies (ESMAP & World Bank Group, 2020). As the production facilities are owned by multiple independent market players (i.e. in contrast only two manufacturers have been reported for PAFCs by ESMAP in 2020 (ESMAP & World Bank Group, 2020)), a vivid and competitive market can be expected in the future. We therefore assume a PEMFC for our base case system.
It is important to note that significantly lower costs have been reported for mobility applications than for stationary applications, which typically require higher a stack lifetime, causing a higher CAPEX. We assume the initial CAPEX of the FC to be 2,700 USD/kW$_{el}$ which is a conservative estimation in line with (ESMAP & World Bank Group, 2020). Notably, stationary AFC systems for baseload power generation and uninterruptible power supply have been reported at costs of 700 USD/kW$_{el}$ by the ESMAP (ESMAP & World Bank Group, 2020). Operating expenditures are assumed to be 5% of the total investment costs (Agency, 2022). We consider reinvestment costs for the stack to be the same share of the total costs as for electrolysis (45% (IRENA, 2020a; T. Smolinka et al., 2018)) with a replacement after 5 years, while the system lasts for another 15 years (ESMAP & World Bank Group, 2020). Electrical system efficiency is assumed with a constant value of 50% (Agency, 2022).

Table 3: Technical characteristics and selected parameter of stationary AFC, PEMFC and PAFC technology from recent literature.

Parameter	Unit	AFC	PEMFC	PAFC
CAPEX*	USD/ kW$_{el}$	700 (ESMAP & World Bank Group, 2020) 1,800 (Kirubakaran, Jain, & Nema, 2009)	1,400 – 4,000 (ESMAP & World Bank Group, 2020) 1,430 USD/kW (Agency, 2022) <1,500 (Kirubakaran et al., 2009)	4,000 – 5,000 (ESMAP & World Bank Group, 2020) 2,100 (Kirubakaran et al., 2009)
OPEX	% of investment	13.4 USD/kW/y (any technology) (Mongrid et al., 2020)	5 or 100$/kW/y (Agency, 2022) 13.4 USD/kW/y (any technology) (Mongrid et al., 2020)	13.4 USD/kW/y (any technology) (Mongrid et al., 2020)
Electrical efficiency (System, LHV)	%	45-58 (ESMAP & World Bank Group, 2020) 45 – 60 (Adamson, 2007)	55-65 (ESMAP & World Bank Group, 2020) 50 (Agency, 2022) 40 (Töpler & Lehmann, 2016)	45-55 (ESMAP & World Bank Group, 2020) 40-45 (Töpler & Lehmann, 2016) 37-42 (Giorgi, 2013)
Lifetime stack	h	5,000 – 6,000 (ESMAP & World Bank Group, 2020) 8,000 (Fuelcell.co.uk)	20,000 – 40, 000 (ESMAP & World Bank Group, 2020) or 34,000 h according to the company Ballard (ESMAP & World Bank Group, 2020) 10 y (Agency, 2022) 5,000 – 20,000 (Bae et al., 2012)	70,000 – 80,000 (ESMAP & World Bank Group, 2020) or 70,000 h according to the company Doosan (ESMAP & World Bank Group, 2020) >50,000 (Giorgi, 2013)
Lifetime system	y	20 (ESMAP & World Bank Group, 2020)	20 (ESMAP & World Bank Group, 2020)	2 (ESMAP & World Bank Group, 2020)

To cover for uncertainties due to technological or market developments the initial investment costs and the electrical efficiency will be considered in our sensitivity analysis. We assume the potential development in cost decrease and efficiency improvements to follow the same slope as the electrolysis technology.

2.1.4 Balance of System

The Balance of System (BoS) is required to control and operate the energy system according to the optimal dispatch, comprising a set of components that measure, monitor and control the electrical loads (Louie, 2018). While the BoS may also be required for only diesel-powered energy systems, the BoS and charge controller´s size is known to be proportional to the capacity of the PV array (Moner-Girona et al., 2018). We recognize the BoS as an optimization component linked to the PV array. We assume a linear cost function of 1.100 USD/kWp for a system including charge controller, inverter, protection board, and cabling (Moner-Girona et al., 2018). Efficiency and lifetime are assumed according to the inverter component with 95% and 10 years respectively (Tim Reber et al., 2018).

2.2 Optimal mini-grid design and operation

To evaluate the economic competitiveness of P2H2P for power supply of an isolated mini-grid against common backup technologies of DG and battery, mathematical optimization is applied.

To develop the mathematical optimization model, we use the open energy modeling framework (oemof). While oemof allows for mixed-integer-linear-problem formulation (Krien et al., 2020), we define a linear objective function within a set of linear constraints to reduce complexity and computational time of the model. The oemof framework has proven to produce accurate and consistent results in comparison to other (linear) optimization tools, especially in small-scale systems (Benderes, Bertheau, & Blechinger, 2018). Oemof is programmed in the object-oriented Python programming language. The scientific developer community of oemof is embedded in the Open Energy Modelling Initiative and follows open-source, open-data and open-science policies.
Oemof is based on a generic graph G based description of nodes N (buses B and components C) connected by directed edges E, which represent the flow of energy carriers, their conversion and consumption (Krien et al., 2020). Components are further distinguishable in Sources C^+, Sinks C^-, Transformer W and Storage S (Hilpert et al., 2018) (equations according to (Hilpert et al., 2018)).

$$\begin{gathered} G := (N, E) \\ N := \{B, C\} \\ E \subseteq \mathrm{B} \times \mathrm{C} \cup \mathrm{C} \times \mathrm{B} \\ C^+ \subseteq C \\ C^- \subseteq C \\ W \subseteq C \\ S \subseteq C \end{gathered} \tag{1}$$

Sources are characterized by having only outflows but no inflows, thereby representing energy entering the energy system border. In our example source components are the PV-plant and diesel fuel source. In contrast, sinks have only inflows, but no outflows, e.g. representing energy leaving the energy system borders. Example of a sink is a consumer of energy, in our considered case AC electricity demand. Transformers have both inputs as well as output flows. The flows can be set into relation according to specified mathematical expressions using parameter. The transformer included in our system are the DG, EL, FC and inverter. A storage component holds both input and output flows with respective mathematical relation but can accumulate flows over time steps. Our system includes the battery and hydrogen storage as storage components.

2.2.1. Model objective

While the objective function of oemof may vary depending on the components and set-up of the energy system (Hilpert et al., 2018), the objective of our optimization is to minimize the total system costs over the time horizon T (20 years) simulated. Our objective function including all components $c \in C$ can be written as

$$\min \sum_{c \in C} (cpx_c^{var} * P_c^{nominal} * CRF + OPX_c^{fix}) + \sum_{c \in C} \sum_{t \in T} opx_c^{var} * \Delta t \; \forall \; c \in C, t \in T \tag{2}$$

where cpx_c^{var} are size specific investment costs of component c (as no fixed costs are considered), with the decision variable of the nominal capacity $P_c^{nominal}$, CRF is the capital recovery factor (CRF) based on the weighted average cost of capital $wacc$ according to equation 3.

$$CRF = \frac{(1 - wacc)^{\tau_d} * wacc}{(1 - wacc)^{\tau_d} - 1} \tag{3}$$

In the objective, OPX_c^{fix} are fixed operating expenditures, e.g. operation and maintenance costs, while opx_c^{var} are variable operating expenses linked to the associated flows of the component c. The fixed operational costs OPX_c^{fix} are dependent on the initial investment costs $\mathrm{CPX_c}$ of the component c

$$OPX_c^{fix} = \mathrm{CPX_c} * \ opx_c^{fix} \tag{4}$$

Where opx_c^{fix} is a factor for the annual operation and maintenance cost as fraction of the investment costs.

To retain comparability, we assume time and technology independent WACC for our energy system. We assume a WACC of 10% p.a., in alignment with the suggestion of the International Renewable Energy Agency (IRENA) of a 10% WACC p.a. for non-OECD countries and 7.5% p.a. for OECD countries and China in (IRENA, 2020b). However, the WACC may vary with the specific country of project, technology status and even ownership models. The WACC will therefore be included as sensitivity parameter during later analysis.

2.2.1 Constraints

While a balance of respective flow is valid at any node and timestep within the energy system, the entire system-wide energy balance may be formulated as

$$\sum_{c \in C} \dot{E}_{e,c,t} + \dot{C}_{c+,t}^{+} = \dot{D}_{d,t} \ \forall\, c \in C, c^{+} \in C^{+}, d \in D\ e \in E, t \in T \tag{5}$$

where $\dot{E}_{e,c,t}$ describes the energy flow e from/to component c in timestep t, $\dot{C}_{c+,t}^{+}$ the flows from source c^{+} supplying the energy demand $\dot{D}_{d,t}$.
The flow through every component is restricted by its nominal capacity via

$$P_c^{nominal} * p_c^{min} * \Delta t \ \leq \ \dot{E}_{e,c,t} \ \leq P_c^{nominal} * p_c^{max} * \Delta t \ \forall\, c \in C, e \in E, t \in T \tag{6}$$

where p_c^{min} and p_c^{max} indicate minimum and maximum part load respectively.

Individual constraints are set for transformer to respect conversion efficiencies. The ingoing flow $\dot{E}_{iw,t}$ is multiplied by the transformer efficiency η_w to calculate the outgoing flow $\dot{E}_{wj,t}$

$$\dot{E}_{wj,t} = \dot{E}_{iw,t} * \eta_w \ \ \forall\, w \in W, t \in T. \tag{7}$$

The state of charge of a storage varies from one time step to the next. Depending on the energy flow $\dot{E}_{is,t}$ provided to the storage, the self-discharge rate η_s^{self}, the charge efficiency η_s^{char} and the discharge efficiency η_s^{dis} the SOC is calculated via

$$SOC_{s,t+1} = SOC_{s,t} * \left(1 - \eta_s^{self} \Delta t\right) + \left(\eta_s^{char} * \sum_{(i,s) \in L} \dot{E}_{is,t} - \frac{1}{\eta_s^{dis}} * \sum_{(s,j) \in L} \dot{E}_{sj,t}\right) \Delta t \ \forall\, , s \in S, t \in T \quad . \tag{8}$$

The final SOC at the end of each simulation year is set equal to the initial SOC. This allows to simulate a typical year of system operation, while not being distorted by annual variations over the project lifetime.

3. RESULTS

In this section, we evaluate the economic competitiveness of P2H2P as a backup technology in SSA mini-grids for various scenarios considered. First, we quantify the impact of varying selected parameters on the competitiveness of P2H2P against the DG and battery separately in section 3.1. Second, we create scenarios to evaluate P2H2P competitiveness in a complete integrated system, building on trends in literature and findings from section 3.1.

3.1 Measuring impact of parameters

We analyze the effect of varying parameters on the economic competitiveness of P2H2P against the DG and the battery separately. Therefore, we constrain the system to a) exclude the battery but allow for hydrogen storage and b) to only use renewable energy – notably excluding the DG – during system optimization respectively. To quantify an effect size, we measure i) the optimized electrical output power of the backup technologies in Figure 2 and ii) the share of electricity supplied by the type of technology in Figure 3. For each subplot of Figure 2, the front right corner of the cube indicates the constellation of today's reference values, including current CAPEX costs for the P2H2P system (1,000 USD/kW$_{el}$ for EL and 2,600 USD/kW$_{el}$ for the FC). The CAPEX for both main components of the P2H2P system are subsequently reduced in steps of 10% absolute to the base case along the x-axis, while the respective other sensitivity parameter changes along the y-axis. Optimal technology output power is plotted along the z-axis and illustrated by the green (FC), red (DG), and blue (battery) surface.

P2H2P is only included in the optimized 100% renewable energy system under today´s conditions, see Figure 2 i.1) and i.2). The total annualized system costs amount to 164,587 USD (LCOE of 0.34 USD/kWh) in case of exclusion of the battery, and 211,924 USD (LOCE of 0.44 USD/kWh) for the 100% renewable system. The optimal system topology in the case of a PV – DG system includes 100 kWp PV and 74.6 kW$_{el}$ DG. The optimized PV – battery – P2H2P system consists of 383.9 kWp PV, 25.85 kW$_{el}$ EL, 40.25 kW$_{el}$ FC, 5,698 kWh hydrogen storage, and 1,495 kWh battery storage. Figure A.3 and Figure A.4 of the Appendix present the optimal operational behavior of the system components for a representative day of the year. In the PV – battery – FC system, excess electricity produced by PV during extraordinary sunny days is converted to hydrogen by the FC. After a sequence of days with low irradiation, the FC reconverts stored hydrogen to electricity at maximum operating capacity during the morning hours. The share of electricity load supplied by the FC amount to 2.7%, see Figure 6).

P2H2P systems may decline in CAPEX by 40% by 2030, and by more than 80% by 2050 (IRENA, 2020a). Notably, for small-scale systems, we may consider a lower decline in costs than for large-scale systems, which benefit from economies of scale. Only reducing the CAPEX of the P2H2P system by 40% leads to economic viable integration of P2H2P in the diesel – P2H2P system. Further CAPEX decline causes an exponential increase of the FC to approximately 20 kW$_{el}$. However, the share of electricity supplied by the FC remains below 5%, see Figure 3 i). Decreasing the P2H2P CAPEX in a battery – P2H2P system has less impact on the optimal FC power, considering the large capacity given at today´s conditions. However, Figure 3 i.2) shows a linear increase in FC size by 13% at a cost reduction of 80% - expected by the IRENA for 2050 (IRENA, 2020a). The share of electricity demand satisfied by the fuel cell increases to almost 8%.
While only increasing the CAPEX of the DG does not significantly influence the results, increasing the battery CAPEX has a contrary influence on the share of electricity supplied by the FC. While both capacity and power of the battery decrease (by approximately 10%) when increasing the battery CAPEX to 332.5USD/kWh, the FC output power remains almost constant, but the share of electricity supplied by the FC triples to almost 10%. Simultaneously, the optimal EL input power increases by 150%. Required hydrogen storage capacity decreases by 10%.

The efficiency of P2H2P systems is likely to increase with ongoing commercialization (Buttler & Spliethoff, 2018). PEMEL systems are expected to increase in efficiency from today´s 60% up to 70%

by 2050 (Tom Smolinka et al., 2018), AEL up to 70%. High-temperature SOEL systems may reach 85% efficiency already in 2030 (Tom Smolinka et al., 2018). Considering analogous development for the FC, Figure 2 ii.1) and Figure 3 i) show significant impact on the optimal size and energy supply by the FC respectively. Increasing the efficiency of both EL and FC by a factor of 1.4 (84% and 77% efficiency respectively), the optimal FC power exceeds the installed DG power in a diesel – P2H2P system when considering a cost reduction by 80%. Considering such efficiencies of high-temperature P2H2P in the scenario lead to the FC contributing to 44% of the electricity supply, while 43% is covered by PV generation directly and only 12% of the supply is generated by the DG. Observing the same effect size in the battery – P2H2P system shows even greater effect on the share of electricity supplied by the FC. While the output power of the FC decreases with increasing efficiency, the contribution to electricity load satisfaction increases to 20% (battery 36%), when considering high temperature P2H2P efficiencies.

Our analysis assumes a likely increase in future diesel prices (U.S. Energy Information Administration, 2021). Increasing the fuel price shows remarkable effects against the DG, see Figure 2 iii.1). When increasing the fuel price to 1.5USD/l, a combination of DG and P2H2P is meaningful under today´s specific investment costs. The break-even point at which the FC´s power and share of energy supply exceeds the DG´s supply is reached at 2.86USD/l cost of diesel. The FC (70.13 kW_{el}) and PV contribute to 32% and 44% of the electricity supply respectively, while the DG accounts for 24%. Further increasing the fuel price follows the trend. However, at a fuel price of 3USD, the DG still contributes 12% of the annual electricity supply, operating for a few days with low solar irradiation.

We analyze the effect of decreasing the battery DoD to 80% in Figure 2 iii. 2) and Figure 3 ii), which is today´s standard for lithium-ion technologies (Spataru & Bouffaron, 2016). The results show a small decline in both FC and EL power by 2% and 17% respectively. Battery capacity and output power decrease by 21%, as the share of useful capacity increases. The share of electricity supplied by the battery increases marginally by 1%, which compensates for the decrease of supply by the FC.

The WACC may be expressed as the rate that a company is expected to pay on average to all its finance providers to finance its assets. Accordingly, such assets with high initial costs are relatively more affected by the WACC. With increasing technology maturity and decreasing risks of investment, the WACC might decrease. The IRENA expects the WACC for P2H2P systems to decrease to 0.06 (IRENA, 2020a). Applying this WACC for our system – notably to any component – shows linear increase of the FC power in the diesel – P2H2P system. The impact is becomes more visible when considering a cost decline of the P2H2P components, see figure 2 iv.1).

We evaluate the effects of different load distribution by subsequently changing the load profile towards a peak-shaped profile in Figure 2 v) and Figure 3. Notably, in this scenario, the absolute peak demand occurring at the evening subsequently increases to 199 kW, as we maintain the same amount of total energy demand. Comparing the P2H2P system and DG in Figure 2 v.1) we see that such distribution of the load benefits the economic performance of the DG. Both power and share of electricity supply increase in relative terms, while the share of renewable energy supply decreases below 25%. Analyzing the same effect size in a battery – P2H2P system shows a similar trend. While both battery and FC optimal power output increase (the FC only slightly), the share of electricity supplied by the battery increases to 67% (comparing 54% in the base case). The contribution of the FC remains unaffected with operating times during the early morning hours.

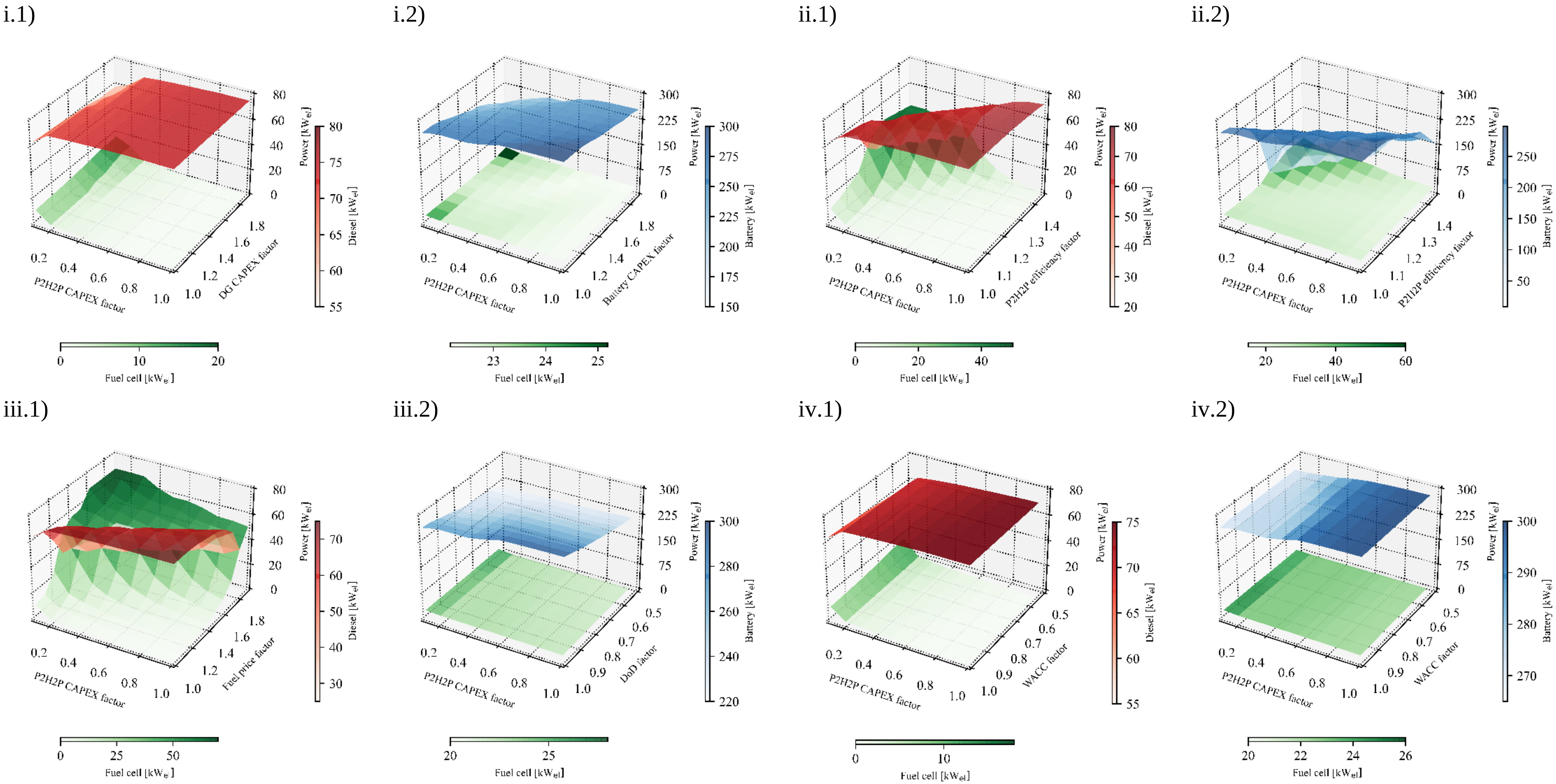

Figure 2: Optimal FC (green surface), DG (red surface) and battery (blue surface) output power at declining P2H2P CAPEX and variable parameter: i.1) DG CAPEX, i.2) Battery CAPEX; ii.1), ii.2) P2H2P efficiency; iii.1) Fuel price, iii.2) DoD; iv.1), iv.2) WACC; v.1), v.2) Load profile (evolving towards peak profile) vi.1), vi.2) Seasonality index.

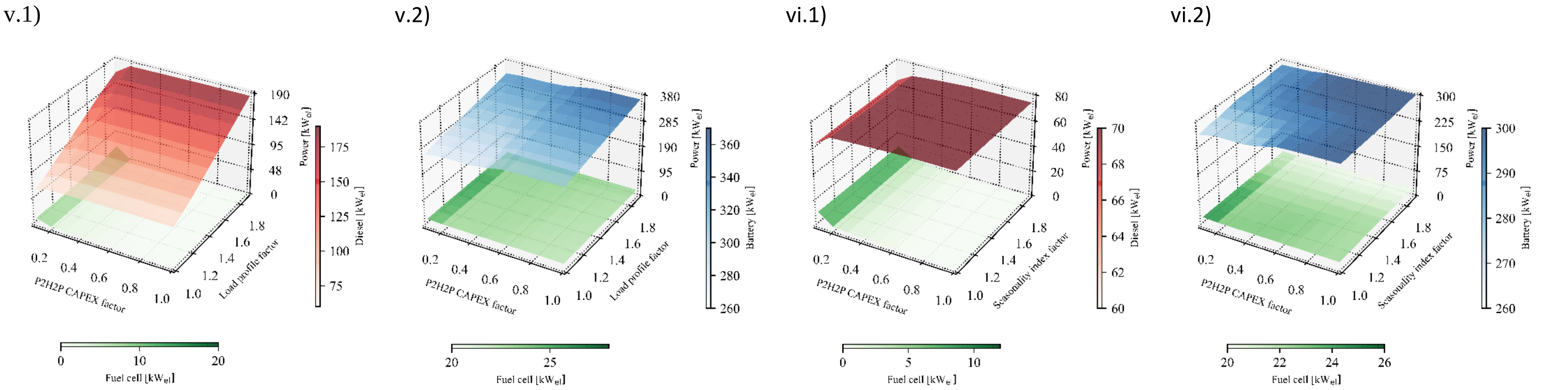

Figure 2 continuation.

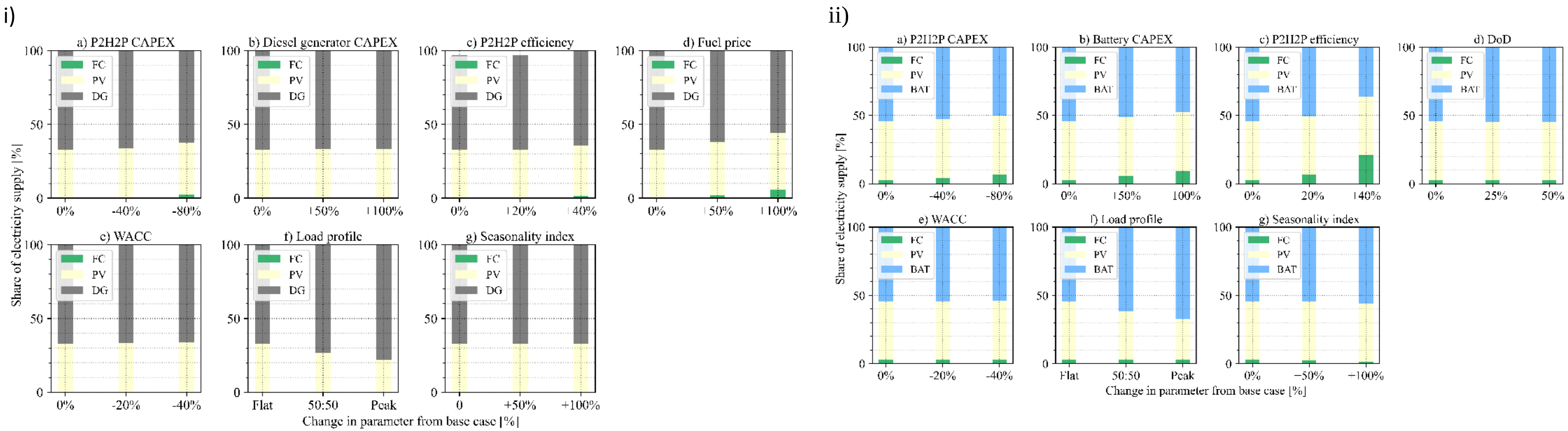

Figure 3: Share of electricity supply by PV, FC, and DG (a) or PV, FC, and battery (b) for varying sensitivity parameters.

Spread in seasonal variation of PV irradiation is limited on the African continent. However, we analyze the effect of increasing the seasonality to a maximum considerable for the continent. At the maximum considerable increase, the optimal FC power decrease when a DG is the only alternative, see Figure 2 vi.1). However, the relative share of electricity supply by the FC remains the same, as more PV generation can be utilized directly and compensates for the decrease in diesel generation (Figure 3 ii). A similar trend is observed when comparing to the battery, see Figure 2 vi.2). However, in this scenario, the optimal P2H2P power is reduced by 10%, while the battery power remains stable, as more PV generation can be utilized directly.

3.2 Economic competitiveness

Taking up outcomes from the previous results, this section presents results on the techno-economic performance of P2H2P while granting the solver total freedom of choice of the backup technologies. We analyze the optimal size of FC and EL under various conditions. As a prominent issue of discussion in literature, we shed light on a future potential decrease in CAPEX of P2H2P systems. We combine such development with those parameters that have proven to be a significant driver of the competitiveness of P2H2P in section 3.1. We combine these trends in the results of figure 4:

- Diesel fuel price: We consider increasing diesel fuel price. As precise estimations of future diesel prices are vague, we artificially increase the fuel price. However, we lean on a common assumption of a 5% annual fuel price increase in relevant representative settings (GIZ, 2016; Mainali & Dhital, 2015). (Notably, this is not a common integration of a fuel escalation rate, which would imply subsequently increasing the reference fuel price by 5% during system optimization over the project lifetime. Instead, we apply the absolute increased fuel price values without fuel escalation rate to simulate a project to take place at a certain time in future).
- P2H2P efficiency: Improvements in efficiency of low-temperature P2H2P systems are likely to occur with increasing market maturity. We consider increasing efficiencies of the EL to 73%, which is expected by the IRENA as the lower border to be reached by 2050 for both PEMEL and AEL(IRENA, 2020a), while the same source indicates 66% efficiency as today´s maximum. As analogous expectations for the FC are vague in literature, we assume similar trends for the FC. We therefore assume 70% efficiency for a PEMFC to be reachable in future, referring to today´s maximum of 65% (ESMAP & World Bank Group, 2020).
- Battery technology: We have seen both technical parameters and specific costs of the battery storage to influence the competitiveness of P2H2P. Therefore, we repeat the optimization for a lead-acid battery (as described in section 2), and a lithium-ion battery– that is with a C-rate of 0.5, DoD of 80%, efficiency of 95%, and Capex of 400 USD/kWh (see section 2.1.3).

Figure 4 shows the optimal FC (left) and EL (right) electrical power. The bottom left of each figure represents today’s assumptions on P2H2P CAPEX and diesel price, as described in Section 2. Following the ordinate, the costs of the FC (FC) and EL (EL) are subsequently reduced in steps of 10% absolute to the reference value each. Analogous, the fuel price is increased in equal steps of 20% absolute to the base case along the abscissa. With this, the most preferable conditions for the P2H2P system would be represented at the top right of each subfigure. While the annotated numbers express the optimized electrical power of the FC (left) and EL (right), the black line accordingly marks limits, under which constellation of parameter an integration of P2H2P improves the economic result of the energy system – thereby indicating thresholds for financial viability of P2H2P. Analogous the black dashed line shows thresholds in case of substituting the lead-acid battery with a lithium-ion battery. The blue dashed line develops financial viability limits in case of increasing the efficiency of the P2H2P system as described above.

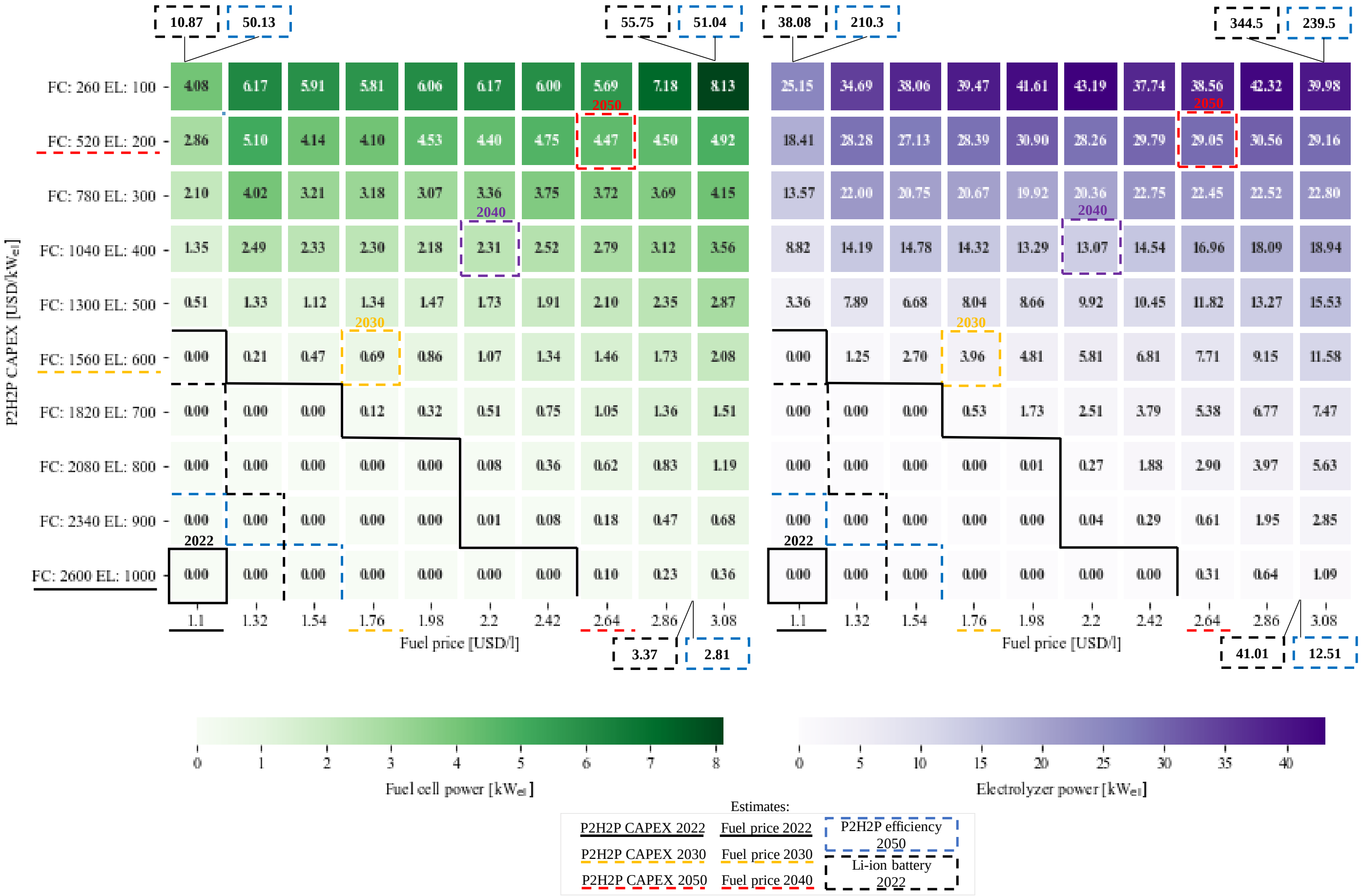

Figure 4 Optimal electrical FC power (left) and EL power (right) for varying P2H2P CAPEX and fuel price in an integrated system with a battery, P2H2P and DG as backup options.

According to our analysis, P2H2P application for African mini-grids is not economically viable under today´s conditions without constraining the usage of diesel fuel or battery. The optimal system topology for the mini-grid today includes 143 kWp PV, 47.8 kW DG, and 274 kWh battery capacity. The share of renewable energy in the system is 49.92%, while 7% of electricity is produced in excess. The stake of costs is dominated by fuel costs 60%). PV accounts for 63% of the investment costs. Assuming today´s efficiencies with 60% and 55% efficiency for EL and FC requires further cost reduction of 50% for profitable P2H2P integration. Notably, such a cost decline may be expected until 2040, when assuming linear cost decline following recent trends (IRENA, 2020a). Further decreasing the CAPEX supports the trend of increasing P2H2P competitiveness.

Considering efficiencies of 73% and 70% efficiency of electrolyzer and fuel cell as might be expected when following technology improvements until 2050, a 20% decrease in P2H2P CAPEX leads to integration of P2H2P into the least cost system. Notably, a 20% decrease in P2H2P CAPEX can be estimated before 2030 for large scale systems (IRENA, 2020a).

When only increasing the fuel price under today´s P2H2P efficiency and CAPEX, the P2H2P system is economically competitive at a diesel price of 2.62 USD/l. Notably, increased costs of lithium-ion batteries compared to common lead-acid batteries do not overcome technical improvements in our economic evaluation. In case of substituting the cheap lead-acid battery with a lithium-ion battery (black-dashed line), required fuel price would decrease to 1.54 USD/l, which can be expected in our setting for 2030.

Various combinations of expected fuel price and P2H2P CAPEX showcase scenarios of economical improvements in the energy system when integrating P2H2P. As an example, following future trends until 2030, thereby assuming a specific investment costs of 2,060 USD/kW$_{el}$ and 800 USD/kW$_{el}$ for fuel cell and electrolyzer respectively, and a diesel price of 1.76 USD/l includes the P2H2P system in

the optimal energy system. Following the trends until 2040 results in a fuel cell of 3.27 kW_{el} and electrolyzer of 22.45 kW_{el}.
We combine the results of our explorative analysis to create three future scenarios, in which we consider simultaneous development of P2H2P CAPEX, P2H2P efficiency and fuel price as considered for the years of 2030, 2040, and 2050 and summarized in table 4.

Table 4: Selected parameter estimated in the future.

Year	P2H2P CAPEX [USD/kW_{el}]		Fuel Price [USD/l]	Electrical efficiency [% LHV]	
	EL	FC		EL	FC
2022	1,000	2,600	1.1	60	55
2030	600	1,560	1.76	64.5	60
2040	400	1,040	2.64	69	65
2050	200	520	4.21	73	70

Table 5 summarizes the total annualized system costs (TACs), renewable energy share, and excess electricity generation for different energy system topologies in the respective scenarios.

Table 5: TAC, renewable energy share and excess electricity for different energy system topologies and parameter constellation estimated in future (see table 4).
*Simplified assumptions for a lithium-ion technology considered as described in section 3.1.
**Optimal energy system topology under given parameter constellation does not include P2H2P.

Year	Indicator	PV/BAT	PV/DG	PV/P2H2P	PV/BAT/ DG	PV/BA/DG/ P2H2P	PV/DG/ P2H2P	PV/BAT/ P2H2P
2022	TAC [USD]	272,963	164,857	348,074	160,831	/**	/**	211,924
	RE share [%]	100	36.02	100	49.92	/**	/**	100
	Excess generation [%]	50.5	3.06	7.09	2.27	/**	/**	14.1.7
2030	TAC	349,351	229,113	266,189	177,584	177,352	222,202	199,653
	RE share	100*	41.05	100	95.4	95.6	60.68	100
	Excess generation	58.3*	7.2	5.77	6.5	5.23	1.25	5.1
2040	TAC	349,351	312,191	220,634	183,876	180,324	212,448	190,990
	RE share	100*	45.87	100	97.11	98.11	97.54	100
	Excess generation	58.3*	12.3	5.68	9.02	5.96	3.56	4.65
2050	TAC	349,351	456,186	184,230	191,288	177,497	182,736	179,216
	RE share	100*	51.25	100	98.13	99.62	99.44	100
	Excess generation	58.3*	18.89	5.64	12.36	6.52	6.54	5.55

The overview of TACs for the respective energy systems suggest the trend that the combination of battery storage and P2H2P result in the lowest system costs when following future developments. Systems including P2H2P follow trends of declining costs, while systems including a DG follow opposite trends. However, the exclusion of the DG from optimal energy system topology is only economically viable beyond 2050 – if not constraining the system towards a 100% renewable energy supply. Table 6 details the optimization results for the scenarios considering a combination of PV, P2H2P, battery storage and DG, including optimized P2H2P power and share of electricity supply. The results show a constant increase in the optimal size of P2H2P systems with expected future development. The share of electricity supply to the total demand is 26.9% in the scenario of 2050. In this scenario, the FC substitutes the former DG supplies base-load electricity during the night. An analysis of the operational behavior shows that the FC constantly operates during the night at maximum capacity, while the battery additionally discharges power varying dynamically to supply during peak hours.

Table 6: Optimal PV/BAT/P2H2P/DG system topology (output power) for parameter constellation estimated in the future.

Year	**P2H2P power [kW$_{el}$]**		**Battery power [kW$_{el}$]**	**DG power [kW$_{el}$]**	**PV power [kWp]**
	EL	FC			
2022	0	0	247	47.8	143
2030	8	1.53	286.93	23.5	332.5
2040	41.19	8.6	253.65	17.92	364.9
2050	133.46	26.98	161.72	10.25	419.93

Comparing the exclusive usage of only one back-up technology, table 5 suggests the battery storage to the most cost-efficient technology today. However, this solution would be approximately 30% more expensive than a combination of battery and P2H2P. Exclusive use of P2H2P will result in lower system costs compared to exclusive use of a DG beyond 2030.

4. DISCUSSION AND IMPLICATIONS

In contrast to previous literature, this paper analyzes the economic competitiveness of P2H2P against DGs and batteries on a representative archetypal African-based mini-grid rather than a case study. Therefore, we expect the findings of the paper including sensitivity analysis to be transferable to a wide spectrum of mini-grids on the African continent.

As global and national policies aim for decarbonization of the energy sector, stakeholders involved in off-grid electrification including mini-grid operators are confronted with the challenge to develop 100% renewable systems. As most prominent solution, PV-battery mini-grids are proposed, while PV systems may be significantly oversized when aiming for a high reliability of supply (Energy and Environment Partnership Trust Fund, 2019). The results of our analysis (section 3.1), however, suggest that when aiming for 100% decarbonization of minigrids, a combination of P2H2P and battery is the least cost option, rather than battery-only systems. This remarkable finding leads us to arguing that battery and P2H2P must not be seen as competitors for future system planning, but as a cost-efficient combination. However, our results do not show P2H2P to be a substitute for battery storage in near future. Future work should include optimizing coupling and operational concepts of battery and P2H2P systems, notably potentially leading to increased economic performance of the system.

The specific investment costs of P2H2P systems are a prominent issue of skepticism towards successful market uptake in the considered application of supplying power through rural African mini-grids. However, studies show that potential learning rates for FCs and ELs are similar to solar PV and can reach values between 16% and 21%. With such learning rates – notably building on an increased number of system deployments on a pathway in line with a 1.5°C climate target – a reduction in the cost of P2H2P systems of over 40% may be achievable by 2030 (ESMAP & World Bank Group, 2020). Our results show a significant decrease in CAPEX by more than 50% – expected by the IRENA between 2030 and 2040 – is required to integrate the P2H2P system into the optimal energy system under today´s parameter constellation. However, our analysis indicates the P2H2P CAPEX to be a less important driver for its economic competitiveness than the P2H2P efficiency and the diesel price.
The efficiency of the P2H2P system influences both P2H2P investment costs – as impacting the required installed power – and operating costs – determining the required energy input. As with ongoing technology development, the efficiency is expected to increase further (Tom Smolinka et al., 2018), future competitiveness of P2H2P may be improved. Notably, our study shows that such enhanced competitiveness due to increased efficiency leads to cost advantages against the DG and battery. We see the P2H2P system substitute the share of energy supplied by both alternative back-up technologies.
As we see the efficiency of the P2H2P system to gain significantly more impact on the P2H2P performance than specific investment costs, we argue that future technical improvements are of more relevance in the considered application than system cost reduction, e.g. via increased unit production. Therefore, integration routes of high-efficient high-temperature P2H2P should be explored.

Interestingly, Roeben et al. find similar evidence in a very contrary setting of decarbonizing a copper production process via integration of hydrogen as a substitute for natural gas in northern Germany (Roeben et al., 2021). This may suggest that the prominent perceived obstacle of high P2H2P investment costs may only pose an initial obstacle to the investor, while being a less decisive lever over a project lifetime. Thus, effective measures to reduce the upfront financial burden may be discussed for hydrogen technologies to accelerate the uptake of the solutions via the private sector.

Still, most African countries have in place subsidies for fossil fuels to enable access to electricity for a wider part of the population (International Monetary Fund, 2013). However, previous research has already demonstrated that removing subsidies on fossil fuels in Africa would lead to fiscal, environmental, and welfare gains (Coady, Parry, Sears, & Shang, 2015). More directly, fossil fuel subsidies are known to be obstructive to a broad integration of renewable energies in mini-grids (Bertheau, Cader, Huyskens, & Blechinger, 2015). Fossil fuel subsidies have shown to be a main barrier to off-grid electrification in Tanzania and Mozambique, along with low household income and lack of private investment (Ahlborg & Hammar, 2014). Our study confirms the importance of rethinking the allocation of financial resources in electrification. The results demonstrate the crucial influence of the diesel fuel price on the competitiveness of P2H2P against the DG. When following policy targets in line with a 1.5°C climate target and the SDGs, energy systems facilitating a maximum share of renewable energy must be supported. Therefore, we argue, that shifting fuel subsidies towards P2H2P may facilitate reaching ambitious political goals while reducing the national financial burden – especially when considering increasing diesel prices in the future.

During sensitivity analysis, we modified the shape of the considered load profile from a *flat* profile to a *peak* profile (Lorenzoni et al., 2020), while keeping the total energy demand constant (see section 2.1.1). Previous literature has shown such profiles often occurring in small to very-small scale mini-grids with low Tier-level of connections (Lorenzoni et al., 2020). From our analysis, we observe negative effects on the competitiveness of both the P2H2P system and the battery compared to a direct supply by PV and DG, when applying a *peak* profile. While this may suggest PV – diesel-supplied electrification because of today´s subsidized diesel prices, the analysis of operational behavior of our system suggests a PV-battery combination as a likely future solution for such systems – given that diesel prices for end-user will increase. As P2H2P contributes to base-load supply rather than serving peaks, which would require costly power output, *flat* profiles are more beneficial to P2H2P systems. This suggests for P2H2P a target market of larger mini-grids, as with increasing system size and coincidence factor of connections (Willis, 2002), aggregated system loads tend to occur flatter.

Our study compared the considered backup options regarding their purpose of power supply. As highlighted in the introduction, a potential advantage of hydrogen against its competing backup technologies is its multi-usability. Hydrogen can be utilized as clean cooking fuel in isolated villages (Topriska et al., 2016; Topriska et al., 2015). Including such additional usage in a techno-economic analysis could potentially impact the competitiveness of hydrogen. For example, diversifying the application of hydrogen leading to larger capacities of the P2H2P components could trigger economy-of-scale effects of the electrolyzer especially, increasing the economic performance of P2H2P itself. Further, producing hydrogen as a clean cooking fuel would lead to an increased utilization of the electrolyzer, and increased overall electricity demand. Such increased utilization of assets evidently improves the economic performance of the energy system (AMDA, 2020). In the past, a variety of “anchor loads" – that are more predictable loads with high demand – have been suggested. The actual energy use of such loads is manifold and include commercial activities and productive use applications (AMDA, 2020). The use of energy to produce clean cooking fuel may be an alternative energy service and a potential pathway to harmonize efforts within the SDG 7 – increasing the access to clean cooking fuels while stimulating the electrification sector. We propose to investigate the relationship between the additional usage of hydrogen as clean cooking fuel and the economic energy system performance in future work. Based on the findings, appropriate business and distribution models may be discussed.

5. CONCLUSION

Our work analyzes the techno-economic potential of integrating P2H2P as a power supply technology into isolated mini-grids in rural Africa. The paper develops a linear-problem-based energy system model of an archetypal mini-grid and investigates the effects of varying technical, economic, and project-setting parameters on the competitiveness of P2H2P against common backup options of DG and battery.

Our analysis finds that, under current technical and market conditions, the integration of P2H2P into African mini-grid energy systems is only economically beneficial when combined with battery storage. Considering 100% decarbonized systems, a combination of battery and P2H2P results in lower electricity production costs, as a battery-only system. However, further developments are required to make P2H2P a financially sustainable solution in combination with both DG and battery, when not restricting the carbon emissions. The sensitivity analysis identifies the P2H2P efficiency, affecting both investment and operational costs, to have the highest potential for improving the system´s economic performance. Increasing the diesel price shows an effect of similar magnitude. At a fuel price of 2.6USD/l, combining P2H2P with battery and DG is the optimal choice for the least-cost electrification through mini-grids at highest level of security of supply. Following likely future trends of decreasing P2H2P CAPEX and increasing fuel price leads to increased P2H2P competitiveness. The results suggest future PV mini-grids combining battery and P2H2P backup technologies, while the DG may not be cost-competitive.

The analysis shows that reducing the investment costs of P2H2P systems in line with expected technology development significantly improves the economic performance of the P2H2P system. However, the effects may be smaller than could be expected, given the prominence of discussion on high investment costs. Therefore, the high initial costs may pose a temporary barrier to investors lacking access to financial resources, rather than being a major lever when considered over a project lifetime. The authors suggest rethinking the allocation of financial subsidies for fossil fuels to reduce the initial burden of investors if aiming to trigger the private sector for uptake of P2H2P systems in rural mini-grids and follow policies in line with the SDGs. Further, the additional usage of hydrogen as clean cooking fuel, should be explored. Such usage could harmonize efforts withing SDG 7, as the predictable electricity consumption used to generate clean cooking fuel via water electrolysis may be seen as an anchor load to the mini-grid operator. Such anchor loads increase the utilization of the mini-grid assets, and thereby offer the potential to improve the economic performance of the minigrid electricity system. We propose to analyze effects of such multifold usage of hydrogen on the minigrid system and discuss potential use cases.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTION

Nikolas Schöne: Conceptualization, Data Curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – reviewing and editing. **Jassem Khairallah**: Software, Visualization, Writing – reviewing and editing. **Boris Heinz**: Supervision, Writing – reviewing and editing.

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6. APPENDIX

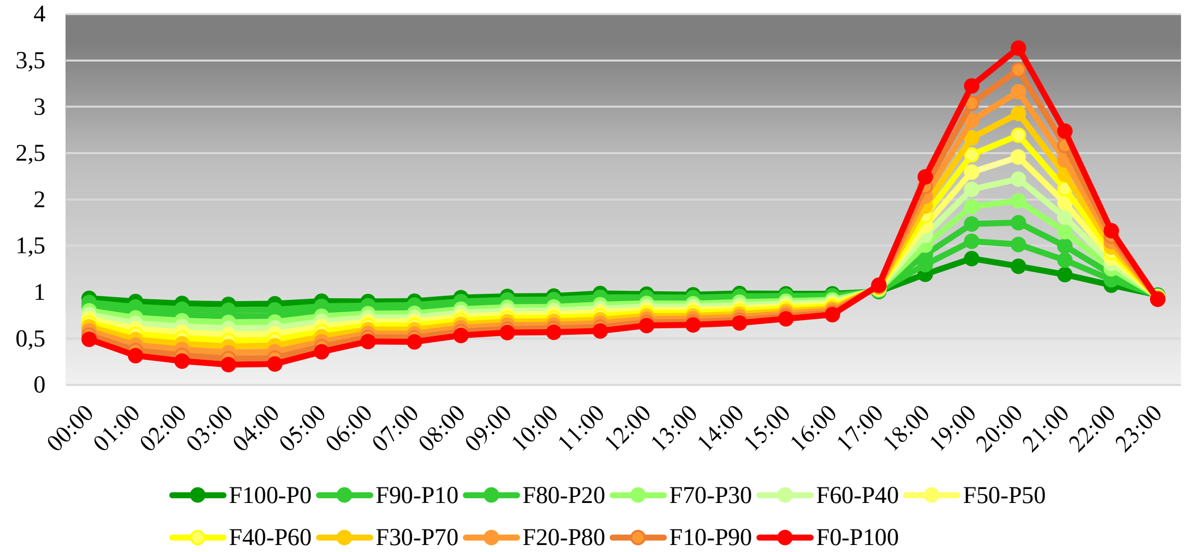

Figure A.1: Normalized demand profiles considered in our analysis. Transformation of a flat profile (F100 – P0) to a peak-profile (F0 – P100) in steps of 10%.

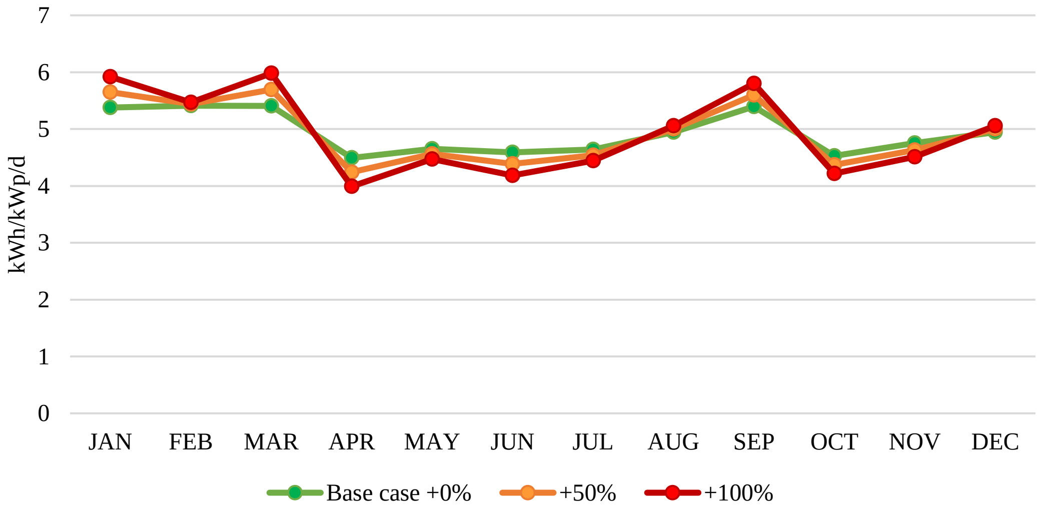

Figure A.2: Seasonal PV production profiles considered in our analysis. Transformation from the base case (simplified seasonality index = 1.24) to increased seasonality (simplified seasonality index = 1.54).

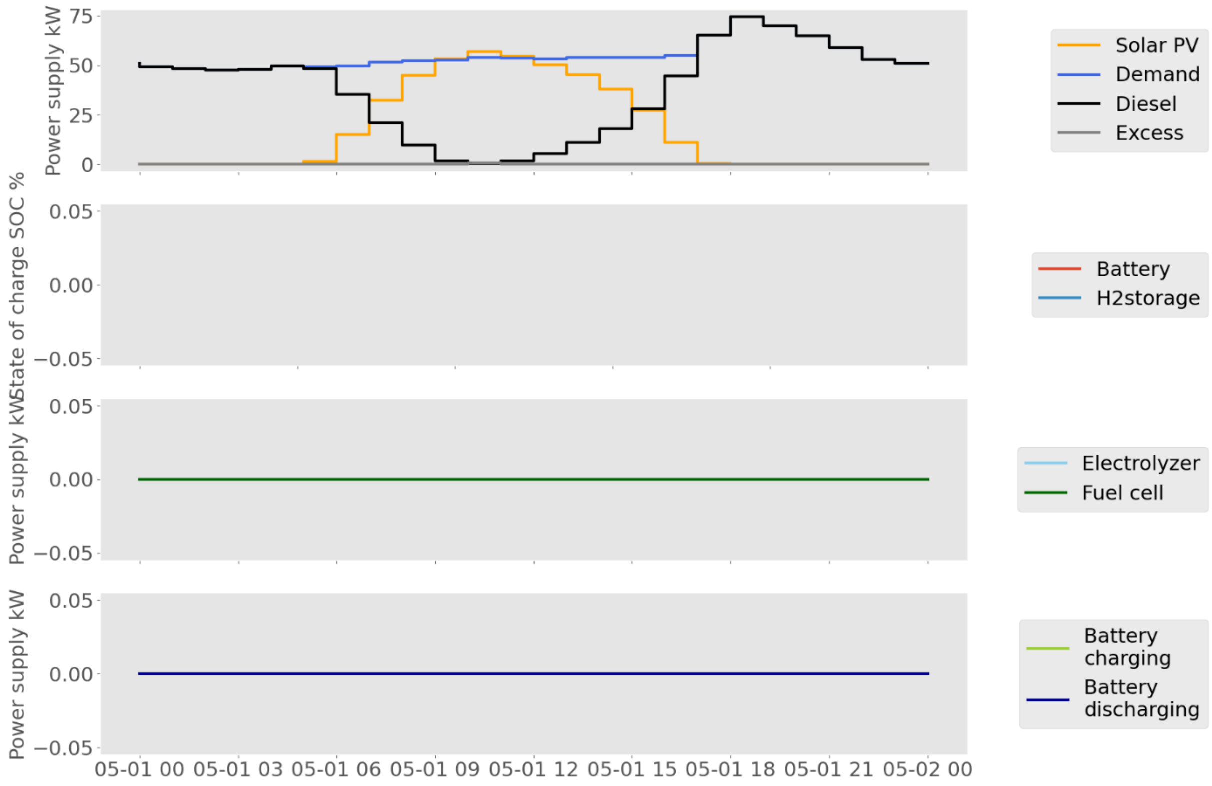

Figure A.3: Optimal operational behavior of the system components considering a system of DG and P2H2P only for a representative day of the year.

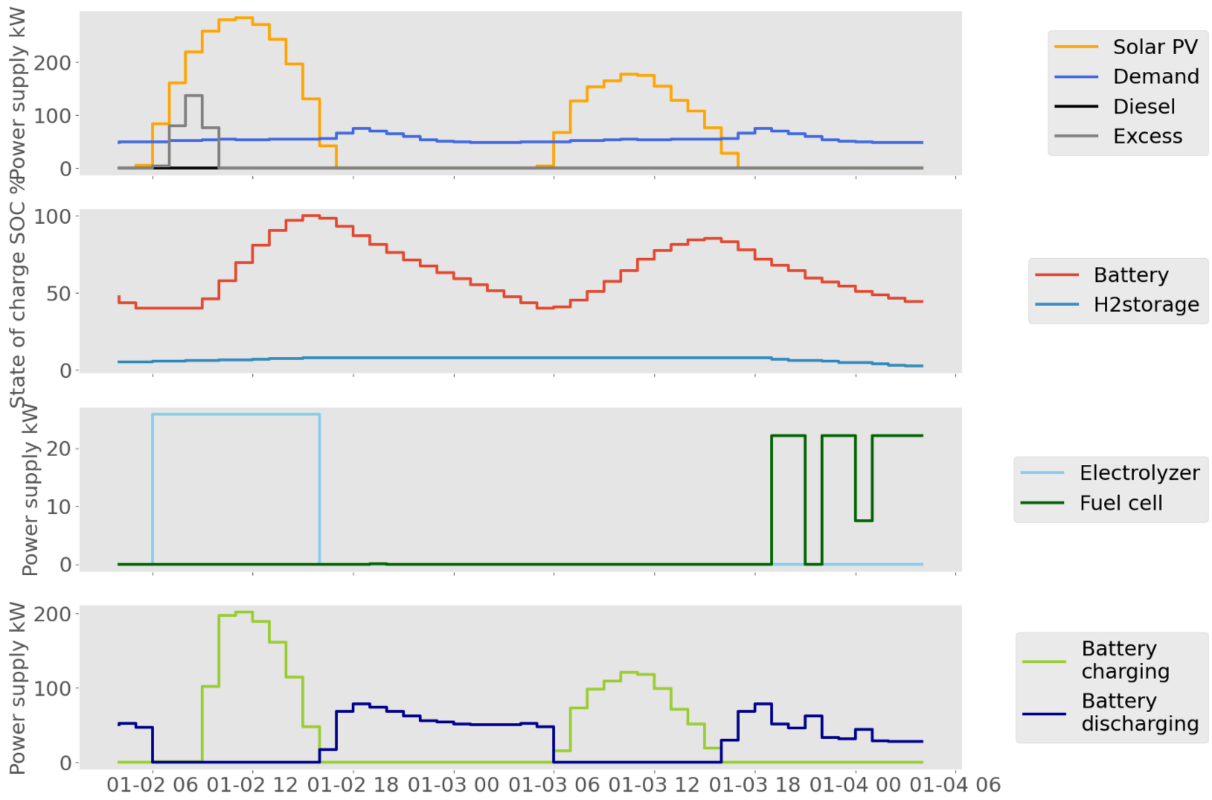

Figure A.4: Optimal operational behavior of the system components considering a system of battery and P2H2P only for a representative day of the year.

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