The Potential of Hydrogen-Based Storage Systems in Sub-saharan Africa

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Abstract. Photovoltaic power systems and mini-grids with energy storage in form of electrochemical batteries are becoming more widespread and are playing an increasingly important role in energy supply. By design, photovoltaic-based power systems often generate a surplus of electrical energy during favourable weather conditions and low electricity demand. Measures such as demand-side management can increase energy use when energy is available. However, when feed-in is not possible, either because a system is off-grid or due to technical or regulatory reasons, photovoltaic generators are either shut down or their output is reduced when energy storage is full and demand is low, resulting in less energy production than theoretically possible and leaving resources unused. One solution for using excess power is to store it in form of hydrogen, using an electrolyser and a storage tank. Energy stored in the form of hydrogen can have multiple usages, such as mid-term, seasonal energy storage, e.g., to bridge low energy production during winter or during a rainy season. Thus, hydrogen-based energy storage can play an important role to decarbonize energy systems in the near future. Based on measurements of an existing 165 kWp distributed mini-grid in Tema, Ghana, a model was created to simulate the mini-grid as it currently exists and with an additional hydrogen power plant, including the generation, storage and conversion to electricity with a fuel cell, which is planned to be added to the mini-grid. As the main result it was found that under high-demand conditions, 10% of the total PV production power can be used to electrolyse hydrogen, which can fulfil 6.2% of the systems demand at other times while ensuring a self-sufficient operation of the mini-grid that may not be possible without the hydrogen storage capabilities.

Keywords: Hydrogen · Sub-Saharan Africa · Photovoltaic · Energy Storage · Mini-Grid

1 Introduction

This study investigates the potential of hydrogen-based storage systems in Sub-Saharan Africa based on the simulation of an existing mini-grid installation at the Don Bosco

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campus in Tema (Ghana) as well as the addition of hydrogen generation, storage and fuel cells under different scenarios.

The existing mini-grid energy system is investigated for the hydrogen storage potential, since the theoretical power output of the installed photovoltaic (PV) modules is not met by the energy demand in place. A hydrogen storage system could increase the overall efficiency of the installed system, be viable in financial terms and ensure self-sufficiency in the future with always increasing demands at the site [1]. The hydrogen can be used as flexible long-term energy storage to meet demand when photovoltaic modules generate low amounts of electricity over a long period of time [2]. This decreases the need to buy electricity from the national grid, which is costly and emission-intensive [3].

The load profiles of the mini-grid locations used to model the mini-grid have been collected using the data collection hardware and software developed in the "MoN-aL" project, funded by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection.

This paper researches how the addition of hydrogen production and storage components as well as a fuel cell for electricity production in a decentralized mini-grid affects the efficient usage of the existing photovoltaic production capacity and increases self-sufficiency of the mini-grid.

2 Current Mini-Grid

As of August 2022, the mini-grid installation consists of five independent power systems, with a total photovoltaic generation capacity of 165 kWp. The five power systems in the mini-grid are installed on the school and solar training center, the canteen, the hostel, the church and the provincial house as shown in Fig. 1, while the distribution of the installation capacities to the different locations is shown in Fig. 2.

Each one of the power systems has a battery and an inverter. Batteries of different types are installed, including lead-acid, Li-ion and NaNiCd2 salt batteries. The nominal capacity of the batteries is of 394 kWh, at a discharge rate of C100 (1% per hour). At a more realistic discharge rate of C10 (10% per hour) and taking into consideration a maximal depth of discharge (DoD) of 50% for lead-acid batteries and of 90% for Li-ion and NaNiCd2 salt batteries, results in a total usable capacity of 233 kWh. An overview is given in Table 1.

On days with a good solar irradiation and low energy demand, e.g., on sunny weekends, batteries in the mini-grid are fully charged very early in the day, for instance for the day and location shown in Fig. 3, when the batteries were fully charged at 10 am. The PV power production has consequently been curtailed after batteries have been fully charged and energy demand in the mini-grid was low, while grid feed-in is not allowed, which is displayed in Fig. 4.

An example of the opposite case with bad weather and regular to high energy demand is given in Fig. 5. In this example, the state of charge of the same battery as above has not raised over 50% during the day.

Fig. 1. Satellite picture with annotations for the different mini-grid locations of the installed system.

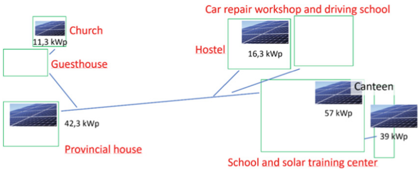


Fig. 2. Distribution of installed photovoltaic generation capacities to locations of the mini-grid.

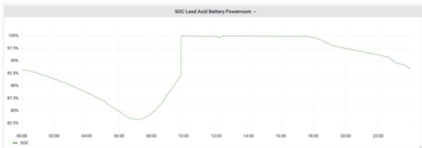


Fig. 3. Battery State of Charge at "School and solar training center" on Sunday, July 23rd, 2022. Favourable weather conditions and low demand result in a fully charged battery very early in the day.

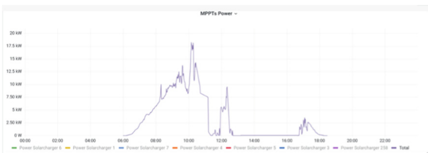


Fig. 4. PV power production at "School and solar training center" on Sunday, July 23rd, 2022. Power generation is curtailed after batteries are fully charged.

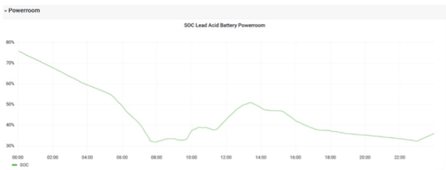


Fig. 5. Battery State of Charge at "School and solar training center" on Monday, August 1st, 2022. Bad weather leads to very low battery state of charge throughout the day.

Table 1. Overview of the battery types installed at the different mini-grid locations including capacities for discharge rates of C100 and C10 as well as the DoD for each battery. C10 is used to estimate the realistically usable capacity.

Installation	Battery type	Battery capacity @ C100 [kWh]	Battery capacity @ C10 [kWh]	Maximal depth of discharge [%]	Usable battery capacity [kWh]
School and solar training center	Lead-acid	174.72	131.52	50	65.76
Chapel	Lead-acid	58.08	43.92	50	21.96
Provincial house	Li-ion ($LiFePO_4$)	30.80	30.80	90	27.72
Provincial house	$NaNiCl_2$	38.60	38.60	90	34.74
Hostel	Li-ion ($LiFePO_4$)	30.80	30.80	90	27.72
Canteen	Li-ion ($LiFePO_4$)	61.60	61.60	90	55.44
Total		394.00	337.24		233.34

3 Simulation Scenarios

In addition to the base scenario of the existing mini-grid different scenarios are simulated to evaluate the effects of adding hydrogen components to the existing system under certain potential future scenarios.

3.1 Base

The Base scenario includes the existing components of the mini-grid as described in chapter 2. It includes a total PV production power of 165 kWp, a total nominal battery capacity of 394 kWh and a total demand of 124 kWh per year at the different locations of the mini-grid.

3.2 Hydrogen

The potential *Hydrogen* scenario includes a set of electrolysers, a hydrogen tank and a set of fuel cells to generate electricity from the stored hydrogen.

Sizing of the hydrogen components has been done after consideration of the energy demand in the mini-grid for a period of time of 36 h that comprises two nights and a day without significant PV energy production. The measured average daily consumption in the whole mini-grid is 190 kWh, while the consumption at night is 151 kWh on

Table 2. Average total consumption for a 36 h period of two nights and one day.

2 x consumption night	302 kWh
1 x consumption day	151 kWh
Total consumption for 36 h	492 kWh

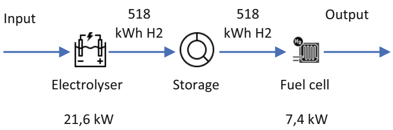


Fig. 6. Schematic Overview of the theoretically needed electrolyser, storage and fuel cell capacities to meet additional demand for a two nights, one day period with full batteries at the start and no PV production.

Table 3. Summary of the additional energy demand needed to fulfil in 36 h period with 2 nights and one day without PV production during that period

Power demand over 36 h: (two nights and one day, no PV production)	492 kWh
Usable battery capacity:	233 kWh
Additional energy demand:	259 kWh

average. Considering the period of two nights and one day results in total consumption of 492kWhs as summarized in Table 2.

Assuming a total usable battery capacity of 233 kWh and full batteries at the beginning of a period of two nights and one day as well as no PV production in that period, the additional energy demand is 259 kWh as summarized in Table 3.

To deliver 259 kWh over a period of time of 36 h, a stack of fuel cells delivering a constant total power of at least 7,4 kWh is needed. Assuming a fuel cell efficiency of 50% and considering the 259 kWh of energy needed from the fuel cell, a hydrogen storage of 2x 259kWh is needed, resulting in 518 kWh hydrogen storage need.

Again, with an assumption of an efficiency of 50% of the electrolyser, the double amount of energy is needed to produce the 518 kWh of stored hydrogen, thus 1036 kWh. The size of the electrolyser depends on the time available to produce the needed hydrogen and assumptions must be made as well: if the electrolyser can produce hydrogen over 8 h a day and there is only one day without PV production a week and 6 days of good solar irradiation, a period of 6x8 hours a week is available for the production of the needed hydrogen. With that, and with the energy needed for the production of the hydrogen, an electrolyser of 1036 kWh / (6 × 8 h) = 21.6 kW is needed as outlined in Fig. 6.

The chosen design in the simulation slightly differs this consideration due to the size of available components on the market. Following components have been chose for a real-life test and thus for the scenarios in the simulations:

- electrolyser: 19 kW,
- hydrogen storage: of 395 kWh,
- fuel cell: 10 kW.

3.3 Increased PV

The *Increased PV* scenario includes an increase of the overall PV generation capacities by 25% per location resulting in a total capacity of 206 kWp. A simulation of this scenario in comparison with these conditions and the additional hydrogen components shows the effects of having additional PV production power in the current system and in a system with hydrogen.

3.4 Increased Demand

In the third simulation scenario *Increased Demand* the demand is increased by scaling all demand curves by a factor of 1.5, thus resulting in an overall increase of electricity demand by 50%. This scenario is also compared with the base scenario and the hydrogen scenario to evaluate the effects of the additional hydrogen plant under these circumstances.

4 Simulation model

Both a mini-grid configuration without and with hydrogen technology has been modelled in the web-based software Kerith[1]. Every location of the mini-grid is modelled as a node with different energy components attached to it as well as connections between the locations reflecting the real system as closely as possible. The energy components used in the model are household rooftop PV modules, generic rechargeable batteries, electricity demands, buy electricity from grid, hydrogen electrolyser, hydrogen tank and hydrogen fuel cell.

The installed peak power capacities are set for the PV components, while the availability timeseries for these is calculated by the software based on historical reanalysis weather data for the location, azimuth angle and tilt angle of the real components [4].

The battery components are modelled as generic rechargeable batteries with a storage capacity and maximum DoD as listed in Table 1 reflecting the real installation as well as the charging and discharge logic implemented in the charging inverters.

Demand components are added to the locations where electricity is used and measured by installed smart meters. The electricity demand for August 2022 was measured by smart meters at the different locations. Based on these measurements, demand curves have been created. For every location, the hourly measurements are grouped by weekday and the hour of the day. For every group (weekday, hour), parameters for a normal

[1] kerith.net.

distribution are obtained in order to draw a value from the corresponding empirical distribution as an estimate for the demand at the non-measured times of the year. The centre of the distributions is estimated with the median of each group instead of an arithmetic mean in order to be less sensitive to outliers in the small sample size. The scale of the distributions is estimated as the lower value of either the distance from the 25% quantile to the 75% quantile or 10% of the median. At the moment of writing, measured consumption data of a whole year has not been available. Applying the consumption of only one month might be the cause for a mismatch in the simulation results, however, the power consumption of the consumers on the mini-grid is quite constant over the year. The geographical location of the mini-grid, close to the equator, leads to a fairly low seasonal variation in the energy demand as well.

For the previously described hydrogen scenario a new node is created. It includes an electrolyser with a power of 19.2 kW, a hydrogen tank with a capacity of 395 kWh and a hydrogen fuel cell with a power of 10 kW reflecting the available components as previously described.

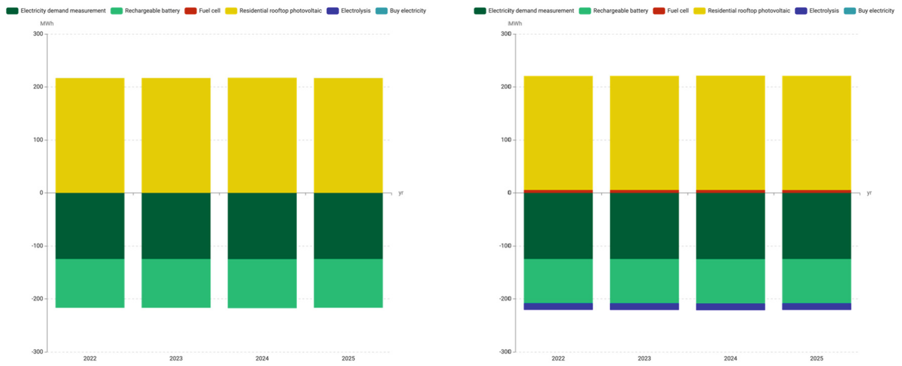
The additional PV scenario is achieved by setting the nominal generation capacities of every PV component to 1.25 times the current value, while the increased demand scenario is achieved by adding a scaling factor of 1.5 to every demand measurement curve in the model.

Overall, the operation of the mini-grid from 2022 until 2025 has been simulated for a combination of every scenario without and with the hydrogen components resulting in eight simulations:

- *Base*
- *Base + Hydrogen*
- *Increased PV*
- *Increased PV + Hydrogen*
- *Increased Demand*
- *Increased Demand + Hydrogen*
- *Increased Demand + PV*
- *Increased Demand + PV + Hydrogen*

5 Results

From the performed simulations different results to assess the operation of the simulated system can be obtained. As a main result, the yearly total energy balances are evaluated. In Fig. 7 the total energy balances for the simulated years 2022 until 2025 are shown. Since the results for the concurrent years do not differ significantly, the results for 2023 are evaluated in more detail as a representative year. In Table 4 a complete overview of the energy balances for the eight simulated scenarios is given.



(a) *Base* (b) *Base + Hydrogen*

Fig. 7. Total electricity energy balances from 2022 until 2025 for the simulation of the existing mini-grid installation without (left) and with hydrogen components added (right). It shows the total energy generated by the PV modules (yellow), the total electricity demanded (dark green), the energy used to charge batteries (light green), the electricity used for hydrogen electrolysis (blue) and electricity generated in the hydrogen fuel cell (red).

Table 4. Overview of the simulation results for the total energy balance in 2023. A positive value indicates that energy is provided by a component, e.g. PV generation, while a negative value indicates that energy is used by a component e.g. electricity for the electrolysis. Values on the left part of the table show electric energy, while values on the right part show energy stored as hydrogen.

	Electricity Energy Balance in MWh						Hydrogen Energy Balance in MWh		
Scenario	demand	electrolysis	fuel cell	PV	battery	buy	electrolysis	fuel cell	hydrogen tank
Base	-124.7	-	-	216.8	-92.2	0.0	-	-	-
Base + Hydrogen	-124.7	-12.6	5.5	215.3	-83.6	0.0	10.5	-10.4	0.0
Increased PV	-124.7	-	-	242.8	-118.1	0.0	-	-	-
Increased PV + Hydrogen	-124.7	-17.4	7.6	174.6	-40.3	0.0	14.5	-14.4	0.0

(*continued*)

Table 4. (*continued*)

	Electricity Energy Balance in MWh						Hydrogen Energy Balance in MWh		
Scenario	demand	electrolysis	fuel cell	PV	battery	buy	electrolysis	fuel cell	hydrogen tank
Increased Demand	-187.0	-	-	245.8	-61.2	2.5	-	-	-
Increased Demand + Hydrogen	-187.0	-26.7	11.7	255.5	-54.0	0.4	22.2	-22.1	0.0
Increased Demand + Increased PV	-187.0	-	-	279.4	-93.4	1.0	-	-	-
Increased Demand + Increased PV + Hydrogen	-187.0	-18.5	8.1	276.1	-78.8	0.0	15.4	-15.3	0.0

6 Discussion

The effects of the hydrogen addition to the system can be discussed for the *Base, Increased PV, Increased Demand* and *Increased Demand + PV* scenario as well as the differences between these three scenarios can be evaluated.

In the *Base + Hydrogen* scenario, 5.9% or 12.6 MWh of the PV generation power are used to electrolyze hydrogen with 10.5 MWh energy content. With this hydrogen 5.5 MWh electricity are generated in the fuel cell with an overall efficiency of 43.7%, while the usage of battery storage decreases by 8.6 MWh or 9.3%. In both simulated scenarios without and with hydrogen, it never occurs that electricity from the grid has to be bought.

In the *Increased PV* scenario, the total PV production increases by 26 MWh as well as the energy used for battery storage. Here, the *+ Hydrogen* scenario results in 68.2 MWh reduction of total PV production power, while 17.4 MWh are used for electrolysis. Since this decrease is technically implausible, we do not rely on the results of this simulation to draw any conclusions. It may occur that this system with highly oversized PV production and no equally high demand leads to instable calculations in the simulation.

In the *Increased Demand* scenario, the total PV generation increased by 29 MWh or 13.4% in comparison to the *Base* scenario in order to meet the high demand, while the energy used for battery storage decreases by 30.9 MWh or 33.6%, since less energy is available for storage. Additionally, 2.5 MWh of electricity have to be bought from the grid in this scenario. Comparing the *Increased Demand + Hydrogen* scenario to these figures shows a decrease of electricity bought from the grid to 0.4 MWh or 84%, which may be due to increased flexibility for energy storage by the additional hydrogen storage capacity. Given the cost of 190 €/MWh this results in savings of 404.5 € per year. Additionally, 26.7 MWh or 10.4% of the total PV generation power, which itself increases by 9.7 MWh or 3.9%, are used for electrolysis which is about twice as much as in the *Base + Hydrogen* scenario. Thus, in a scenario with a highly increased demand the addition of hydrogen to the system would lead to a significant increase of total PV generation power, while still remaining almost completely self-sufficient and independent from the national grid, saving costs as well.

The results for the *Increased PV + Demand* scenarios fit in between those of the *Base* and *Increased Demand* scenarios, while offering no new insights, but not showing the difficulties found for the results of the *Increased PV* scenario.

In conclusion, the addition of hydrogen to the current mini-grid system may be a large investment, but the added value increases for higher demand and higher PV production capacities in the system by maintaining self-sufficiency and independency from the grid as well as increasing the flexibility for long-term energy storage.

7 Outlook

In the future different improvements can be achieved in addition to the work in this study. For once, the accuracy of demand curves can be increased by collecting data from the demand sites over extended time periods. Additionally, the operation of the batteries included in the system can be investigated on a shorter timescale in order to evaluate detailed effects and changes in the flows of energy when adding hydrogen to the system. Furthermore, inconsistencies in the simulation results for systems with a very high PV production power can be studied and understood in the future.

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