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Seasonal energy storage system based on hydrogen for self sufficient living

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ABSTRACT

SELF is a resource independent living and working environment. By on-board renewable electricity generation and storage, it accounts for all aspects of living, such as space heating and cooking as well as providing a purified rainwater supply and wastewater treatment, excluding food supply. Uninterrupted, on-demand energy and water supply are the key challenges. Off-grid renewable power supply fluctuations on daily and seasonal time scales impose production gaps that have to be served by local storage, a function normally fulfilled by the grid. While daily variations only obligate a small storage capacity, requirements for seasonal storage are substantial.

The energy supply for SELF is reviewed based on real meteorological data and demand patterns for Zurich, Switzerland. A battery system with propane for cooking serves as a reference for battery-only and hybrid battery/hydrogen systems. In the latter, hydrogen is used for cooking and electricity generation. The analysis shows that hydrogen is ideal for long term bulk energy storage on a seasonal timescale, while batteries are best suited for short term energy storage. Although the efficiency penalty from hydrogen generation is substantial, in off-grid systems, this parameter is tolerable since the harvesting ratio of photovoltaic energy is limited by storage capacity.

1. Introduction

1.1. Challenges in off-grid renewable energy systems

Moving towards a sustainable energy supply will become a necessity as fossil fuel energy sources are depleted. While integration of renewable energy sources into the grid is on-going, new challenges have to be met in order to achieve future goals for sustainability. Supply must be strictly correlated with demand since electricity is an energy flux and not an energy carrier. Current storage methods on the large scale (100 MWh–100 GWh range) rely on hydropower or compressed air, which offer very low energy storage density per volume and mass, but are capable of high power delivery rates. These methods are strongly location dependent and are therefore not a universal solution. On an intermediate level (1 MWh), solutions based on superconducting coils, flywheels, supercapacitors, and batteries are accessible; the latter two also scale down into the kWh range and are therefore applicable in a variety of situations, also in small off-grid units. Flywheels and supercapacitors are usually applied in situations where high power but low energy density are needed (such as on the timescale of minutes) whereas batteries are better suited to high energy and medium power applications (on the timescale of hours) [1]. Traditionally, regulation of grid demand and supply is performed by balancing production capacities and forecasting expected loads, stabilized by limited energy storage via pumped hydro or similar means. Integration of large quantities of renewable energy dramatically changes the way such a system must be managed. In this case, both supply and demand exhibit fluctuations which escape direct control.

Renewable off-grid systems face similar challenges, but fluctuating input is dominant and load offsetting holds limited potential. The off-grid energy sector is believed to outpace the growth of grid connected renewable systems in the near future [2]. Novel approaches therefore will find an interesting market space to prosper. As buffering supply fluctuations on longer time scales (weeks to months) by batteries is neither economically or technically sensible, resulting gaps are generally filled with generator sets relying on non-renewables. But often, the cost of transporting the fuel to the location largely exceeds the cost of the fuel itself, dramatically affecting cost of energy at the point of use. Producing hydrogen for long term fluctuations is a viable option as storage is comparatively cheap and scales very easily [3]. By this means, the renewable energy production can be maximized which is otherwise limited by storage capacity. Dominant cost driving parameters are the production and reconversion to electricity. Consequently, implementing

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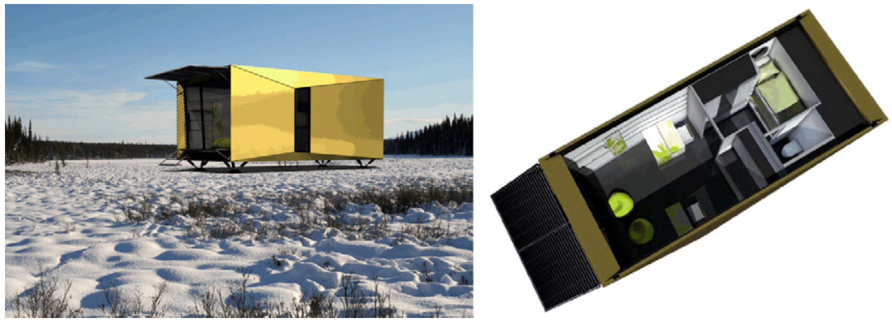

Fig. 1. The SELF stand-alone living unit. The size of the system is 3.5 m × 7.5 m × 3.2 m (W × L × H). The roof accommodates the PV system for energy production.

hydrogen technology for peak power is usually not the best choice. Battery and hydrogen technology are therefore complementary and not mutually exclusive.

Current standard technology relies on coupling wind and/or solar energy sources with lead acid batteries for storage, and complementing gaps by generator sets. While other batteries (NiCd, FeNi, NiMH, Zebra) are used for special applications, particular drawbacks (self-discharge, low charge/discharge efficiency, environmental concerns) prevent widespread application in off-grid systems. Readers with a need for technical details on the different battery technologies are referred to these comprehensive sources [4,5]. Lithium-ion batteries are only beginning to be used for bulk energy storage, driven by developments of high capacity cells for mobility. The main advantages (high round-trip efficiency, no memory effect, high energy density, promising cycle life at high depth of discharge levels) make them interesting for stationary applications. But uncertainties over cost, cycle life, shelf life, and the need for stringent battery management have prevented market penetration. Recent LCA studies showed that the Mn and Fe-based chemistries are environmentally less straining than anticipated and they promise a more environmentally friendly option than current technology [6]. The combination of Lithium-based batteries for short term and hydrogen for long term storage potentially offers unique functionality unavailable by any other approach [7].

1.2. The SELF project

SELF is a mobile, stand-alone living unit and work environment acting as a research and demonstration platform for novel building and energy technology systems (Fig. 1). The scope of the project comprises all aspects of living, ranging from energy supply and storage, water collection and purification, and grey/black water management to space heating and advanced construction technologies for insulation and low energy consumption. The system is transportable and can therefore be deployed on different locations, offering common amenities like a shower, toilet, cooking area, and other services. Stringent requirements on weight and size impose strong restrictions on energy production and storage possibilities, which are much less critical in a stationary application.

In this study, only energy supply and demand are considered. The individual demand requirements are either treated collectively or categorized into subsystems as necessary. A more detailed analysis of construction technologies and water management will be given elsewhere.

2. Results and discussion

2.1. General energy analysis

For small, stand-alone energy systems, solar and wind energy are available, regenerative sources. Wind energy is strongly time and location dependent and therefore cannot be considered as a viable source of energy for the purpose of SELF. Solar energy can provide electricity through photovoltaics (PV) and thermal energy for heating purposes. While solar thermal systems have a higher efficiency for providing thermal needs during the summer, they offer limited flexibility. Specifically for SELF, where the available surface area for energy harvesting and the available space for storage are limited, using solar thermal energy is less practical than using photovoltaics and advanced heat pump technology to provide hot water. As the total surface area of SELF is restricted by design, the maximum PV production is a set parameter. To maximize electricity production, solar cells with 23% cell efficiency are used. The total cell area is 19.4 m^2 resulting in a 4.4 kWp system. Solar input is subjected to 4 main parameters:

- day/night cycles
- geographic location
- weather conditions
- seasonal cycles

While these aspects are inherently coupled, to a first approximation they express themselves on different timescales. Day/night cycles and weather conditions are aspects, which affect energy input on a short timescale (days). Geographical location and seasonal cycles are dependent on the average solar constant, and the variation between the maximum and minimum thereof. Batteries serve well for compensating short-term variations in solar input, while on the seasonal level, the requirements are not met. The SELF project prioritizes weight and volume constraints, while cost constraints serve to define the potential significance to other applications.

Input analysis is performed on a daily interval because the required battery capacity largely exceeds the peak production of the PV system. Consequently, variations during the course of the day are irrelevant to the validity of the analysis.

3. Demand side

The design layout and the key parameters of SELF resulted from previous work, which was based on detailed hourly data sets and an hourly dynamic simulation of the energy balance [8,9]. The demand can be classified into two main categories with respect to their seasonal and location dependence, as summarized in Table 1.

The most fluctuating demands like heating and light show a maximum in winter when solar inputs is lowest, and therefore have a detrimental effect on the system layout. The energy consumption of the heat pump was modelled using daily average temperature data at a specific location, taking into account the respective COP (coefficient of performance); it is the most fluctuating demand parameter due to changing climatic conditions over the year. Most other demand parameters show little or no fluctuation annually.

Table 1
Season and location dependence of demands.

Independent	Dependent
Sanitary services	Heating
Ventilation	Light
Drinking water	
Warm water	
Grey water	
Kitchen appliances	
Convenience appliances	
Cooking	

Table 2
Characteristics of considered locations.

Location	Environment	Characteristics
Zurich	Urban location, low altitude (400 m), high fraction of indirect light, variable weather	Lower solar constant moderate temperature higher input fluctuation
Lugano	Mediterranean climate location, low altitude (270 m), high fraction of direct light, mild climate in winter	Average solar constant moderate climate low demand fluctuation
Davos	Alpine location, high altitude (1560 m), mostly direct light, cold in winter	Higher solar constant cold temperature lower input fluctuation

3.1. Supply side

To assess the dependence of energy supply on location, three distinct possibilities within Switzerland have been chosen as representative locations (a, b, and c), showing particular differences in solar input, and are summarized in Table 2. Based on real solar data, the average PV energy output per day was simulated and is shown in Fig. 2. While the average production in summer is not significantly different between the three locations, location (a) shows the most pronounced seasonal impact. It relates to the majority of locations with high population density in Switzerland. Therefore, future analysis will focus on (a), which is the most demanding input situation for a Standalone Power System (SAPS). While the other locations have been simulated as well (to validate the system layouts), they are substantially less challenging and are well serviced by systems that can operate in location (a).

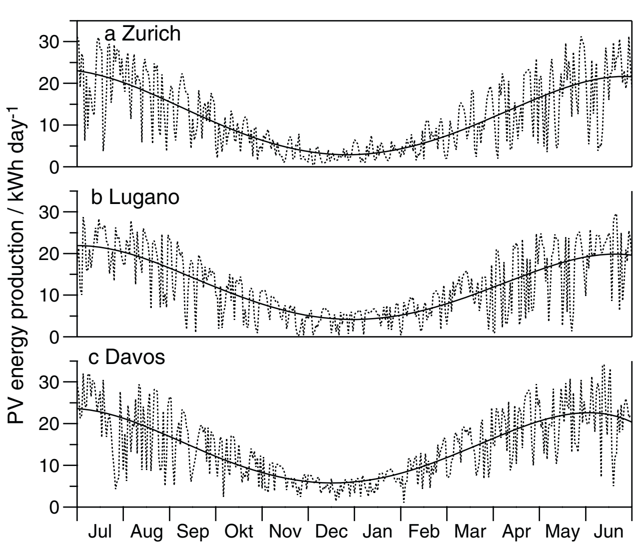

Fig. 2. PV production projections for locations specified in Table 2 based on actual solar data for SELF. The average daily production variations between summer and winter are: (a) 8:1, (b) 5:1, and (c) 4:1.

3.2. System layout options

Four different design options were investigated. The models serve to clarify the potential role of hydrogen in SELF. Table 3 summarizes these models and clarifies their role in the presented design investigations. Basic technical parameters concerning energy sources and storage capacities are summarized in terms of usable energy. These parameters are a result of the demand/supply analysis and are discussed in detail in subsequent sections of this paper.

In models A and B, the battery is always charged as soon as there is unused PV production capacity available. In models C and D, the PEM-electrolyser acts as an additional load which is only operational when unused PV production is available and the battery is fully charged. Therefore, the battery is always prioritized over hydrogen production to ensure maximum battery state of charge (SOC). Produced hydrogen is stored in low pressure, metal hydride storage tanks avoiding the need for compression. The PEM fuel cell (FC) in Model D is set to operate as soon as the battery SOC drops below 20%. The FC is sized to have an output power capable of serving the average load and is therefore capable of preventing further drop in battery SOC. It operates at the point of maximum efficiency rather than maximum output power in order to keep hydrogen consumption to a minimum. By this strategy, the necessary battery capacity is reduced substantially, but is kept at a reasonable level. The battery capacity is large enough to fully compensate for the normal daily production by PV without wasting energy and ensure operation during minimum 2 days of low solar input. Therefore, it guarantees the highest flexibility and sustainable supply even in the case of down-time of the hydrogen sub-unit.

The major difference between the scenarios is the way in which cooking service is accomplished. The reference scenario (Model A) assumes cooking by a traditional propane burner, and is therefore not fully energy independent. Efficiency of propane cooking is assumed to be 60%, according to current standards [10]. Model B is fully energy independent and uses induction cooking which has a higher efficiency rating (from primary energy to required service). Model C and D use a novel, self-igniting, catalytic hydrogen burner especially developed for SELF and the efficiency is similar to a traditional gas burner. The major advantages of such a system compared to an open-flame design are the absence of NO_x emissions [11] and full power modulation capability.

3.3. Detailed input/demand analysis

The following analysis uses real meteorological data for solar input and estimates demand based on real consumption data. The analysis refers to the location Zurich, the most challenging of the selected locations.

4. Demand

While energy demand for appliances, warm water, and cooking essentially remains the same throughout the year, the energy necessary for heating increases substantially in the winter months (Fig. 3). In periods of low overall demand, the energy required for cooking is substantial compared to the overall energy needed. Cooking energy is differentiated between electric cooking energy (assuming induction as the method of choice) and the additional energy needed when using gas as a primary energy source. This is less efficient and therefore increases the primary energy demand. While daily fluctuations (not shown) are of course substantial, heating is the only strongly fluctuating major energy demand over extended periods of time and therefore defines strongly the necessary energy storage capacity.

Table 3
Model systems summary.

Model	A Partial SAPS (Reference)	B SAPS	C Partial H-SAPS	D H-SAPS
Description	PV and battery Propane (cooking, external source)	PV and battery Cooking (induction)	PV and battery on-site H_2 generation H_2-cooking	PV, FC, and battery on-site H_2 generation H_2-cooking, fuel cell
Effects studied	Reference excluding cooking energy	System impact of full energy independence	System impact of shifting to hydrogen for process heat	System impact of shifting to hydrogen for process heat and electricity generation
Battery capacity[a]	60 kWh	135 kWh	60 kWh	30 kWh
H_2-capacity[b]	N/A	N/A	130 kWh (3.3 kg)	200 kWh (5.3 kg)
Fuel cell	N/A	N/A	N/A	200 W (η = 50%)
Electrolyser	N/A	N/A	1 NL/min (η > 50%) [17]	1 NL/min (η > 50%)
Cooking[c]	Propane (η = 60%)	Induction (η = 90%)	H_2 catalytic (η = 60%)	H_2 catalytic (η = 60%)

[a] Actual available capacity, self-discharge neglected.
[b] HHV = 39 kWh kg^{-1}.
[c] Efficiency for gaseous fuels relate to HHV.

5. Input

Maximum PV production is plotted as a reference and reflects the total power potentially available to the system. PV, battery, and FC energy comprise the individual contributions to the total input and are represented as stacked plots. The battery contribution reflects the power that is withdrawn from the battery and supplied to the system in addition to the available PV energy. Energy flows used to charge the battery and for electrolysis are plotted as dashed areas to highlight the shares of PV energy being used for that particular service. The fuel cell output is expressed in terms of electrical energy generated rather than hydrogen energy flow to make direct comparison possible and is therefore subjected to fuel cell efficiency. In models C and D, energy demand for hydrogen production is expressed in terms of electrical energy for the same reason. By this approach, the graphs reflect the impact on electricity demand rather than chemical energy for cooking and the fuel cell.

5.1. Model A: reference system with propane

The input energy flows as well as the evolution of battery SOC are plotted in Fig. 4. Between mid-November and February, direct PV input is insufficient for sustained operation as demand increases to around 5 kWh day^{-1}. The battery acts as a source to fill this gap. This period essentially determines the necessary battery capacity. While requirements for heating water, powering appliances, and cooking represent a constant demand, the energy demand for heating shows pronounced peaks in the colder winter months from December to March. Battery storage capacity is only fully restored from March onwards.

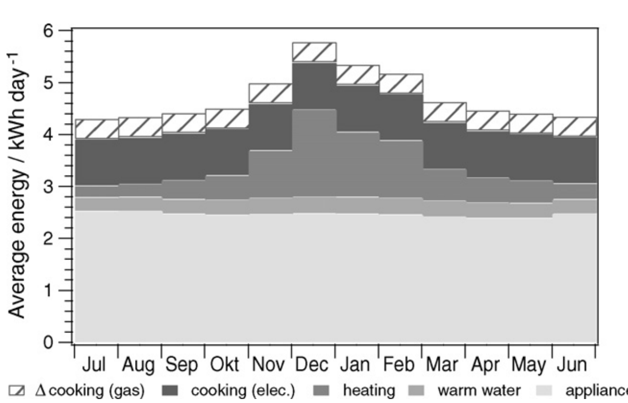

Fig. 3. The average energy demand per day for the individual services. The values represent average electrical energy for the respective service with the exception of cooking, where gas is applicable depending on the Model. Additional primary energy required for using gas vs. electricity is plotted separately.

5.2. Model B: SAPS with electrical cooking

While cumulative energy requirements for cooking are substantially reduced by using induction heating (90% efficiency) instead of a gas stove (60% efficiency), the energy has to be stored internally in contrast to Model A. Fig. 5 shows that, while otherwise similar to Model A, the additional energy for cooking requires a much higher total battery capacity. The battery capacity has to be increased by more than a factor of two to cope with the additional load. Battery capacity is fully restored only from April onwards. The amount of energy harvested from the PV system increases due to higher available battery capacity.

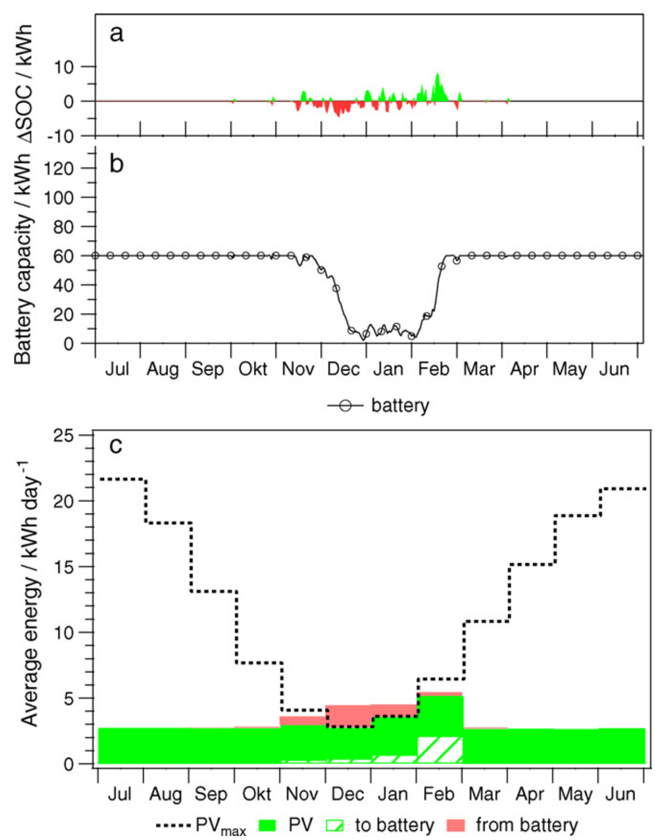

Fig. 4. Model A input analysis: (a) net energy flow to and from the battery as daily averages, (b) the evolution of absolute battery capacity, and (c) energy per day as monthly averages. "PV" represents the harvested share from the PV system. PV energy used to charge the battery is plotted as a dashed area while energy being sourced from the battery is marked in red as a stacked bar plot.

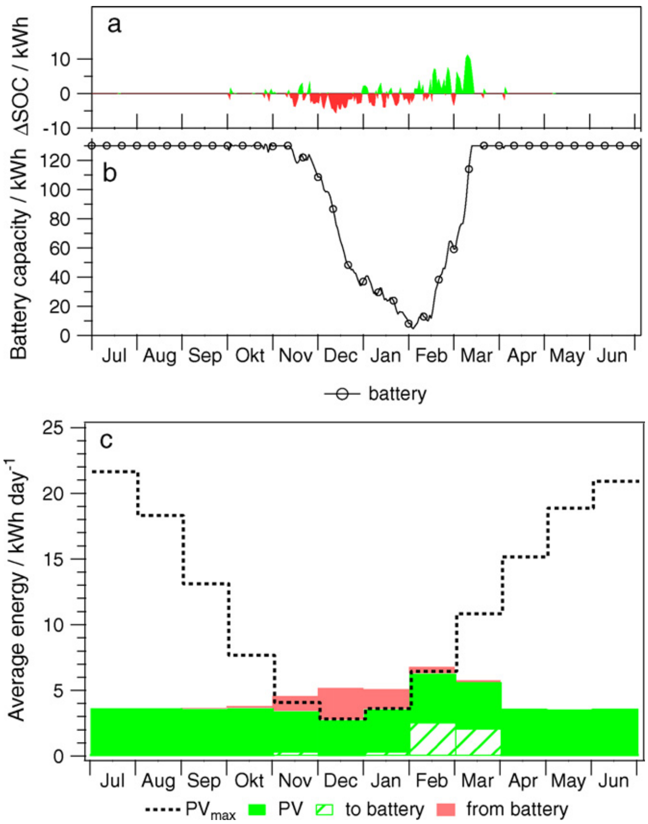

Fig. 5. Model B input analysis: (a) net energy flow to and from the battery as daily averages, (b) the evolution of absolute battery capacity, and (c) energy per day as monthly averages.

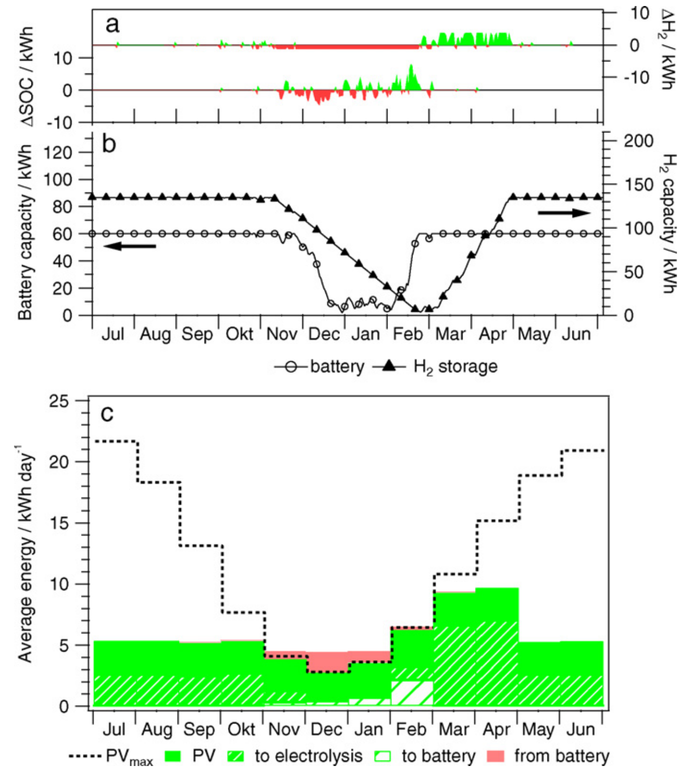

Fig. 6. Model C input analysis: (a) net energy flow to and from the battery and hydrogen storage as daily averages, (b) the evolution of absolute battery capacity and hydrogen capacity, and (c) energy per day as monthly averages. Fractions of PV production being used for battery charging and electrolysis are plotted as dashed areas.

5.3. Model C: H-SAPS with H_2-cooking

The effect of shifting to hydrogen cooking energy reduces the required battery capacity substantially (Fig. 6). Additionally, contributions to energy flows to and from the battery, electrolysis and changes in hydrogen storage capacity are displayed. Net energy flows of the battery are almost identical to Model A, as the battery is responsible for providing the same service. Overall, a distinctly higher share of available PV energy is used. This additional share is directly used to produce hydrogen. Therefore, the PV harvesting factor (while still fairly low) increases substantially. In this operational regime, the electrolyser is allowed to operate only when the battery is fully charged. Essentially, no hydrogen is produced between November and mid-February as there is no excess energy available and charging the battery has first priority. This is a fail-safe choice to guarantee maximum battery capacity for unforeseen input disruptions. After mid-February, the batteries are fully loaded and the electrolyser resumes operation at its full capacity to refill the depleted hydrogen tank. From May onwards, the tank is fully charged and electrolyser operation is restricted to the daily consumption of hydrogen, which is produced the same day. It is interesting to note that by adapting the charging strategy of the batteries via PV production forecasting, and thereby allowing the electrolyser to resume operation earlier by anticipating a full battery capacity, a reduction in necessary hydrogen storage capacity of up to 15% can be potentially realized.

5.4. Model D: H-SAPS with fuel cell and H_2-cooking

As depicted in Fig. 7, the main PV production gap in December is compensated by the fuel cell, according to the strategy that the fuel cell resumes operation as soon as the battery SOC drops below

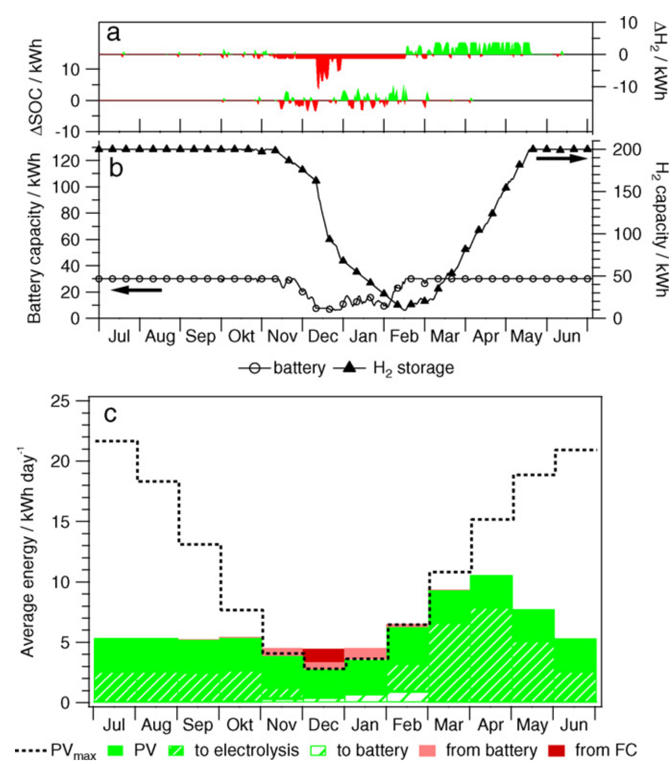

Fig. 7. Model D input analysis: (a) net energy flow to and from the battery and hydrogen storage as daily averages, (b) the evolution of absolute battery capacity and hydrogen capacity, and (c) energy per day as monthly averages.

Table 4
Peak PV production and unused excess energy.

Model	PV total ($kWh\ year^{-1}$)	Excess energy ($kWh\ year^{-1}$)	Excess energy (%)
A	5000	3100	62
B	5000	2780	55
C	5000	2150	43
D	5000	2050	41

20%. The electrolyser resumes operation earlier than in Model C due to the resized battery capacity. The electrolyser will operate for a longer period of time since the hydrogen storage tank must be resized to accommodate the additional hydrogen necessary for fuel cell operation. In principle, a further resizing of the battery at the cost of higher hydrogen storage capacity would be feasible. However, battery capacity was chosen to coincide with the projected daily production by the PV system, therefore allowing the batteries to be fully charged within one day in the best case scenario (if no consumers are present). By this approach, operation is guaranteed in the case of down-time of the hydrogen system, allowing reduced but continuous service for most of the year.

The total maximum annual PV production as well as absolute and relative unused excess energy for the different model systems is summarized in Table 4. Daily excess energy ranges from 0 to 84%. The excess energy is potentially available for other purposes such as electric mobility. Assuming a well-to-wheel efficiency of 18 kWh $100\ km^{-1}$ for a small compact car [12,13], driving ranges of up to 15,000 $km\ year^{-1}$ can potentially be serviced. Unfortunately, the quality of such service cannot be guaranteed as the available excess is strongly fluctuating. Assuming an average commuting distance of 45 km, 170 days can be served in the best case (Model A), and only 110 days in the worst case (Model D). On all other days, the available range is below this figure. In all models, during at least 4 months, no energy for mobility is available. Nevertheless, it remains an interesting option as an additional energy sink to reduce the wasted excess energy.

5.5. System weight and volume comparison

As SELF is sensitive to system weight and volume, the models are discussed in terms of these parameters. A clear differentiation between the storage densities for batteries and hydrogen has to be made. The storage density of battery cells is substantially higher than that of a battery system. In addition, the available usable energy is an important consideration, which depends on the minimum depth of discharge (DOD). The DOD must be chosen to optimize a trade-off between lifetime, size, cost, and weight constraints. In this study, battery size is discussed in terms of usable capacity, for consistency purposes. A maximum DOD of 80% has been selected for comparison, which can be considered as a safe lowest usable limit without overstressing the lifetime and safety of the batteries, assuming modern $LiFePO_4$ batteries are used. These batteries show acceptable cycle life even at substantial DOD level, while presenting a safe chemistry without the possibility of thermal runaway [14,15]; expected cycle life is >2500 cycles at 80% DOD [16]. While batteries with higher energy densities exist (e.g. with Co-based cathode materials), these batteries are not considered due to their inherent safety drawbacks [17]. Self-discharge, while low for lithium based systems compared to lead-acid or NiMH technologies [5], can play a role for seasonal storage but is marginal over 1–2 months. For simplicity, self-discharge is neglected in the analysis.

For hydrogen storage, AB_5 metal hydrides in conjunction with PEM electrolysis are used. Compression is not required and hydrides offer volumetric storage densities surpassing that of the equivalent 300 bar compressed hydrogen storage system [18]. The necessary thermal integration to achieve high absorption/desorption kinetics is not critical in this particular application due to the slow charging and discharging rate. Compressed hydrogen would offer a further reduction in weight, but at the cost of lower volumetric density. This solution is only an option if PEM electrolysers emerge on the market with substantially higher output pressures than the unit used in SELF, which is currently limited to 17 bar. Nonetheless, it is worthwhile to mention that for stationary applications without stringent volume restrictions, pressurized hydrogen is indeed a viable option at fairly low pressures. The current mass storage densities of lithium batteries are achieved at an equivalent pressure of 60 bar, including the efficiency penalty associated with reconversion by a fuel cell. PEM-electrolysers with output pressures of 30 bars currently in development will make direct charging of AB_2 instead of AB_5 based alloys accessible, improving storage density by another 25%. So in the near future, a number of options to implement hydrogen storage will become accessible other than the one presented here.

Hydrogen storage densities are discussed on a system level, considering the container, hydride, valves, and tubing. The hydrogen storage units where tested in the lab and perform in agreement with our assumptions. The technical values refer to the pure system storage parameters and exclude chargers and inverters (for batter-

Table 5
Storage density comparison for battery and hydrogen storage.

Component	Level	Total energy density ($Wh\ kg^{-1}$)	Total energy density ($Wh\ L^{-1}$)	Usable energy density ($Wh\ kg^{-1}$)	Usable energy density ($Wh\ L^{-1}$)
Battery	Cell	110	170		
	System[a]	100	140	80	110
Hydrogen storage	Tank[b]	430	1600		
	System[c]	300	400	>260	>350

[a] Basis: $LiFePO_4$ cells with 110 $Wh\ kg^{-1}$ and 170 $Wh\ L^{-1}$, 80% DOD.
[b] Basis: AB_5–Alloy $1.35\%_{mass}$ in 11 L Al7000 containers including system components.
[c] Basis: 10 Units with 11 L water volume, parallel configuration, total system volume of 440 L, p_{min} = 1.1 bar.

Table 6
System weight and volume comparison.

Model	A partial SAPS (Reference)	B SAPS	C Partial H-SAPS	D H-SAPS
Battery weight	750 kg (60 kWh)	1630 kg (130 kWh)	750 kg (60 kWh)	380 kg (30 kWh)
H_2-storage weight	N/A	N/A	400 kg (135 kWh)	600 kg (200 kWh)
Battery system volume	550 L	1200 L	550 L	270 L
H_2-storage volume	N/A	N/A	290 L	440 L
Total weight	750 kg	1630 kg	1150 kg	980 kg
Total volume	550 L	1200 L	840 L	710 L

ies) or the electrolyser and fuel cell (for hydrogen). They account for roughly the same weight contribution in SELF (∼40 kg) and are omitted to ease direct comparison. As summarized in Table 5, much higher energy storage density per volume and per mass are realized with hydrogen. Even considering the efficiency penalty of using a fuel cell or a gas burner instead of an induction stove, the densities remain well superior to battery systems.

Consequently, increasing hydrogen storage capacity at the cost of reducing battery capacity yields substantial reductions in mass and volume of the complete system. In Table 6, the different variants based on the input and demand analysis are summarized. The hydrogen hybrid system offers a 40% reduction in weight and volume over a battery only system. Additionally, by dynamically assisting the battery with the fuel cell overall flexibility is improved, as energy can be transferred over longer time periods.

The abilities to store energy and deliver power are two strictly separate parameters of a hydrogen system. While electrolyser and fuel cell sizing defines the ability of the system to consume and generate power when needed, the ability to store energy is a matter of storage sizing. Component sizing therefore is strongly dependent on the application considered. Batteries do have a coupling of power delivery capability vs. energy storage capacity defined by their design. Optimizing for high power ultimately leads to lower energy storage density. The best battery for off-grid use is optimized for energy density but with sufficient power delivery rate in the particular application. Most batteries optimized for high energy density offer the capability to discharge at a rate of 0.5 C, which is sufficient for most applications and does not form a bottleneck. The ability to deliver power is therefore a parameter that depends mainly on the selected inverter/charger.

For these reasons, cost structure is different for batteries and hydrogen systems. For batteries, cost can be expressed as cost per unit of energy stored. Based on capacity, cycle life and cost per unit capacity, a rather simple metric for cost of energy delivered to the user can be expressed. For hydrogen, cost per unit of power consumed/delivered relates to the investments in electrolyser and fuel cell. Cost per unit of energy depends on storage cost and depreciation of the electrolyser and fuel cell but both are largely independent—no simple metric can be defined. Consequently, estimates of total cost of energy delivered based on this singular case cannot promote economic understanding for off-grid systems in general. In the current case, the hydrogen hybrid system is economically viable above battery cost of 500 USD $kW\,h^{-1}$. This is currently the case and will remain so in the foreseeable future [19,20]. In a different usage profile this might be substantially different. Therefore, a generalized cost sensitivity analysis for relevant model cases including battery parameters (cycle life, shelf life, cost per unit of energy) and hydrogen related parameters (lifetime expectation, efficiency, cost per unit of power, cost per unit of energy stored) has to be performed to assess the economic viability of a particular case. This would largely exceed the scope of this paper. Such an analysis is currently in progress.

6. Conclusion

Three models for renewable energy supply of the project SELF have been compared. On-site hydrogen production and storage proved beneficial to achieve complete energy independence, continuous service, minimal weight and volume. The buffer seasonal fluctuations of PV production would demand for excessive additional battery capacity. This is not acceptable for a transportable system from a weight and volume perspective. The addition of on-site hydrogen generation and storage is ideally suited for the purpose of seasonal energy storage due to their high energy density. As a conclusion, Li-Ion will not be competitive to hydrogen in the foreseeable future if large energy storage capacity is demanded and weight or volume constrains apply [19]. While batteries serve high power loads and absorb high power flows from the PV system, the hydrogen subsystem handles production fluctuations over long periods. It is in line with the trend in fuel cell driven hybrid power trains for mobility, where fuel cells provide average power while batteries deliver peak power and regenerative braking capability, thus optimizing efficiency and lifetime of the overall system.

As capacity to store electrical energy in a renewable off-grid system is limited, it puts the lower round trip efficiency over the hydrogen path into perspective. The energy used to produce hydrogen is strictly confined to PV energy that is otherwise unused—the choice is use or waste energy. It is a solution to maximize energy harvesting with fluctuating input and limited control over demand on longer time frames. Currently, generators or load offsetting are the only means of maximizing energy harvesting from renewables in off-grid systems but at the cost of independence. The fuel cell acts as a generator replacement with onsite fuel production. As a novelty, the catalytic hydrogen burner will be implemented. Cooking in the unit represents a non-deferrable band load all year around. The use of hydrogen for this purpose reduces the strain on the critical battery storage capacity.

The SELF project will yield critical experience on system viability of hydrogen and lithium battery technology in off-grid power systems. This data is crucial to establish a sound basis for economic comparison to traditional renewable energy–battery–generator combinations.

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