Open Access Journal

Journal of Power Technologies 96 (1) (2016) 63–71

journal homepage:papers.itc.pw.edu.pl

Use of NaNiCl battery for mitigation of SOFC stack cycling in base-load telecommunication power system—a preliminary evaluation

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Abstract

Fuel cells are among the most promising technologies for clean power generation. Solid oxide fuel cells (SOFC) are characterized by high efficiency, fuel flexibility and a wide range of operating conditions. SOFC are the preferred fuel cell technology for micro-combined heat and power (micro-CHP) units, but they are prone to rapid performance degradation when exposed to thermal and electrical cycling. To overcome this issue, alternative methods are sought to assure high durability and long-lasting operation by mitigating the cycling. This can be achieved by limiting the number of cycles and maintaining stable operating conditions. One of the proposed solutions is to create a hybrid system combining an SOFC stack with a molten salt (NaNiCl) battery module. The NaNiCl battery is well known for its high energy density, high durability and zero electrochemical self-discharge. This hybrid system is a solution in which the fuel cell stack and the battery module are thermally and electrically integrated and operate as a part of a cogenerator. Since both modules operate at elevated temperature, heat generated in the stack can be partially used to maintain a sufficient operating temperature of the battery pack. The SOFC/battery hybrid enables high operational flexibility which is achieved by proper selection of the power ratios between the two components. In this configuration the battery pack can be used to stabilize operation of the fuel cell stack and to allow for load-following operation of the hybrid. To evaluate the operation of a SOFC/battery, the dynamic models of the battery and fuel cell stack were developed in Aspen Hysys 8.5. The simulator enables predictive modeling of various operating conditions corresponding to the different power demand profiles.

In the transitional states of the telecommunication system, the hybrid unit can either charge or discharge the battery without cycling the fuel cell stack. Simulations are needed to evaluate the performance of the SOFC/battery hybrid system, in particular to analyze the capability to follow the load profile during operation in island mode.

Keywords: ZEBRA battery, Solid Oxide Fuel Cells, System dynamic modeling

1. Introduction

The energy industry faces multiple challenges, from rising demand to environmental concerns. Grid dependence limits the use of alternative options for energy delivery. For that reason, power consumers in isolated locations are looking to completely new and advanced technologies. As an example, telecommunication companies are looking for ways to overcome several obstacles and meet future power demands caused by increasing service needs and a worldwide push towards faster and more accessible networks and internet connectivity. For that reason, telecommunication around the world is looking into power technologies capable of meeting their current and future demands [1].

Novel systems include highly efficient and reliable solutions, including fuel cells. When used in distributed energy systems as 'on-site' generators, such units are

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able to provide electricity and heat simultaneously during stationary and dynamic operation [2]. In some cases, trigeneration systems with cooling capabilities are under consideration [3]. Among the existing fuel cell technologies [4, 5] suitable for micro-combined heat and power (micro-CHP) generators, hydrogen-fed proton exchange fuel cells (PEFC) and multi-fuel solid oxide fuel cells (SOFC) are mostly considered [6]. In general, solid oxide fuel cells offer higher fuel flexibility and the high operating temperature, typically in the range 700..900℃, makes it possible to design highly efficient systems. However, SOFCs still have notable limitations: an insufficiently quick response to electrical load transients, long start up and time to reach operating temperature, high costs of suitable materials and short lifetime compared to technologies with a strong position in the market such as internal combustion engines (ICE) or micro gas turbines (MGT).

For that reason, to overcome the technical limitations of solid oxide fuel cells alternative solutions for stabilization of the operating parameters are under investigation. Among the existing options, integration of the fuel cell stack with a battery makes it possible to substantially reduce the number of electrical and thermal cycles of the fuel cell stack. This solution is based on the concept that the SOFCs are operating in a stable manner over a long period of time and the battery is responsible for compensating load variations. In such case the hourly, daily and weekly variations in demand can be accommodated by a properly sized battery which is combined with the fuel cells. Electrical power is therefore exchanged between the fuel cells and battery pack, and the complete system and user. Combining the battery and a fuel cell stack enables delivery for a certain time of power higher than the nominal power output of the stand-alone fuel cell stack.

Beside the electrical integration of the battery and the SOFC-based system, it is possible to achieve thermal integration when proper batteries are engaged. Recent studies revealed that sodium-nickel-chloride (SNC) batteries are good candidates for such power units [7]. Combining (electrically and thermally) SOFCs and NaNiCl batteries within a single hybrid would create a system in which the NaNiCl battery pack provides additional power during peak times or in cases of emergency, and then is recharged by the SOFC during periods of reduced energy demand (or load valleys). This creates a reliable energy system in which the SOFC experiences minor variations of load, thus extending the lifetime of the system and bringing economic benefits. Combining a battery with high temperature fuel cells such as SOFCs is a challenging task. Firstly, the system topology has to provide the functionality and operation flexibility required from power generators. Secondly, the size of the fuel cell stack and the battery has to correspond to the power demand profiles, which are not always predictable and are a subject to monthly and seasonal variations.

2. Battery

The concept of a molten salt batteries was already under investigation in 1980s, mostly as a solution of automotive applications [8]. Preliminary studies were related to the development and synthesis of proper materials, mostly alumina. A pilot line delivering batteries under the commercial name ZEBRA was established in 1994 and batteries were industrialized afterwards. Over the years a number of advances were introduced, and batteries combining ceramic electrolyte and a molten salt finally arrived at a specific energy of 120 Wh/kg and specific power of 180 W/kg [9]. A wide range of applications were taken into consideration, including the integration of molten salt batteries with urban bus propulsion systems. Capasso and Veneri [10] reported the evaluation of a 65 kW electric drive integrated with two 20 kWh ZEBRA batteries connected in parallel combined with 100 kW regenerative electric break. In general, automotive applications require the battery to be able to follow rapid transients and extensive cycling. To improve the performance at such operating conditions, the design was modified to enable effective cycling at intermediate temperatures [11]. The concept of integrating the ZEBRA battery with solid oxide fuel cells was presented [12] and evaluated, initially for an automotive application based on intermediate SOFCs [13].

Beside numerous studies related to the use of batteries in transportation, use of electrical energy storage in the form of a ZEBRA battery in residential micro-combined heat and power generator was under consideration [7]. In the study, several prime movers with rated electric power in the range 1 kW to 10 kW were under consideration. The discussed technologies included: (I) internal combustion engines; (II) micro gas turbines; (III) Stirling engines; (IV) micro Rankine cycles.

Over the years the ZEBRA undergone several modifications. The sodium-nickel-chloride battery pack currently considered is made of a matrix of prismatic 36 x 36 mm FIAMM Sonick cells, each weighing about

Figure 1: Front view of a 48TL200 battery module. Source: FIAMM

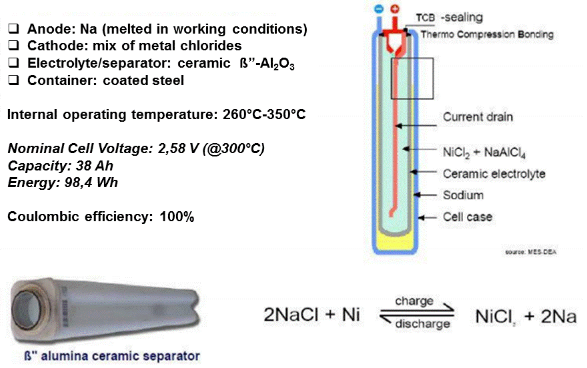

Figure 2: Main features and the design of a single prismatic SNC cell

690 grams and measuring 235 mm. The energy density of SNC cell is 317 Wh/l and the specific energy is 140 Wh/kg These values place the SNC cells among the highest energy density technologies, however at battery level the contribution to weight and volume of the battery assembly must be taken into consideration. Several alternative connection configurations can be realized to create a battery packs of different sizes with the required voltage and the rated capacity. Due to the elevated operating temperature, the battery pack is insulated with a micro-porous silica-based material. The European Project ONSITE—Operation of a Novel SOFC-Battery Integrated Hybrid for Telecommunication Energy Systems [14] is focused on the development and operation of a hybrid unit combining solid oxide fuel cells and a SNC battery for powering telecommunication station. For this application, FIAMM has designed 48V Sonick battery modules within a capacity range of 80Ah to 200 Ah. The battery pack is shown in Fig. 1.

Main features and the operating principle of a single prismatic SNC cells making up the 48TL200 battery module are presented in Fig. 2.

Table 1: Selected values recorded during warm-up of the battery

Elapsed time, h	Temperature, ℃	Power of electric heaters, W
0	25	440
7	160	440
14	260	440
>14	265	115

Due to the presence of molten salts, SNC battery requires elevated temperatures for efficient operation. The operating temperature ranges from 265℃ to 350℃, therefore a warming process is needed and takes approximately 14 hours. Internal electric heaters are used to heat the batterywith . The required electrical power and the internal temperature are monitored. Typical values presenting the duration, internal temperature and power of the heaters recorded during the battery warming process are presented in Table 1.

The SNC battery offers stable performance within a range of temperatures from -20℃ to +60℃. The battery management system (BMS) has a low voltage disconnect function that disconnects the load from the battery pack when either the voltage decreases below a lower limit or when the nominal capacity has been fully discharged. This prevents the battery to be over discharged below the voltage that could shorten the service life or damage the cells. Based on the FIAMM data the operational state of charge of the battery lays in a range from 10% to 90%. The internal electric heaters control the internal temperature during different discharge rates to assure the required working conditions (thermal-wise).

3. System

The general idea behind the concept discussed in the paper is based on a fully integrating the battery with the system. Combining the SNC battery pack with the SOFC-based power unit includes both electrical and thermal integration. Although the thermal aspects of the hybrid are still under development, the electrical issues were resolved and the initial design proposed. Connecting the battery with the power system requires the engagement of several additional components, including a battery management system, DC/DC inverters and additional sensors. The general concept of the telecommunication base-load power hybrid can be presented using Fig. 3.

The conventional micro-CHP unit with solid oxide fuel cells operates without major power variations. Constant connection to the local electrical grid enables ex-

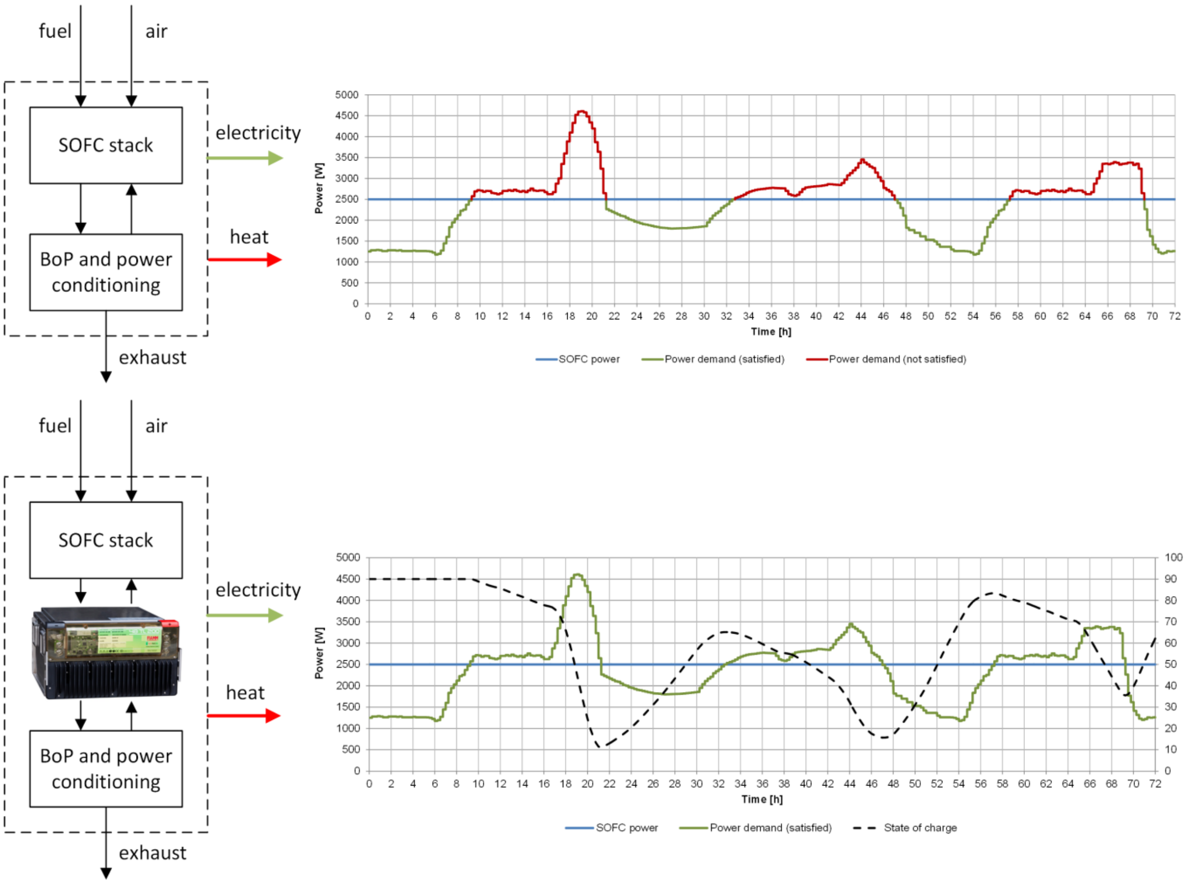

Figure 3: Comparison of the performance of a standard and modified system operating in island mode during reference power demand profiles for a duration of 72 hours

change of electricity between the grid and the system. As presented in Fig. 3 the system satisfies the base-load power demand. The peaks and valleys require cooperation with the grid to withdraw the excess electricity of the supply additional power when the demand exceeds system capacity. In fact the system is not capable of continuously operating in islanding mode. In general, such solutions would be suitable for residential applications when bidirectional meters make it possible to monitor operation of a micro-CHP system as a part of an electrical grid. As can be seen in Fig. 3the modified outline considers the SOFC stack as a prime mover. The battery together with fuel cells provides power to the user. The balance of plant (BoP) plays an active role in delivering the required output based on the stable constant input from the SOFC stack and the adjusted input from the SNC module.

The application currently considered is a remote base-load power generator which, by definition, has to exhibit the ability of satisfying power demand over the entire operation time. This requires technical means which can simultaneously assure constant operating conditions of the SOFC stack and follow the hourly, daily and weekly variations of power beyond the nominal capacity of fuel cells. Combining the battery and stack makes it possible to substantially reduce or even eliminate a number of load cycles of the SOFC stack. The battery acts as a buffer which is charged and discharged during valleys and peaks, respectively (Fig. 3).

The system's ability to follow demand depends on several factors. The most important include: (I) load profile, including the expected minimum and maximum values; (II) rate of change of demand; (III) nominal power capacity of the fuel cell stack; (IV) nominal power capacity, size and discharge rates of the battery pack which are defined by its characteristics; (V) ability to accommodate the excess power by a slight reduction in the power output of the SOFC stack. If these characteristics are carefully selected, the system is able to follow the generic reference load profiles. It should be noted that the special character of the telecommunication base-load station influences the profile of power demand, which is generally different to the profile of standard residential applications. For the purpose of comparing the two systems, the load of a reference detached dwelling was used in Fig. 3to show the behavior of both configurations. In order to simulate the behavior of the hybrid and a power generator in the telecommunication base-load station, demand profiles reported by Lorincz et al. [15]. were adopted for the study. The profiles have to be normalized to adapt the maximum and minimum values, but the rates of change remained as original data. This approach was introduced for investigation of a single repeatable module with the 2.5 kW SOFC stack and 2.5 kW battery pack considered in the current study. The behavior of the system following such power demand is shown in Fig. 4 together with the excess power generated by the hybrid.

Since the intention of the design is to minimize or eliminate the number of load changes of the SOFC stack to assure its high performance and long durability, the battery has to be carefully selected to fully utilize the excess power when the load profiles are below the nominal capacity of the SOFC stack, but at the same time satisfy high demand, exceeding the power output of the fuel cells. In Fig. 4 it can be seen that the overall duration of the excess power periods is currently 11 hours 25 minutes during 72 hours of operation. Evidently, this is affected by the initial state of charge (SOC) of the SNC battery pack. As shown in the most conservative case, the operation begins with the battery pack fully charged (SOC=90%) and ends with SOC equal to 48%.

Taking into account the difference between the three reference days included in the 72 hours long operation, system is capable of remaining fully operational with the SOFC stack operating steadily with the overall power output in a range from 1100 W to 3900 W. These numbers correspond to 44% and 156% of the SOFC nominal power output, respectively. The scenario presented in Fig. 4 was simulated with the battery pack fully charged. These conditions can be expected only in particular situations when earlier operation made it possible to achieve maximum SOC. As an opposite case, the second simulation initiated with the battery fully discharged (SOC=10%) can be used for the same load profile. In such case the initial excess power is accommodated in recharging, but at a certain moment, the system is unable to meet demand (Fig. 5). The overall balance of the system indicates a short period in which the system is unable to deliver the required power. The remaining section showing days 2 and 3 in Fig. 5 is similar to the results obtained from the first simulation. It can be observed that the final state of charge of 49% is achieved.

The profiles presented in Fig. 4 and 5 are evidence of two extreme conditions when the battery is either completely charged or fully discharged. Slope of the demand and daily variations of the electrical needs affect the capability of the system to follow the power profile

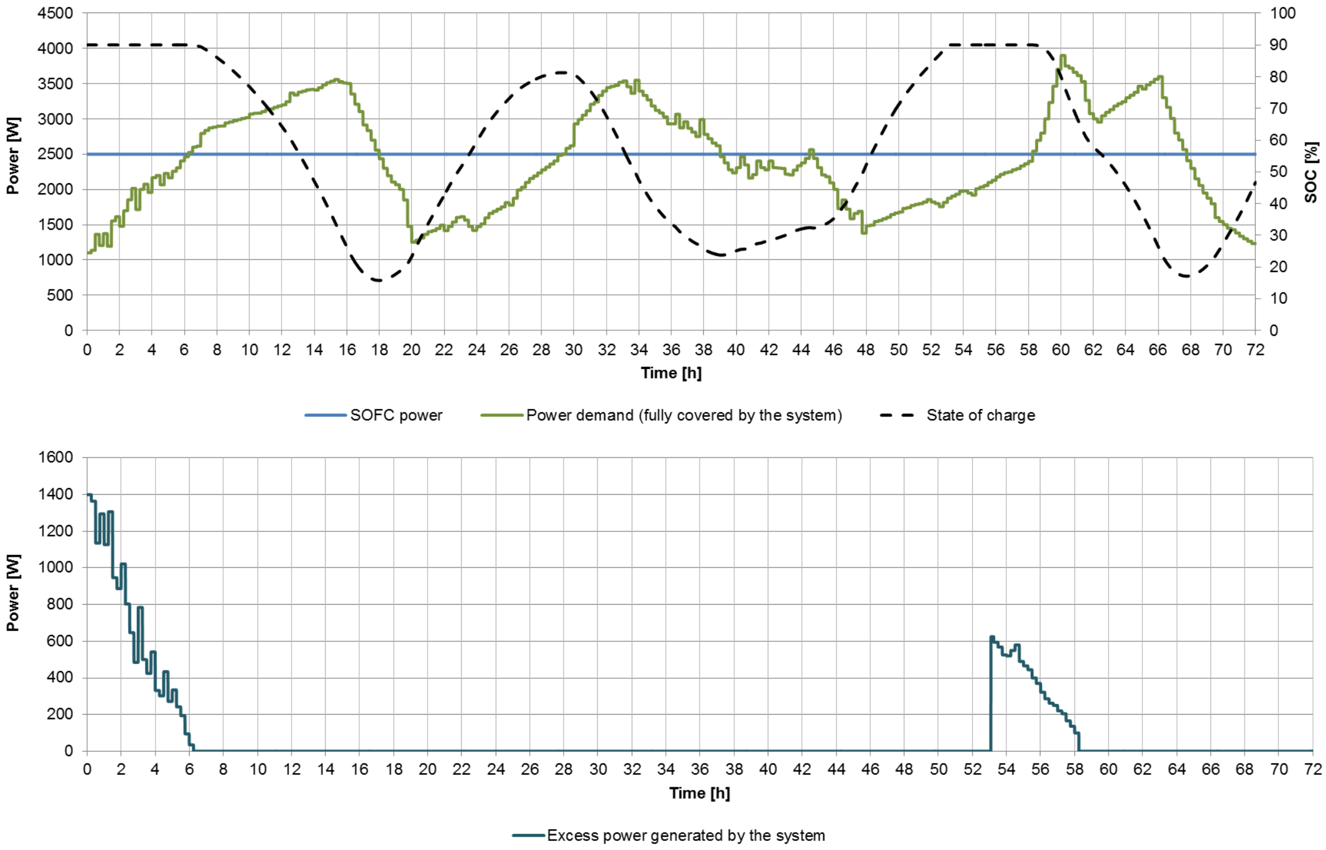

Figure 4: 72 hours of operation of the SOFC-SNC hybrid following the base-load station power demand profile (upper) and excess power generated by the system (bottom) for a battery that is initially fully charged

of the telecommunication base-load station.

The embedded battery management system is responsible for monitoring the operation of the battery pack and adjusting the control system to specific conditions. Automation and control of the complete power unit are responsible for the overall control of the hybrid, including selection of either the charging or discharging mode. The current topology of the unit, with 2.5 kW installed in the SOFC stack and a 2.5 kW SNC battery pack, can be modified to accommodate the specific needs of the telecommunication base-load station. The complete unit considered in the ONSITE project is comprised of 4 modules, totalling 10 kW in fuel cells and 10 kW in molten salt batteries. The control strategy currently under development will introduce greater flexibility to the system and make it possible to follow complex load profiles.

With the current focus on electrical integration, thermal management of the complete unit was excluded from the study. For that reason, elaboration on the electrical and overall efficiencies lie beyond the scope of the paper. The main purpose of simulating a stand-alone SOFC module and SNC battery was to observe the operation of the core part of the hybrid during the reference working conditions. Since the battery serves as a technical means to substantially reduce or even eliminate electrical and thermal cycling of the fuel cell stack, it was critical to define the required nominal capacities of the fuel cells and the battery. As a result of the initial phase of the ONSITE project the ratio 1:1 was selected.

The SNC battery operates steadily within the required range of temperatures. The thermal interaction with the system is mostly influenced by the discharging/charging rates. The molten salt battery can be operated easily with either slow discharge, lasting about one day, or rapid discharge with the maximum power being drawn. Different modes are selected continuously as a result of the optimization done by the algorithm, assuring constant power of the SOFC stack. In the current work, it was assumed that there should be no cycling of the stack at all. In fact, the specification of the SOFC stack is not needed to analyze the connection of SOFC and SNC. A complete set of physical and geometrical data will be necessary to evaluate the thermal integration of the fuel cells and the battery pack in the next phase of the project.

Figures 4 and 5 indicate the presence of short episodes when the system is unable to provide the required power or when there is excess power. As mentioned earlier, the complete power unit will consist of 4 modules 2.5 kW + 2.5 kW each, delivering additional operational flexibility and enabling the hybrid to internally manage the balancing of supply and demand. With respect to the scope of the current work, it was crucial to analyze the ability of the system to operate continuously following complex load profiles. The input data presented in Fig. 4 and 5 show major variations in both the current power required by the base-load station and the daily demand of electricity. In the demonstration phase of the ONSITE project the flexibility of the hybrid system will be analyzed to define any potential modifications required to improve the system's operability.

4. Conclusion

Functionality of a hybrid system was under consideration. A combined solid oxide fuel cells stack and molten salt battery, based on sodium-nickel-chloride, deliver total power of 5 kW, with power ratio of 1:1. The battery is used to stabilize the operation of the SOFC stack to enable long-lasting operation without electrical and thermal cycles. The hybrid power system will consist of 4 modules with fuel cells delivering 2.5 kW and an SNC battery providing up to 2.5 kW in each module. Two opposite cases were considered in the current study. In the first one, the battery was initially fully charged, in the second, 72 hours operation started with the battery pack fully discharged. Simulations were run with respect to the specification of the battery, including the nominal capacity and allowable discharging/charging rates. Parallel connection of four 2.5 kW + 2.5 kW modules makes it possible to achieve higher operational flexibility and to maintain different states of charge of each of the battery packs to follow the power demand profiles. Beside the electrical integration of the SNC battery pack and the SOFC stack, thermal management of the SOFC and SNC modules and the complete system is of a high importance. Further work will be related to alternative concepts for maintaining proper operating temperature of the battery through utilizing low-enthalpy heat from the SOFC stack and the hybrid system. Advanced measures enabling elimination of the need to use internal electric heaters embedded in the battery will yield high electrical and overall efficiency of the telecommunication base-load power system. Finally, it is possible that the topology of the system will change during the ONSITE project, including different ratios between the battery pack and the fuel cell stack in each of the modules making up the hybrid

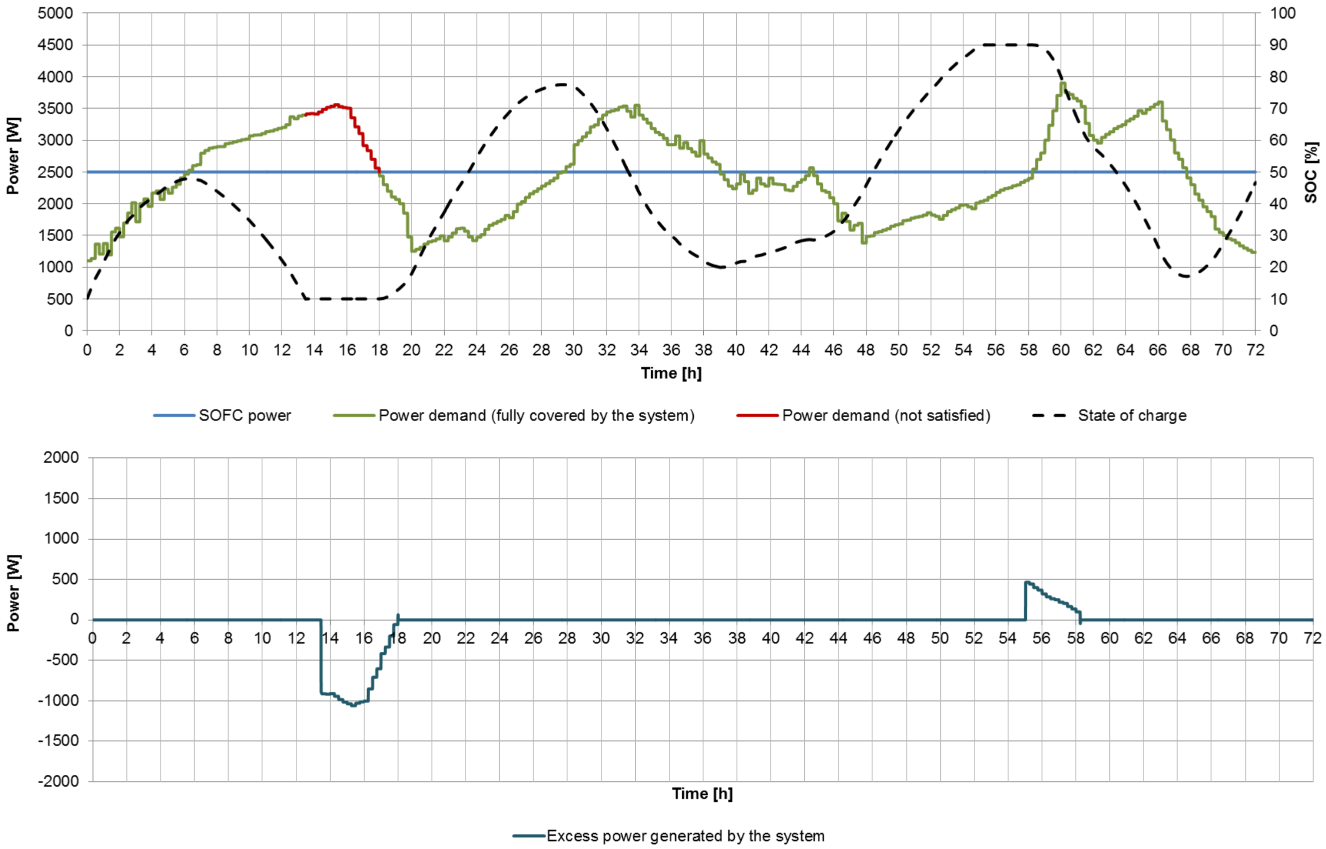

Figure 5: 72 hours of operation of the SOFC-SNC hybrid following the base-load station power demand profile (upper) and excess power generated by the system (bottom) for a battery that is initially fully charged

system.

Acknowledgments

The authors would like to gratefully acknowledge the support received from the EU through the ONSITE project (grant agreement 325325).

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