ISSN 2004-2965 Energy Proceedings, Vol. 21, 2021

International Conference on Applied Energy 2021
Nov. 29 - Dec. 5, 2021, Thailand/Virtual
Paper ID: 005

Heat and Power Management and Economic Assessment of a Green Hydrogen-Based Microgrid Employing a Reversible Solid Oxide Fuel Cell

Califano[1], M., Sorrentino[1], M., Pianese[1], C., Rosen[2], M.A.

1 Department of Industrial Engineering, University of Salerno, Fisciano (Salerno), 84084 Italy

2 Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, Oshawa, Ontario, L1G 0C5, Canada

ABSTRACT

This paper proposes and examines a highly integrated microgrid based on a reversible solid oxide cell, aimed at satisfying electrical and thermal loads of a 20-unit residential complex as well as the requests of electric and fuel cell vehicles. Such a system has been conceived as a profitable ready-made solution to be embedded into existing plants already equipped with renewable energy sources (i.e., wind farm and photovoltaic panels) by means of a reversible solid oxide cell and energy storage technologies. A dynamic programming-based routine has been suitably implemented as an algorithm for both electrical and thermal sides of the plant managing the power split indices. In addition, an external routine has been deployed to consider the economic aspects; in particular, attention has been paid to a levelized cost of energy analysis allowing for comparisons with current reliable energy generation technologies. The analyses involved parametric assessments of multiple reversible solid oxide cell sizes and economic discount rates while fixing the lifetime of the plant at 30 years. In accordance with the results of the optimal microgrid design, by exploiting 100% of the rSOC working time (shared by mode as 40% fuel cell and 60% electrolyzer) a simple payback period of 5.97 years has been achieved along with a levelized cost of energy index value in the 0.1 €/kWh-0.2 €/kWh range.

Keywords: green hydrogen, multigeneration, reversible solid oxide fuel cell based microgrid, hydrogen storage, thermal energy storage, renewable energy sources.

NOMENCLATURE

Abbreviations

DHW	Domestic hot water
DP	Dynamic programming
ES	Energy storage
HST	Hydrogen storage tank
LHV	Lower heating value
PV	Photovoltaic
RES	Renewable energy sources
rSOC	Reversible solid oxide cell
SI	Split index
SOC_{HST}	HST state of charge
SOC_{TES}	TES state of charge
SOEC	Solid oxide electrolyzer cell
SOFC	Solid oxide fuel cell
SPB	Simple payback
TES	Thermal energy storage

Symbols

ABC	Annual bill cost
$C_{bought,el}$	Unit electricity cost
$C_{bought,th}$	Unit heat cost
$C_{sold,el}$	Unit electricity selling price
$H_{2,ref}$	Economic value of hydrogen refills
$HST_{capacity}$	HST storage mass capacity
IC	Microgrid initial costs
J	Performance index
LCOE	Levelized cost of energy
LCOA	Levelized cost of auxiliaries
LCOD	Levelized cost of delivery
LCOS	Levelized cost of storage
$m_{H_2,car,j}$	Mass of hydrogen by FC vehicles
$m_{H_2,tank,j}$	Mass of hydrogen in/out HST
$m_{SOEC,j}$	Mass of hydrogen in SOEC
$m_{SOFC,j}$	Mass of hydrogen in SOFC
MC	Maintenance costs
η_{SOEC_j}	Current first-law SOEC efficiency
η_{SOFC_j}	Current first-law SOFC efficiency
$P_{boilers,j}$	Boilers thermal power
$P_{bought,el,j}$	Electrical power purchased
$P_{bought,th,j}$	Thermal power purchased

Selection and peer-review under responsibility of the scientific committee of the 13th Int. Conf. on Applied Energy (ICAE2021).

$P_{grid,j}$	Electrical power provided by grid
$P_{PV,j}$	Power produced by photovoltaics
$P_{rSOC,j}$	rSOC electrical power output/input
$P_{SOEC,j}$	SOEC electrical power input
$P_{SOFC,j}$	SOFC electrical power output
$P_{sold,el,j}$	Electrical power sold
$P_{th,rSOC,j}$	rSOC thermal power
$P_{th,SOEC,j}$	SOEC thermal power
$P_{th,SOFC,j}$	SOFC thermal power
$P_{th,TES,j}$	TES in/out thermal power
$P_{W,j}$	Wind turbines electrical production
$Q_{in,j}$	Thermal energy entering TES
$Q_{out,j}$	Thermal energy leaving TES
RTE_{TES}	TES round trip efficiency
TC	Microgrid total cost
TD	Tax deduction
$TES_{capacity}$	TES capacity
$TL_{,j}$	Total hourly electric load
$t_{SOEC,j}$	SOEC operating time
$t_{SOFC,j}$	SOFC operating time
x_{direct}	Direct coefficient of utilization
$x_{surplus}$	Surplus coefficient of utilization

1. INTRODUCTION

Nowadays, developments in the conventional energy industry are constrained by the need to reduce pollution and carbon/greenhouse gas emissions. In order to overcome the latter challenge, it is expected by many that renewable energy sources (RES) will have an increasing role to play in decarbonization scenarios, providing green energy. Although, RES can effectively help to address current energy problem, it is also worth remarking that this type of energy is discontinuous and intermittent, causing the energy not to be always available when needed. Consequently, RES-based systems benefit notably from being integrated with controllable and stable technologies able to reduce power fluctuations, such as energy storage (ES) technologies as well as fuel cell and traditional energy systems. The benefits to microgrids of the latter integrations can ensure normal power supply even with changes in environmental and weather conditions (e.g., solar irradiance and wind speed), thus offering better energy security and flexible operation modes (i.e., islanded operation). Adding a fuel cell system means having a predictable and controllable power sources as well as a system using the electricity surplus to synthesize hydrogen or methane, which can be stored and later converted back to electricity. To this end, within this work a dual state dynamic programming procedure has been implemented thus allowing the parallel management of the electrical and thermal power split indices (SIs) of the plant. In spite of the continuous evolution and growth of the hydrogen market, the benefits associated with ES and fuel cell technologies on energy exploitation and grid stabilization are not always perceived as sources of "income". As a result, this paper uses a levelized cost of energy (LCOE) [2] analysis for pinpointing the economic benefits associated with the use of hydrogen-based technologies along with ES, in terms of €/kWh. This information can help potential investors make sound decisions on a technoeconomic basis, considering energy efficiency, quality of energy supply and long-term economic profitability.

2. PLANT SCHEME OVERVIEW

2.1 General characteristics

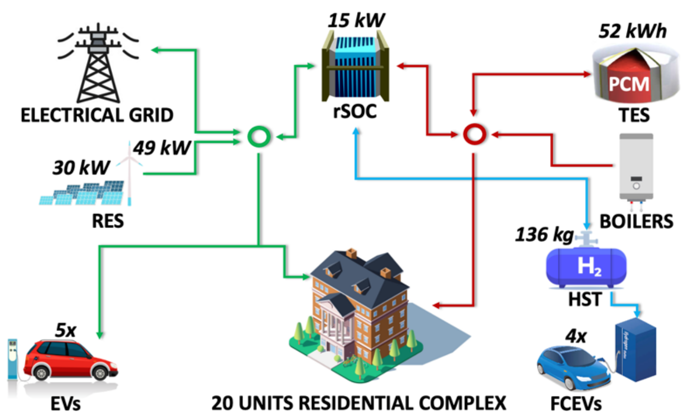

Figure 1: Overview of the grid-connected rSOC based microgrid.

The grid-connected microgrid analyzed here is located in Policastro Bussentino (40°03'60.00'N) in the province of Salerno, Italy. As depicted in Figure 1, the microgrid can exchange electricity with the national electric grid and it is boiler-connected, since the coupling between RES and the reversible solid oxide cell (rSOC) is not always capable of satisfying the requested load (made up of both electricity and heat). To avoid wasting renewable energy, two ESs have been included, namely a hydrogen storage tank (HST) using gaseous hydrogen at 700 bar and a high-temperature thermal energy storage (TES) using a phase change material. This way, it is expected to be possible to compensate for energy deficits by purchasing from the network, and/or taking thermal energy from the TES, and/or drawing on the HST and thus producing electricity and heat through the rSOC. Conversely, in case of a RES surplus, the energy can be stored in the form of hydrogen by utilizing the rSOC (in electrolyzer mode) or more straightforwardly by selling it to the national grid. The design of the main components of which the plant is comprised (i.e., wind turbines, photovoltaic panels, HST, TES and rSOC) is shown in Figure 1. This starting configuration is taken as the input for the dynamic programming optimization problem.

2.2 Loads

2.2.1 Electrical loads

The residential complex taken into account consists of twenty units, each requiring 3700 kWh of electricity per year. In addition, the electric car fleet consists of 5 vehicles.

In constructing the electrical load diagram for a typical day, the following loads have been considered for each housing unit: two TVs, a fridge, an oven, a dishwasher, a washing machine, a microwave, two unitary air conditioners, and a lighting system [1].

2.2.2 Thermal loads

In a rSOC-based microgrid, utilizing of waste heat sources can play an important role in satisfying the thermal loads in a cost-effective way. In this work, it is proposed that the recovered heat of the rSOC (in electrolyzer mode) be utilized either directly for the load or by storing it in the TES as well as satisfying SOEC thermal needs.

The users' thermal load is represented by the domestic hot water (DHW) demand. To attain the most efficient and cost-effective microgrid, thermal management is needed to determine the expected heat load and its typical daily profile. The overall DHW in a year requested by the overall residential complex is 920 kL with an average desired temperature by the users of 40°C. This considers for each housing unit: a short load with a 3L/min mean flow rate, a medium load with a 6L/min mean flow as well as a bath and a shower with a 8L/min mean flow rate.

2.2.3 Hydrogen request

The hydrogen car fleet consists of 4 hydrogen vehicles. To suitably predict the hydrogen daily requirement in terms of fuel refills, a Montecarlo procedure has been used [3].

3. METHODOLOGY

3.1 Problem formulation

Starting from a known initial design and loads, this work aims at evaluating the best control policy to obtain satisfactory values of the SI concerning power sharing between the rSOC and the electric power grid as well as the TES and the boilers. It is clear that the problem is strongly nonlinear. Thus, a DP controller is expected to be effective by taking into account constraints for each 1 h time step (e.g., upper and lower values for SOC_{HST} and SOC_{TES} and so on). Moreover, once the process is performed for all possible paths, the one with the best result is selected according to the following objective function:

$$J = \int_{0\,h}^{t=8760\,h} \left(P_{bought,el,j} \cdot C_{bought,el} + P_{bought,th,j} \cdot C_{bought,th} - P_{sold,el,j} \cdot C_{sold,el} \right) dt \quad (1)$$

By means of the external routine, this work accounts for the economic assessment of the plant in terms of simple payback period (SPB) and LCOE as follows:

$$SPB = \frac{TC(1 + IC) + TD}{ABC_{el} + ABC_{th} + J - MC + H_{2,ref}} \quad (2)$$

$$LCOE = x_{direct} LCOD + x_{surplus} LCOS + LCOA \quad (3)$$

The abovementioned algorithm is depicted in Figure 2.

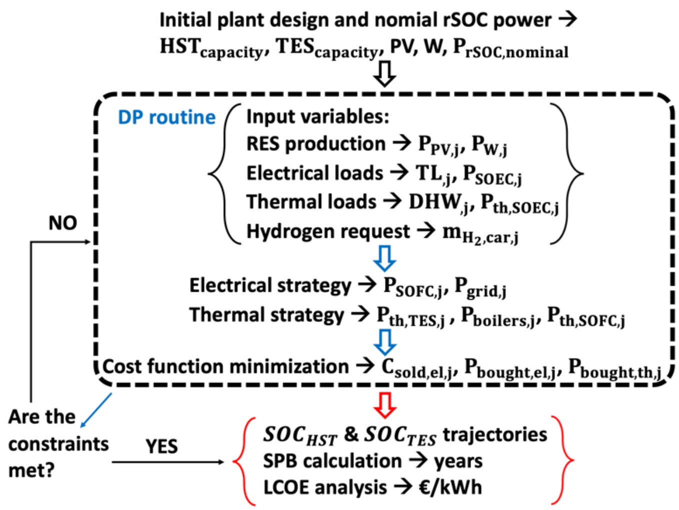

Figure 2: Synoptic diagram detailing the overall algorithm.

3.2 Microgrid management

3.2.1 Electric side

The optimization problem starts with the electric power balance equation:

$$P_{rSOC,j} + P_{grid,j} = P_{PV,j} + P_{W,j} - TL_j \quad (4)$$

The rSOC system works in solid oxide electrolyzer cell (SOEC) mode when $P_{rSOC,j} > 0$ ($P_{SOFC,j}$) and in solid oxide fuel cell (SOFC) mode when $P_{rSOC,j} < 0$ ($P_{SOEC,j}$). Similarly, a negative value of $P_{grid,j}$ means that the system is selling electricity to the grid, and a positive one indicates that the microgrid is not able to satisfy the overall electric load autonomously and requires the electrical grid contribution. The mass of hydrogen required by the fuel cell to provide a given quantity of electricity is inversely proportional to the efficiency, and can be calculated as follows:

$$m_{SOFC,j} = \frac{P_{SOFC,j} t_{SOFC,j}}{\eta_{SOFC_j} LHV} \quad (5)$$

Likewise, the hydrogen produced in the SOEC mode is given by:

$$m_{SOEC,j} = \frac{\eta_{SOEC_j}(P_{SOEC,j}+P_{th,SOEC,j})t_{SOEC,j}}{LHV} \quad (6)$$

A mass balance on the hydrogen tank can be written as follows:

$$m_{H_2,tank,j} = (m_{SOEC,j} - m_{SOFC,j}) \quad (7)$$

Here, $m_{H_2,tank,j}$ is the mass of hydrogen entering or exiting the HST at a given time j.

The hourly variation of HST state of charge is defined as follows:

$$SOC_{HST,j+1} = SOC_{HST,j} + \frac{m_{H_2,tank,j} - m_{H_2,car,j}}{HST_{capacity}} \quad (8)$$

3.2.1 Thermal side

The DP-routine, simultaneously with Equation (1), manages the thermal side of the plant as well, using the following balance equation:

$$P_{th,TES,j} = P_{boilers,j} + P_{th,rSOC,j} - DHW_j \quad (9)$$

When the rSOC system operates in SOEC mode, $P_{th,rSOC,j}$ is less than 0 and equal to $P_{th,SOEC,j}$. In SOFC mode, $P_{th,rSOC,j}$ represents the power that the rSOC provides to the TES/thermal loads, so $P_{th,rSOC,j} = P_{th,SOFC,j} > 0$. The energy accumulated in the TES at time j, $Q_{in,j}$ strongly depends on the released SOEC thermal power bonded to the energy required by electrical and DHW loads, as follows:

$$Q_{in,j} = P_{th,TES,j} t_j \sqrt{RTE_{TES}} \quad (10)$$

The TES output energy at time j, $Q_{out,j}$, depends on the rSOC thermal requirement, the DHW load and the boiler energy integration, and can be calculated as follows:

$$Q_{out,j} = P_{th,TES,j} t_j / \sqrt{RTE_{TES}} \quad (11)$$

where RTE_{TES} is the round trip efficiency. The hourly TES state of charge is defined as follows:

$$SOC_{TES,j+1} = SOC_{TES,j} + \frac{Q_{in,j} - Q_{out,j}}{TES_{capacity}} \quad (12)$$

4. RESULTS AND DISCUSSION

By a parametric analysis, it is pointed out that the best management strategies for SOC_{HST} and SOC_{TES} besides the lower SPB & LCOE values are achieved by considering a 15 kW SOFC and SOEC.

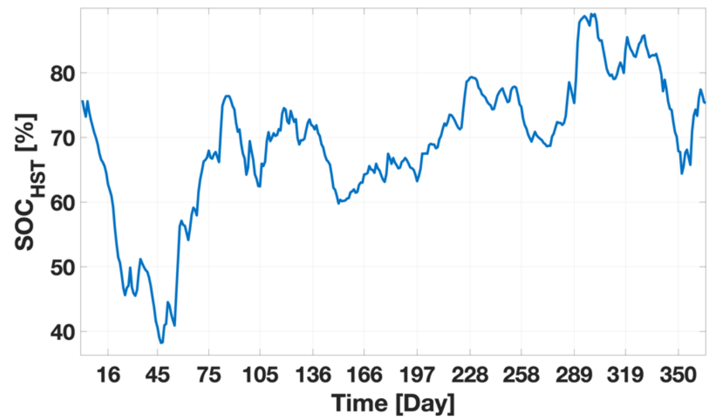

Figure 3: Variation with time of HST state of charge.

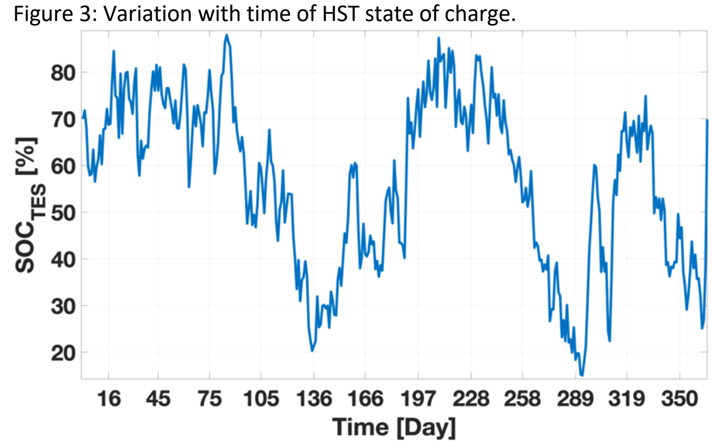

Figure 4: Variation with time of TES state of charge.

In this configuration, the rSOC system operates 100% of the time, broken down as 3406 h in SOFC mode and 5354 h in SOEC mode, as depicted in Figure 5. Note that thanks to the thermal energy saved it is reasonable and economically profitable to keep continuously operating the rSOC for the entire available working time. In light of the electric grid and boiler connections, the DP optimization pointed out an external energy integration that is seen to be 5.31% as regards the electric side and 83% regarding the thermal contribution. Moreover, it is possible to evaluate the microgrid self-sufficiency period in the case where renewable energy is not available. This can be straightforwardly done by considering the electrical load, the hydrogen consumption, and the HST and TES capacities. Specifically, in the case of a RES interruption, the system can sustain the electric loads for 12 days due to the HST energy, while on the thermal side the TES can provide sufficient energy for 4 days.

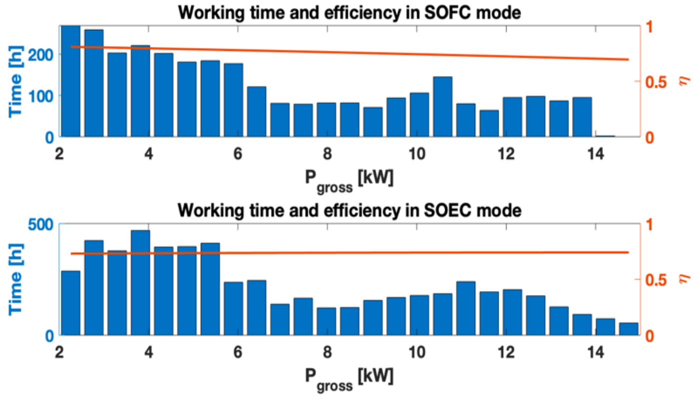

Figure 5: rSOC working time distribution.

As far as the cost analysis is concerned, a SPB period of 5.97 years has been obtained. Considering a project duration of 30 years and carrying out a parametric LCOE analysis by using a discount rate in the 4-10% range, it is determined that a cost of energy per kWh produced in the range 0.1 €/kWh-0.2 €/kWh is comparable to the values provided by the actual technologies available in the market. The latter aspect reflects the fact that the combination of various RES technologies and rSOC along with energy storages, and their overall optimization, highlights the best aspect of each of the technologies, thus minimizing the external energy integrations (i.e., electrical grid and boilers). By considering each term of the LCOE calculation, it is emphasized that the levelized cost of storage (LCOS) function scales down significantly after 10 years due to the large initial cost incurred for the storage systems. Therefore, in order to increase the appeal for systems like the studied microgrid, it would be good practice to acknowledge the extra value added by storages in terms of grid stability.

5. CONCLUSIONS

This paper analyzes the energy management of a microgrid relying mainly on renewables (i.e., wind turbines and photovoltaic panels), a rSOC system and ESs besides on the electrical grid and boilers in case of energy balance purposes. On the one hand, the effectiveness of this configuration is outlined by means of economic indices such as:

- LCOE that is seen to be equal to 0.1 €/kwh-0.2 €/kwh depending on the adopted discount rate. The obtained values turn to be excellent compared to that of the single RES, for instance, the solely photovoltaics has a medium value of the LCOE in the range of 0.2 €/kWh to 0.6 €/kWh.
- SPB proven to be equal to 5.97 years which in turn means that this is a viable microgrid for the potential investors.

On the other hand, from the microgrid resiliency standpoint, are envisaged tangible metrics like:

- Self-sufficiency of the microgrid by taking fully advantage of the energy stored into the ESs. Particularly, the microgrid results able to withstand energy shortages of both electric and thermal requests respectively for 12 and 4 days.
- Suitable integration among renewables, ESs and the rSOC that makes the latter system able to work 100 % of the available time. Therefore, avoiding rSOC start-up and shut-down phases, it is foreseen to keep the rSOC degradation effect under control and thus having reasonable costs of maintenance.

Specifically, the results obtained in this paper confirm that, even though the introduction of ES technologies makes the initial investment difficult to provide a return for, the rSOC system suitably mitigates the cost by making the most of the energy provided by the HST, TES and RES systems. Once the multiple services offered by ESs will be recognized by an economic reward and the hydrogen value chain will be deployed, this microgrid solution is expected to provide additional profitability and economic appeal for potential investors.

REFERENCES

[1] Rispoli, N. (2019). Constrained optimal design of an rSOC-based renewable microgrid for multiple loads, Master's thesis. UNISA (University of Salerno) DIIN (Department of Industrial Engineering).

[2] Baldinelli, A., Barelli, L., Bidini, G., Discepoli, G. (2020). Economics of innovative high capacity-to-power energy storage technologies pointing at 100% renewable micro-grids. Journal of Energy Storage, 28, 101198.

[3] Rispoli, N., Vitale, F., Califano, F., Califano, M., Polverino, P., Sorrentino, M., Rosen, M.A. (2020). Constrained optimal design of a reversible solid oxide fuel cell-based multiple load renewable microgrid. Journal of Energy Storage, 31, 101570.