2013 ISES Solar World Congress

Coupling of a Solid-Oxide cell unit and a linear Fresnel reflector field for grid management

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Abstract

Recent analyses on energy scenarios for countries with high contribution of intermittent renewables point out that electricity generation from solar and wind energy may exceed the overall electricity demand during a large number of hours per year (that include peak periods). Thus, large-scale electrical energy storage systems are required for grid balancing. Hydrogen production through solid-oxide electrolysis cells (SOEC) stands for promising power storage systems due to its high capacity and wide variety of applications. SOEC operates with steam in the range of 600-1000 °C, which, in this work, is supplied by a concentrating solar system. Based on its simplicity and low cost of the components, a linear Fresnel reflector coupled with castable ceramic thermal energy storage system was selected. Thermal oil was retained as heat transfer fluid avoiding phase change through the solar receiver. The heat is stored during the day for later use by the SOECs.

The proposed hybrid plant, located in Seville, Spain, is analyzed under two scenarios. In the first one, the Solid-Oxide unit is only used as steam electrolyser producing hydrogen that is directly sell to a hydrogen bus refueling station. In the second case, the device operates either as electrolyser or fuel cell, generating hydrogen that is stored and later used to produce electricity during peak periods. The capacity of the plant operating under both scenarios has been evaluated as a function of the storage capacity.

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Selection and/or peer-review under responsibility of ISES

Keywords: Solid-Oxide cell; Linear Fresnel reflector; Hydrogen; Grid management.

1. Introduction

Environmental concerns and limited resources of fossil fuels have stimulated energy policies pursuing large share of renewable energy (RE) within the power and transport market. The European Commission established mandatory targets to be achieved by 2020 for a 20% overall share of RE in the energy mix...
and a 10% share in the transport sector [1]. Within this framework, the last Spanish government established policies that have resulted to levels of 39.4% of RE share along the last 12 months [2]. However, the electricity from RE resources is not constant and reliable due to their sensitive response to local weather conditions. To level out the variable generation of energy, large-scale electrical-energy storage is required [3–5]. Whereas batteries, compressed air, flywheels or capacitors are suited for the short-term storage of electricity, long-term storage could be realized with hydrogen as an energy vector through the so-called power-to-gas (P2G) plants [6].

With P2G, excess electricity is converted into hydrogen by water electrolysis. This hydrogen can be stored in pressurized tanks and, when needed, it can be reconverted into electricity with fuel cells or hydrogen combustion engines. Besides its use as energy storage for electricity, hydrogen can be used as fuel for transport applications, as a raw material for the chemical industry, or for the synthesis of various hydrocarbon fuels such as methane. Additionally, a certain percentage of hydrogen could be directly fed into the gas distribution system; furthermore, there should be no limitations, whereas hydrogen is previously converted to methane [7–9]. Since 1990, more than 41 international power-to-gas (P2G) pilot plants have been installed and run producing hydrogen for Grid balancing [10]. Most projects integrates alkaline or proton exchange membrane (PEM) electrolyser. These kinds of electrolysers are fed with liquid water, achieving efficiencies of 75-80 and 90% respectively (versus high heating value, HHV). Within these plants, hydrogen is converted back to electricity through PEM Fuel cell or internal engines. However, several studies have shown great advantages of high temperature steam electrolysis with Solid-Oxide electrolysis cells (SOEC) over liquid water electrolysis, which operates in the range of 600 to 1000 °C. From a thermodynamic point of view, hydrogen split reaction can be described by the Gibbs function,

$$\Delta G = \Delta H - T \cdot \Delta S$$

where $\Delta H$ is the overall energy needed, $\Delta G$ is the electrical energy and $T \cdot \Delta S$ is direct heat. As can be seen Fig. 1, electrical requirement decreases and heat energy demand increases with increasing temperature. Even though total energy demand increases, the decrease in electrical energy demand is more noticeable. From the kinetic point of view, high temperature helps to promote electrode activity and reduce cell overvoltage. It means that power density can be increased, reducing the size of the electrolyser for a given production. Additionally, lower cell overvoltage can be translated to lower energy losses, thus more electric efficient process [11]. And finally, Solid-Oxide systems are able to work either as electrolyser (SOEC) or as fuel cell (SOFC), reducing the number of units and its auxiliary elements of a P2G plant. All these advantages projects lower generation cost than with the current technology [12], [13].
SOEC systems are characterized by the high temperature at which it works, thus the requirement of feeding directly with steam. Therefore, for this work, a concentrating thermal solar system is proposed to deliver enough heat for the evaporation of the feed water. Based on their simplicity and the low cost of the components, a linear Fresnel reflector (LFR) and castable ceramic thermal energy storage (TES) were selected [14], [15]. Due to the maximization of storage capacity with temperature gradient the Therminol VP1 thermal oil was retained as heat transfer fluid [16].

In the present study, the proposed P2G plant is located near Seville, South Spain. This is analyzed under two different scenarios: (i) the Solid-Oxide unit is only used as steam electrolyser producing hydrogen that is directly sold to a hydrogen bus refueling station; and (ii) the device operates either as electrolyser or fuel cell, generating hydrogen that is stored and later used to produce electricity during peak periods. In relation with these scenarios, the capacity of the plant to achieve two different goals has been analyzed as function of the thermal storage capacity. Firstly, the capability of the plant to feed 20 hydrogen metropolitan busses, which requires among 400-600 kg/day of hydrogen [17]. Secondly, the availability of the system for grid balancing. In the first scenario, where hydrogen is directly dispatched to a bus refueling station, the hybrid plant is used to minimize the reduction of the Spanish demand during night hours. Additionally, in the second scenario the hydrogen is stored for later used in fuel cell mode to produce electricity during peak periods, so electricity excess can be moved from off-peak to peak demand hours. For this study, Ebsilon Professional software has been used [18].

2. Hybrid plant description

The P2G plant proposed in this work is presented in Fig. 2. At the upper section, it can be seen the concentrating thermal solar system (CSP); while at the bottom, the SOE/FC system is shown. In both scenarios, hydrogen is compressed up to 30 bar before it is delivered to the refueling station or stored for later use in fuel cell mode. The compressor has five stages. Each of them has a nominal compression ratio of 2 that result in a maximum outlet temperature of 130°C. Before entering the next compression stage, the gas is cooled down to 45 °C, and the condensed steam is drained.
2.1. Concentrating thermal solar system

The solar system consists of several LFR collectors and a number of castable ceramic TES modules, five in the scheme shown in Fig. 2. Concerning the LFR collectors, among the different models implemented in Ebsilon Professional, Mirroxx LFR collectors were selected. This model is well suited for the proposed plant due to its modularity; the use of PTR 70 receiver manufactured by Schott Solar GmbH, which allows reaching high temperatures, up to 400 °C at a maximum pressure of 40 bar; and its previous use in industrial heat applications [16]. A total of eight collectors, divided into two lines of four collectors in series were implemented. Regarding the TES modules, they have been simulated based on the methodology proposed by Tamme et al., and the experience presented by Laing et al. [19], [20]. Each TES module is 10 m long and has a square section of 4.84 m². It has been simulated as a unique pipe of 350 m long that makes 36 passes along the module. Thermal losses are considered negligible. Specifications of the LFR and the TES modules are presented in Table 1.

In Fig. 2 it is shown the flow path of the thermal oil during the TES charge process (green and green-orange dashed lines), and the discharge operation (orange and green-orange dashed lines). During the charge process, a constant mass flow of 8 kg/s of thermal oil are sent from the reservoir tank to the LFR system where it is heated up. Afterwards, the mass flow is divided in equal parts to charge every TES module at the same time. Finally, the thermal oil goes back to the reservoir tank, and from there, it is recirculated again. On the other hand, during the discharge process, the thermal oil is sent directly to the TES through the orange pipe, to increase its temperature. Afterwards, it is sent to the SOEC boiler, where dry steam at 115 °C is produced as demand of the electrolysis system.
Table 1. Concentrating thermal solar system characteristics

<table>
<thead>
<tr>
<th>Mirroxx Linear Fresnel reflector</th>
<th>Storage material properties</th>
<th>Storage module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector length</td>
<td>Storage medium</td>
<td>Module length</td>
</tr>
<tr>
<td>65 m</td>
<td>Castable ceramic</td>
<td>10 m</td>
</tr>
<tr>
<td>Gross aperture</td>
<td>Thickness of storage</td>
<td>Section</td>
</tr>
<tr>
<td>7.5 m</td>
<td>(around the pipe)</td>
<td>2.2 x 2.2 m</td>
</tr>
<tr>
<td>Net aperture area</td>
<td>Density</td>
<td>Number of passes</td>
</tr>
<tr>
<td>351 m</td>
<td>3500 kg/m³</td>
<td>36</td>
</tr>
<tr>
<td>Focal length</td>
<td>Specific heat capacity</td>
<td>Pipe length</td>
</tr>
<tr>
<td>4 m</td>
<td>866 J/kg K</td>
<td>350 m</td>
</tr>
<tr>
<td>Absorber inner diameter</td>
<td>Thermal conductivity</td>
<td>Pipe inner diameter</td>
</tr>
<tr>
<td>0.0656 m</td>
<td>1.3 W/m K</td>
<td>0.04 m</td>
</tr>
</tbody>
</table>

2.2. Electrolysis process specifications

Regarding the SOE/FC system, it is composed of two units of 2.5 MWₑ. Each unit has 38400 cells that are assembled into 192 stacks of 200 cells each. At the same time, these stacks are grouped into modules that have two lines of 8 stacks in series. The final unit has 12 of these modules divided into two levels, each one with 6 modules set together, see Fig. 3.

Concerning the characteristics of the cells, these have an active surface of 69.3 cm². The electrolyser stack operates at 700 ºC, at the thermoneutral point with a current density of 0.63 A/cm², corresponding with a cell voltage of 1.241 and 0.759 V in the SOEC and SOFC mode respectively [21]. Furthermore, to prevent the degradation of the cathode, reducing conditions have been ensured recirculating a fraction of hydrogen into the cathode feed steam, yielding to 10 % vol hydrogen content; and limiting the "fuel" conversion in the stack at a maximum level of 60 % under SOEC mode, and 75 % in SOFC mode [13]. Also equal molar flow rated on the cathode and sweep loops was assumed. Under these conditions, the stack achieves an efficiency of 115.2 and 60.6 % vs. HHV in SOEC and SOFC modes respectively [21].

Concerning the SOE/FC unit, it consists of two differentiated gas loops: the cathode loop for feeding the steam or hydrogen (see Fig. 2 down on the left); and other for the sweep gas, which removes the produced oxygen called sweep loop (down on the right). Both loops include a heat recovery system to make the most of the heat that contains the electrolysis exhaust gases. Thanks to this system, the external
heat supply is exclusively used to carry out the evaporation of the feed water of the electrolyser. In SOEC mode, liquid water is pumped to the system, preheated in the economizer and evaporated in the boiler by means of hot thermal oil. Afterwards, the steam is superheated and mixed with a hydrogen enriched stream to maintain reducing conditions at the cathode [22]. Then, the resulting mixture is finally heated up to the stack temperature, 700 °C, by electrical heater-1. Lastly, the mixture enters to the electrolyser modules, where 60 % of the inlet steam is electrically reduced, producing hydrogen at the cathode, and oxygen at the anode. The resulting exhaust gas of the cathode is routed through the superheater and economizer of the heat recovery system. Along this process the exhaust mixture reduces its temperature from 700 to 71 °C. To remove most of the water before the compression process, the gas is further cooled down to 45 °C into an air-cooled condenser, yielding to a 90 %vol hydrogen mixture. Afterwards, 15 % of this mixture is recirculated and mixed with the inlet stream, as explained previously. The rest of the hydrogen enriched mixture is compressed into a five intercooler-stage compressor up to 30 bar. After each intercooling stages, the condensed water is removed to avoid the erosion of the turbine blades. Lastly, a molecular sieve desiccant is used to remove the rest of the moisture before hydrogen is stored. Under SOFC mode, the hydrogen stream flows as the purple/shining-green dash line shows. Main differences with the SOEC mode are that: (i) the economizer, the evaporator and the compressor are not used, and (ii) that the un-reacted hydrogen is injected into the inlet stream, before the superheaters of the heat recovery system.

Besides the steam/hydrogen loop, there is the sweep gas loop shown in the center-right of Fig. 3. This is used to remove or supply the oxygen produced or consumed depending on the system operation mode, as SOEC or SOFC respectively. The air is fed into the system with a blower. Firstly, a filter removes particles and harmful gases from the air. Then, this is preheated through the anode-HX and also through the electrical superheater. Afterwards the exhaust air enters the stack, flows through the anode-HX system, and finally is sent to the atmosphere.

3. Analysis of the results

The proposed P2G plant has been analyzed under two different scenarios. In a first one, the goal of the plant is to feed a hydrogen bus refueling station, at the same time that the system helps to minimize the reduction of the grid demand during night hours. In the second scenario, the Solid-Oxide device operates either as electrolyser or fuel cell. As well as in the first one, in this scenario, during night hours the SOE/FC is only used as steam electrolyser producing hydrogen. This hydrogen is stored for later use to produce electricity during peak periods operating in SOFC mode. For both analyses, it was assumed that the electrolyser operates between 1:00 and 6:00 a.m. This corresponds with hours at which the demand falls to its minimum values. In the second scenario, the fuel cell operates during the 5 hours with maximum demand. The availability of the system has been analyzed as function of the thermal storage capacity. Within the analysis, the number of TES modules has been varied from 4 to 10.

Fig. 4 shows the profile of the DNI, the temperature at the inlet and outlet of the TES, as well as the storage average temperature, and hydrogen production profile along two representative days. As can be seen, during a day with good radiation, the TES modules can be completely charge and reach temperatures above 350 °C. This makes possible to operate the SOEC at full load along the 5 hours, producing a total amount of 666.3 kg/day. However, it can be seen that during cloudy periods the TES reach lower temperature levels, even though the previous day it was not completely discharge. Due to the poor charge level of the storage, the SOEC is able to work at full load only the first two hours. Afterwards, starts the operation at partial load during the next 1h 45 min. Under this condition, the mass flow of hot oil towards the boiler of the electrolyser is limited to 10 kg/s, and the heat transfer decreases
with the time as function of the temperature of the TES. Finally, the last 1h and 15min the SOEC reaches its minimum capacity level (60%) and has to be switched off.

Fig. 4. DNI, temperature in the thermal storage and hydrogen production profiles in two representative days

Concerning the first scenario, hydrogen production is analyzed as function of the number of TES modules. Table 2 shows the annual hydrogen production, which reaches levels above 200 ton/year. Due to cloudy periods, the best production level is 90 % of the maximum possible production. In Fig. 5 it is shown the average daily production of the electrolyser exceed 400 kg/day in all cases, which is enough for 20 busses. Even more, above 5 TES modules, hydrogen production exceeds 550 kg/day. Thus, a slightly larger number of busses might be fed with this plant.

Table 2. Annual hydrogen production

<table>
<thead>
<tr>
<th>Nº TES</th>
<th>Hydrogen production (ton/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>177</td>
</tr>
<tr>
<td>5</td>
<td>199</td>
</tr>
<tr>
<td>6</td>
<td>208</td>
</tr>
<tr>
<td>8</td>
<td>215</td>
</tr>
<tr>
<td>10</td>
<td>219</td>
</tr>
<tr>
<td></td>
<td>Max. possible production</td>
</tr>
</tbody>
</table>
The increase of hydrogen production with the number of storage modules is due to the improvement of the availability of the plant with larger number of TES modules. As can be seen in Fig. 6, just increasing the number of modules from 4 to 5, the number of days that the SOEC units work at partial load decreases enormously, more than 150 days. Additionally, the SOEC system is able to work at full load along 200 nights. Thus, it can be concluded that four TES modules would be insufficient to deliver the heat demanded by the SOEC units. Moreover, oversizing the TES makes possible to store heat from sunny days for later use in following cloudy days, increasing the number of days at which the SOEC is able to work at full load. However, this capacity gain achieves lower relevance with the increase of the number of TES modules. On the other hand, the number of days, at which the proposed plant is not available for grid balancing, does not decrease significantly with the storage.

Regarding the second scenario, Fig. 7 shows the accumulated energy that the plant consumes from the grid during the night, and delivers during the day. So, in the case that hydrogen is not sold directly, but reconverted to power during peak periods, the average round-trip efficiency of the system is 43.1 %. It is seen that the energy re-injected into the grid does not increase much above 5 TES modules.
4. Conclusions

From the analysis, it was found that the proposed plant would be able to produce above 500 kg/day, which fulfills the fuel requirement of a hydrogen refueling station with a capacity above 20 metropolitan busses. Annual production with 10 TES modules would be 90% of the maximum hydrogen production that could be produced by a more stable thermal source such as geothermal plants. Regarding the second scenario, it was seen that the P2G plant is able to reach a round-trip efficiency of 43.1%.

Lastly, it is clear than, for the system proposed in this study, it is necessary to implement more than 5 cascade ceramic TES modules. Nevertheless, it should be mentioned that the gain achieved with the increment of TES modules is reaching an asymptote; and for example, the number of days that the system is not available is almost constant. Thus, the best solution for an active grid balancing system might be to integrate 5 or 6 cascade ceramic TES modules. However, further economic studies would be necessary to define the optimum number of units.

Acknowledgements

The research leading to these results has received funding from the European Union’s Seventh Framework Programme (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant agreement nº 256755 of project ADEL “Advanced Electrolyser for Hydrogen Production with Renewable Energy Sources”. Specials thanks are due to ADEL Project partners Jan Peter Brouwer and Michael Walter (Hygear, The Netherlands) for their contribution providing information on SOEC stack architecture and performance.
References


