Assessing the Utilization of Fuels Cells for the Valorization of Produced Excess Energy in Isolated Grids – The Green Transition of Agios Efstratios

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Abstract The island of Agios Efstratios is a unique case, since a pilot green energy transition program is taking place. Wind and solar photovoltaic technologies have seen tremendous growth during the past decade and various policy measures have been introduced in support of their growth. For the cases of islands that are not connected with the mainland grid the integration of renewable energy systems (RES) is a challenge, due to the variable performance for wind and solar. This study investigates the integration of electrolysis and fuel cells as a method to increase the penetration of RES in the isolated system of the island and to store hydrogen for other uses like green transportation. The software RETSCREEN was used for the analysis and the available excess energy from the renewables showed that it can support the operation of a 200 KW fuel cell system and the replacement of two small 90 KW diesel engines and would increase the overall RES penetration. At the same time, more than 20 tons of hydrogen could be stored annually for other uses.
Keywords: Wind, Solar PV, Fuel Cells, Electrolysis, VRE

1. Introduction

The Greek electrical transmission and distribution grid has a centralized and a non-centralized part. The non-centralized electrical grid consists of several isolated grids in clusters of islands and some smaller completely autonomous power stations. Although several bigger islands are connected (or will connect the following years) either to the centralized grid or to the non-centralized electrical grid clusters between them, this is not the case for several small and medium size islands of the Aegean. Electricity production in isolated grids rely primarily in Fuel Oil/ Diesel combustion (Georgiou at al., 2011. Autonomous systems on islands provide a great potential for RES development and the gradual green transition into a low-carbon energy production system. Wind and solar photovoltaic technologies have seen tremendous growth in many countries during the past decade and according to all projections they will continue to grow for many years to come. Many countries used various policy measures and incentive to foster renewables growth which so far have proved extremely successful, such as generous public funding, favorable loans, tax incentives, along with power purchase legislations and feed-in-tariff arrangements (Abdmouleh et al., 2015). On the technology improvement side, for onshore wind the global weighted-average Levelized Cost of Electricity (LCOE) fell by 39% the past decade, whereas for offshore wind the reduction was 29%. In PV the reduction of LCOE was a staggering 82% for the same period (IRENA, 2020).

Traditionally, the most common application of electricity storage is in islands and/or remote off-grid areas where it can have a share in power generation up to 100%. In a large power system these services usually comprise black start support, frequency regulation and voltage control, as long as operating reserve and power quality improvement. Thus, large-scale electricity storage deployment along with other measures can provide the required flexibility in power systems in a high VRE environment. Other domains are for example demand response, smart grid operations, flexible generation, and sector coupling. In addition, no power generator is designed to operate 100% of the time. Conventional power plants (gas, oil, etc.) periodically shut down for maintenance or go off-line due to unexpected breakdowns. Wind generation leads to steeper ramps (rate of change in dispatchable generation to follow changes in demand), deeper turn downs (operation of dispatchable generators at low levels) and shorter peaks (periods where generation is supplied at higher level) in power system operations (Castillo et al., 2014).

The high carbon footprint of diesel engines, along with the overall willingness to move towards a greener electricity mix, demands a stable non-variable renewable energy resource that could assist the undisrupted production of electricity. Such an alternative can be the utilization of fuel cells that can operate with hydrogen from electrolysis that is powered with the excess VREs. Hydrogen is the fuel that is primarily used in fuel cells, although several technologies that operate with natural gas or methanol have been reported. The main technologies have been reported to be proton-exchange membranes (PEM), phosphoric acid fuel cells (PAFC) and Solid Oxide fuel cells (SOFC). Fuel cells are slowly gaining market share and are becoming larger in scale and more reliable. Staffel et al. (2019) identified more than "225.000 fuel cell home heating systems". In addition, the development of hybrid systems has further advanced the commercialization of fuel cells along with their potential scale of operation (Ma et al., 2021). Thus, fuel cells are gradually becoming reliable solution not only for residential or mobility applications, but also for medium scale off-grid applications. Nonetheless, the overall design, the sizing and the ability of a said fuel cell to start-up rapidly can be critical for the success of a potential installation and thus these are parameters that can significantly affect the decision-making process (Sazali et al., 2020).

The present work takes into consideration the undergoing green transition of an isolated electrical network at the island of Agios Efstratios in the North Aegean. On this island, a pilot-scale innovative energy project has been designed and announced by the Center for Renewable Sources and Energy Saving (CRES) with the distinctive title "Ai Stratis – Green Island". The main goal is to cover more than the 85% of the electrical needs of the island from RES. At present, the total electricity demand of the island is covered by five conventional diesel engine units with a total capacity of 840kW. After the development of the planned intervention, the local system will be reformed with the integration of wind turbines and a photovoltaic park along with an electricity storage system and a district heating system. In accordance with the planned layout of the CRES, more than 2000 MWh of energy produced by RES will be in excess and will not be absorbed by the existing infrastructure, i.e. consumption, district heating or batteries (Dimou and Vakalis, 2021).

The scope of this work is to investigate the use of this excess renewable energy for the production of hydrogen via electrolysis and the downstream utilization in fuel cells by modelling the process for different technological alternatives. The expected result of the study is to present viable scenarios for the production of base load electricity from fuel cells in order to gradually reduce the dependence on diesel generators that -at present- are projected to be kept as reserves. Potential success of this effort would be an important step towards the total decarbonization of isolated grids.

2. Materials and Methods

2.1. Available data and presentation of the case study

Agios Efstratios is a small island of 43.23 km^2, located in central and north Aegean archipelago with a year-round population of 270 people. It is one of the most isolated islands in the Aegean Sea with the nearest island being 18 nautical miles away (Limnos). The island is a non-interconnected, autonomous electrical grid which is served by conventional diesel-powered generators. The local power system consists of 5 thermal generators, 3 x 220kW and 2 x 90kW nominal power, a total of 840kW. The public call for the green transition of the electrical grid of Agios Efstratios is a pilot project in Greece and its main goal is covering the electrical and thermal demand at a percentage of more than 85% with renewable energy systems.

The utilized data and the baseline scenario analysis of this study have been presented by Dimou and Vakalis (2021). According to this study but also according to the planned layout of the CRES, the system will have two components: the hybrid power station consisting of a wind turbine, a photovoltaic array and a battery energy storage system, and the heat storage and distribution system. It should be denoted that at the moment there are no renewable energy systems installed. The island has an average electrical load of 1110.51 MWh/year with a peak load at 428.15 kW. Although there are no data on thermal requirements, according to the public call the total thermal load is 856 MWh/year with a peak load at 482.73 kW. The assumption is made that there is no thermal need during the three summer months.

The proposed installation of renewable energy systems consisted by a 900 KW wind turbine, a 150 KW PV solar system and a 2.5 MWh battery storage system. The analysis presented by Dimou and Vakalis (2021) showed that the proposed design has some advantages but also some drawbacks. Overall, the electricity demand of the island is 1109 MWh per year and the thermal demand has been measured to be 855.9 MWh per year. Although the peak load is not met 100% of the time, the wind turbine produces multiple times the electricity that is requested, as it surpasses the amount of 3577 MWh per year. By also adding the electricity production of the solar PV system the overall excess electricity has been calculated to surpass 2155 MWh per year, even when the thermal load is accounted. This amount of excess electricity is almost double the demand of the electricity demand of the island, but the system is still not capable of have a renewable energy penetration that exceeds 80% – 85%. Thus, the diesel engines need to cover the remaining demand.

2.2. Proposed design and methods of analysis

Fig. 1 presents the proposed addition of fuel cells, for increasing the RES penetration in the electricity production in Agios Efstratios. The main concept is the utilization of the excess electricity for the electrolysis of water and the subsequent production of hydrogen. The hydrogen can be stored and utilized on demand by means of hydrogen fuel cells. A significant amount of hydrogen is expected to be available in storage for other potential use like in vehicles or as alternative fuel for green maritime transportation.

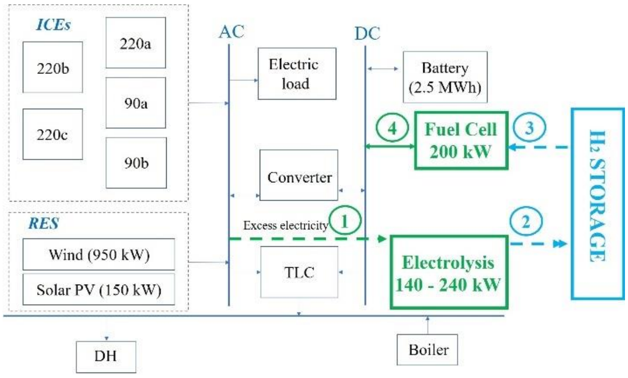

Figure 1. Proposed addition of fuel cells, for increasing the RES penetration in the electricity production in Agios Efstratios

For the purpose of analyzing the potential production of hydrogen, Table 1 present several commercial electrolysis systems, the minimum and maximum nominal production of hydrogen, and the energy demand for the production of 1 kg of hydrogen. The maximum power outputs of the electrolysis systems range from 144 kW for the Norsk HPE 30 up to 288 kW for the Norsk HPE 60.

Table 1. Commercial electrolysis technologies

Model	min/ max H_2 (kg)	kWh/kg of H_2
Norsk HPE 30	0/ 2.7	53.4
Teledyne EC-500	0/ 2.5	62.3
Teledyne EC-600	0/ 3.0	62.3
Norsk HPE 40	0/ 3.6	53.4
Stuart IMET 1000	2.8/ 4	53.4
Teledyne EC-700	0/ 3.8	62.3
Norsk HPE 50	0/ 4.5	53.4
Norsk HPE 60	0/ 5.4	53.4

The production of hydrogen has been simulated for all the electrolysis systems that are presented in Table 1, in accordance with the available excess power. In order to account for the fluctuation in energy demand and thus the fluctuation in excess electricity availability we implemented a Monte Carlo sensitivity analysis with ± 20% of the average available excess power. Overall, more than 1000 simulations were performed for the calculation of the average produced hydrogen quantities per year. The standard deviations are presented as well, as part of the sensitivity analysis.

The proposed fuel cells installation alternatives were simulated by means of the software RETSCREEN. The most representative fuel cell technologies were considered, and Table 2 presents the fuel cell technologies that are included in the database of the software RETSCREEN and were used for the analysis. The scope in each case was to use fuel cells of nominal power output of 200 KW and in order to cover the operation of the two smaller 90 KW diesel engines that are used primarily, since they cover the 853 hours from the total 881 hours of total engine operation. This means that some systems with nominal output power of 200 KW were modelled "as is" (e.g., PureCell 200) and others with smaller outputs, like "Plug power-System 50" were assessed as modules of 4 in order to cover the 200 KW level. Again, a Monte Carlo sensitivity analysis was implemented with ± 20% margin in order to assess the consumption of hydrogen. More than 1000 simulations were performed for the calculation of the average consumed hydrogen quantities per year.

Finally, the hydrogen mass balances were implemented in order to calculate the amount of the available stored hydrogen on annual basis after the operation of the fuel cells. These results have also been statistically analyzed.

Table 2. Utilized fuel cell technologies in RETSCREEN.

Manufacturer	Model	Technology
Ballard	Stationary Fuel Cell	PEM
UTC Power	PureCell 200	phosphoric acid
ZTEK	SOFC modules	solid oxide
Toshiba	PC 25 series	Phosphoric acid
Plug power	System 50	PEM
Nuvera	Hydrogen H2e	PEM
Hydrogenics	H2X Series	PEM

3. Results and Discussion

The simulated produced hydrogen quantities from the electrolysis systems of Table 1 are presented in Fig. 2 and the range is from 21.9 tn to 40.95 tn of hydrogen per year. The larger electrolysis systems have larger deviations in their performance because several simulations return available excess power values that are below the maximum power of the system. Contrary to that, the maximum power of the smaller electrolysis systems is met in full even for the lower range of the sensitivity analysis therefore the deviations from the average are close to zero.

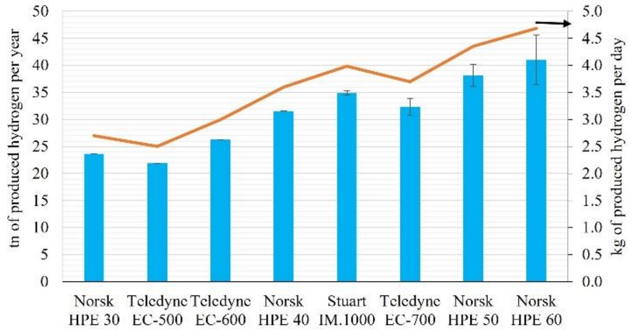

Figure 2. Simulated produced hydrogen quantities from commercial electrolysis systems

Figure 3 presents the consumption of the different fuel cell systems that were modelled to have a nominal power output of 200 KW and to cover the operation of the two smaller 90 KW diesel engines that operated for 853 hours in order to produce 27.7 MWh per year and cover a significant part of the peak demand. It has to be denoted that another (bigger) engine operates for 28 throughout the year and has a maximum nominal output of 220 KW. This study does not aim to eliminate totally the use of diesel engines but with the proposed configuration, the total RES penetration exceeds 90% and goes far beyond the conventional penetration percentages which rarely exceed 85%. This can be a significant step towards a total green transition while taking into account the carbon footprint.

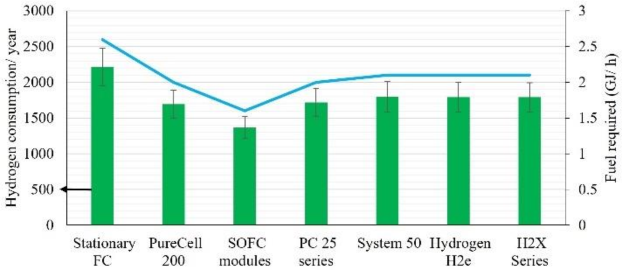

Figure 3. Simulated consumed hydrogen quantities from commercial fuel cell systems (nominal output: 200 KW)

Figure 4 presents the available hydrogen after the operation of the fuel cells. The average available hydrogen has been calculated to be from 20.44 tons up to 21.68 tons per year, with the sensitivity analysis providing lower and higher potential values of 19.2 tons and 22.44 tons respectively.

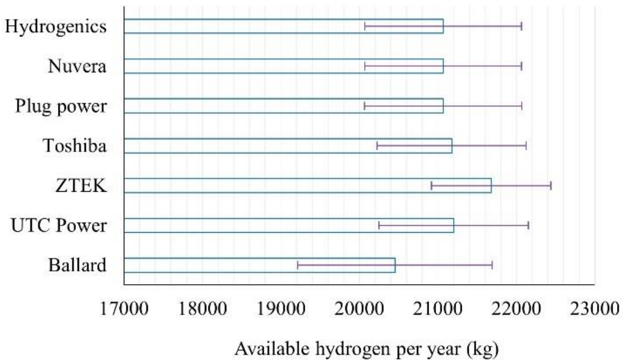

Figure 4. Available hydrogen for storage and other uses (per year)

4. Conclusions

The ongoing decarbonization schemes led to the development of a RES plan for Agios Efstratios, with the installation of a renewable hybrid system. This present study proposes the utilization of the excess electricity for electrolysis and then subsequently the use of hydrogen in fuel cells in order to cover the majority of the peak demand and increase the RES penetration. Commercially available electrolysis systems and fuel cells were assessed by means of the software RETSCREEN and by means of additional sensitivity analysis. The investigated electrolysis systems have been simulated to produce 21.9 - 40.95 tn of hydrogen per year. The utilization of hydrogen in 200 KW fuel cells can substitute the total operation of the two smaller 90 KW diesel engines and the 96.8% of the operation hours of these said engines. After the use of fuel cells, approx. 21 tons of available hydrogen can be stored per year and can be available for other applications like green vehicles and can assist the pathway towards 100% decarbonization.

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