AN INTEGRATED ENERGY SYSTEM TECHNO-ECONOMIC ASSESSMENT FOR NON-INTERCONNECTED ISLANDS: THE CASE OF AMORGOS ISLAND, GREECE

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ABSTRACT

This study aims to design a power generation system using 100% Renewable Energy Sources (RES) and Green Hydrogen to cover the energy needs of an off-grid island in the Aegean Sea, and particularly Amorgos Island. The primary electricity generation alternates between wind and solar energy to optimize energy efficiency, while the state-of-the-art technology is energy storage in the form of green hydrogen. Green hydrogen is produced from water electrolysis utilizing the energy excess [1] (Power-to-H2), while it is consumed and converted to electricity (H2-to-Power) when there is renewable energy shortage. Two scenarios are examined for H2-to-Power, namely Combustion through Gas Turbines and Utilization of Fuel Cells. The overall production and use of Hydrogen, as a rechargeable battery, overcomes the intermittent and weather-dependent RES electricity generation, by providing adequate power supply to the island via indigenous resources, and achieves zero direct greenhouse gas emissions. Both technical and economic aspects of the investment have been studied. The technical analysis, which has been carried out, includes the island's energy demand based on historical data [2] and the energy balance settlement for the calculation of significant parameters for each unit of the system. The Levelized Cost of Hydrogen production (LCOH) and the Levelized Cost of total Electricity generation (LCOE) are analyzed and compared to the existing diesel-based electricity generation system of the island and to similar sustainable projects in the relevant technical literature [3]. Regarding financial attractiveness, this particular investment is assessed as marginally profitable with very optimistic results. The findings of this research contribute valuable insights into the development of sustainable energy solutions for non-interconnected islands, paving the way for environmentally friendly and resilient power systems in remote regions. The successful integration of photovoltaic panels, wind energy, and hydrogen storage, presented in this study, indicates a viable model for other isolated communities striving to achieve energy independence and reduce their carbon footprint.

KEYWORDS: Power-to-H2-to-Power, Green Hydrogen, Non-Interconnected Islands

INTRODUCTION

Climate change mitigation is a global priority. The European Union is making a continuous effort to reduce the consequences of climate crisis by setting ambitious energy and environmental targets for the member-states. However, these initiatives have a significant impact on the economy, such as the energy crisis that started towards the end of 2021. As far as Greece is concerned, apart from the obligation of compliance with the European directives, there are great difficulties in the energy sector. For instance, the existence of hundreds of habitable islands increases energy generation and distribution costs. Besides the electricity grid on Greece's mainland, there are 30 more energy systems established on different non-interconnected islands in order to satisfy the energy needs of the islanders [4]. This situation requires either the inefficient production of energy from multiple generation sources or the undersea interconnection of the islands, leading to increased energy costs. At the same time, the energy mix consists of an important amount of fossil fuels that are responsible for high greenhouse gas emissions like diesel and natural gas. Renewable energy sources (RES) provide intermittent and weather-dependent power generation that cannot ensure energy safety and adequacy of supply to meet demand on the islands. For this reason, conventional energy generation is needed to provide energy at peak loads. Moreover, most of the fuel used for electricity generation is imported from abroad, so Greece is very dependent on geopolitical incidents.

Considering all the above, the focus of this study is on the design and implementation of a sustainable energy system for electricity production on a non-interconnected Greek island, called Amorgos. The project utilizes exclusively renewable energy sources – wind and solar energy – while the state-of-the-art technology is energy storage through green hydrogen. Green hydrogen is produced and stored when electricity production exceeds electricity demand. The use of hydrogen as a fuel during periods of energy shortage resolves the main drawback of renewable energy sources, which is the intermittent production of energy. This independent energy system that is being developed gives energy supply security to the island. The project aims to achieve the following goals:

- No need for undersea interconnection of islands with the mainland
- Zero direct greenhouse gas emissions
- Continuous RES production through hydrogen
- Energy independence of third countries

Both the technical and economic characteristics of the investment have been studied. After the establishment of the necessary parameters for the design, the project was examined in terms of its financial attractiveness.

METHOD

Several important factors played a role in choosing the island of Amorgos for the project. Amorgos belongs to the Cyclades Islands, and is in the southeastern Aegean Sea, far from the mainland. According to authorities, there are no plans for interconnection at least until 2027 [5], while the main fuel for electricity production is light diesel. Furthermore, this island seems to have good meteorological conditions, which results in high photovoltaic (PV) and wind turbine (WT) performance (average solar irradiation: 1.656 kWh/kW, max wind potential: 12 m/s).

The proposed system consists of five main units: a photovoltaic park, a wind farm, an electrolyzer, a hydrogen storage tank and a hydrogen gas turbine/fuel cells unit. The following diagram represents the processes of the project.

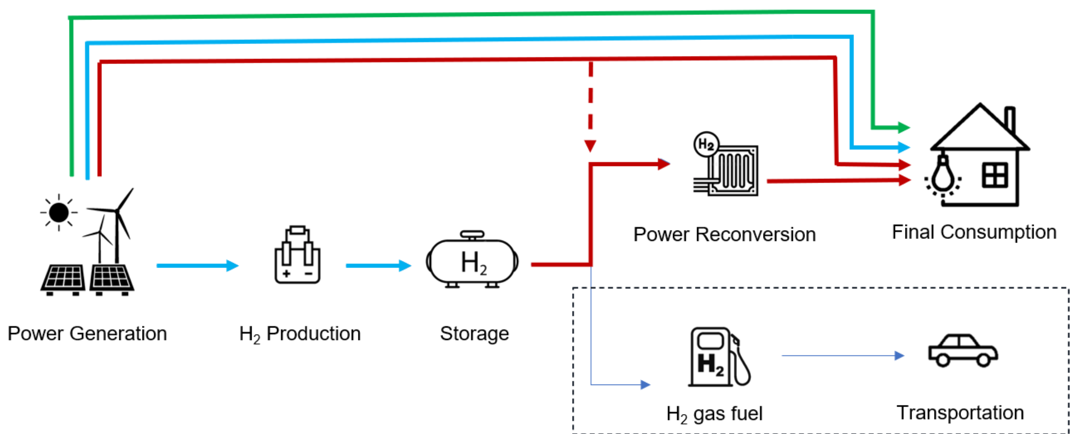

Diagram 1: Flow Chart of the Project

The energy is produced exclusively from RES and is then either injected into the grid or is led to the electrolyzer where electrolysis takes place to produce hydrogen. Among a variety of hydrogen production processes, water electrolysis (with electricity produced from RES) is the only way to produce green hydrogen, without direct greenhouse gas emissions. The following electrochemical reaction shows how water is split into oxygen and hydrogen using electricity: $\mathbf{H_2O_{(l)} + energy \rightarrow H_{2\,(g)} + \frac{1}{2}\, O_{2\,(g)}}$

Afterwards, the produced hydrogen is compressed to be stored at high pressure, for later use. When there is energy demand, the hydrogen is led into a hydrogen combined cycle gas turbine with 60% efficiency, where it is used as a fuel to generate electricity through combustion. Electricity production from hydrogen Fuel Cells was also examined. This method is the opposite reaction of electrolysis, and it is a very promising technology. However, the costs are high which make fuel cells impossible to be used on an industrial scale. Furthermore, the efficiency of fuel cells unit was found low regarding to the hydrogen combined cycle gas turbine unit.

Overall, there are three energy flows (Diagram 1) that can be followed depending on the energy balance between RES electricity production and demand of final consumers:

i) <u>RES electricity production = Electricity demand (green colour)</u>: The whole amount of RES electricity production is directly consumed by the inhabitants.

ii) <u>RES electricity production > Electricity demand (light blue colour)</u>: The needed amount of RES electricity production is led to final consumption and the excess energy is led to the electrolyzer to be stored as hydrogen.

iii) <u>RES electricity production < Electricity demand (red colour)</u>: The whole amount of RES electricity production is led to final consumption and the energy supply shortage is covered by generating electricity through hydrogen combustion in gas turbine.

The hydrogen production process can also be used in other projects, like transportation.

Subsequently, the study includes an analysis of the technical aspects of the energy conversion processes. Two of the biggest challenges of the project design were the selection of the equipment and the selection of the necessary power for each unit. For each separate unit, the types of technology that could be used were investigated and the most suitable were chosen based on the characteristics of similar projects already implemented. The electricity needs of the island were examined in detail, based on historical data. The average annual consumption found was 12.820 MWh (1,46 MW) and the peak demand throughout the last five years was 3,50 MW. As for the electricity generation systems, the PV panels were chosen to have a dual axis tracking system to achieve high performance rates (2.252,4 MWh/MW-y or 25,71% efficiency), while the technical characteristics of the wind park were chosen to simulate an existing park located on a Greek island, called Agios Georgios (3.000 MWh/MW-y or 34,25% efficiency). The mix of solar and wind energy simultaneously brings periodic electricity production because of PV and a significant electricity production at night from the WT, when there is no solar irradiation. As for hydrogen processes, the Proton Exchange Membrane (PEM) electrolysis method is used for production due to high efficiency (75%) and high purity of the products (99,9%). The compression takes place at a two-stage hydrogen compressor and the product is stored in a Type II hydrogen tank. For the conversion of chemical energy, from hydrogen to electricity, a combined cycle gas turbine is used.

In order to find the parameters of the project, a mathematical model was designed according to the energy balance. As shown in *Diagram 2*, the light blue line represents the total RES production on an hourly basis, which means that it is the sum of PV production and WT production. The dark blue line indicates the average electricity demand-consumption. For the area where Total RES production curve is higher than Island Consumption curve, the surplus energy is stored as compressed hydrogen. For the area where Island Consumption curve is higher than Total RES production curve the shortage of energy is covered by electricity generation from hydrogen combustion. However, the designed system not only needs to satisfy the average energy demand but also the peak demand that may occur at any hour of the day. For this reason, the calculations were initially done based on the average annual consumption of the island, but then the results were revised according to the peak demand (purple line), to be able to cover any load. The green line is the new Total RES production needed.

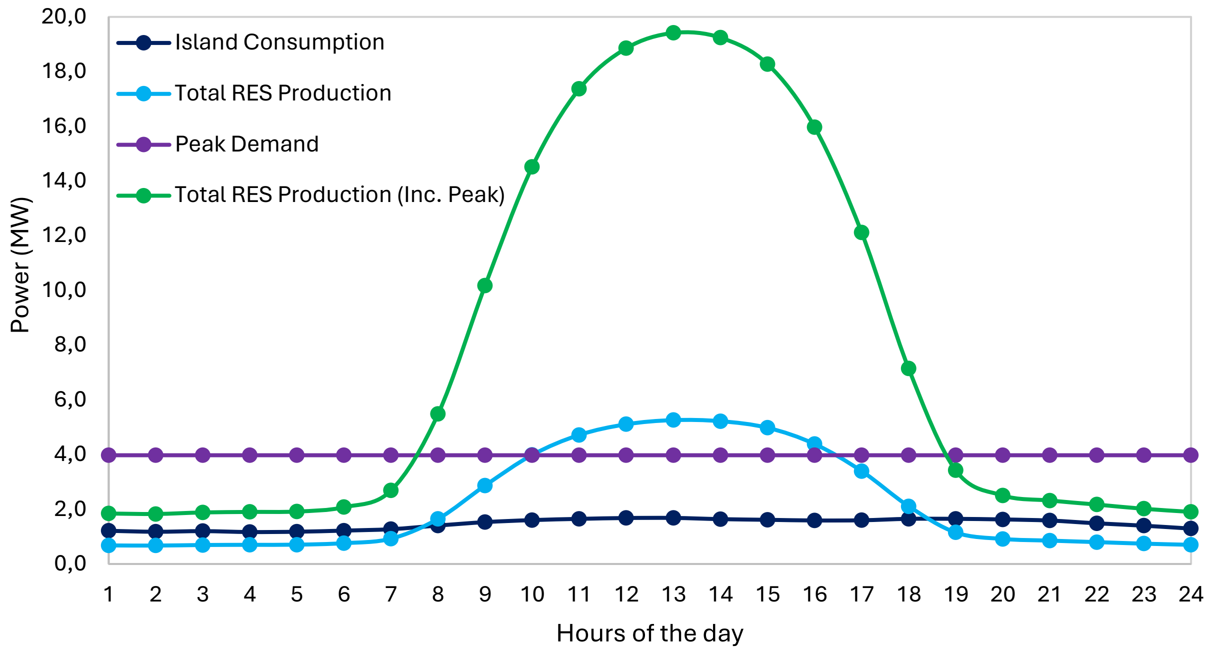

Diagram 2. *Energy Curves of Amorgos*

RESULTS AND DISCUSSION

The crucial variable of this project is the hydrogen tank capacity (m^3) because the charging and discharging rates may vary and a suitable balance should be achieved. After the necessary assumptions made, the parameters of the project were determined as follows:

Table 1. *Amounts of physical parameters of the project*

Physical Quantity	Amount
Photovoltaic plant installed power	17,34 MW
Wind Park installed power	2,44 MW
PEM electrolysis installed power	10,44 MW
H_2 production flow rate	198,72 kg/h
Compressor inlet pressure	35 bar
Compressor outlet pressure	300 bar
Tank charging rate	198,72 kg/h
Charging hours per day	11 h
Gas turbine installed power	6,63 MW
Tank discharging rate	168,15 kg/h
Discharging hours per day	13 h
Tank volume	109,30 m^3

Aside from the technical aspects, the study encompasses financial analysis. The Capital (CAPEX) and Operational (OPEX) expenditures were estimated by considering contemporary studies as well as existing projects and market data. For a twenty-year project lifetime, the total CAPEX is assessed as 45,6 M € and the yearly OPEX as 1,3 M €/y.

For the purpose of comparing the project with other similar ones, the Levelized cost of hydrogen (LCOH) was calculated as LCOH = 3,54 €/kg H_2. This value seems very promising compared to literature, as the prediction for LCOH is 2 – 3 €/kg H_2 till 2050 [6]. The levelized cost of electricity (LCOE) of the project is LCOE = 386,41 €/MWh, while the actual weighted average cost of electricity in Amorgos has been 371.98 €/MWh for the last 6 years. Even though the design deals with a very ambitious project, the results were particularly encouraging as they did not have excessive deviations from the current state. Even though the high price of the proposed project does not allow an immediate implementation, since the cost of the equipment is likely to decrease in the coming years, the investment has a great chance of becoming competitive. What is more, there is another important revenue from Guarantees of Origin which has a range of 1 to 5 €/MWh.

In the context of the investment evaluation, three financial indexes were calculated for a range of selling prices: Net Present Value (NPV), Profitability Index (PI), Internal Rate of Return (IRR). The results show that the investment is assessed as marginally profitable – valuable but with a small profit – which is very optimistic for such an innovation.

In conclusion, the findings of this research contribute valuable insights into the development of sustainable energy solutions for non-interconnected islands, paving the way for environmentally friendly power systems in remote regions. By successfully integrating photovoltaic panels, wind energy, and hydrogen storage, this study presents a viable model for other isolated communities striving to achieve energy independence and reduce their carbon footprint.

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