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Analysing economic and environmental sustainability related to the use of battery and hydrogen energy storages for increasing the energy independence of small islands

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ABSTRACT

Energy costs, carbon dioxide emissions, security of supply and system stability are common challenges in small islands. Many European islands have become pilot sites of energy innovation, but this green transition goes slowly in other ones usually not connected to the national grid. This study investigates the economic and environmental sustainability related to the integration of hydrogen and batteries storage in small islands, considering at the same time the use of the stored hydrogen for fuelling Fuel Cell Electric Vehicles and Hydrogen Compressed Natural Gas vehicles to meet electricity and public transportation demand of islands, so as to increase the Renewable Energy Sources penetration level. Selecting the island of Favignana (Italy) as case study, HOMER software has been used to carry out the energy analysis of different scenarios, in order to identify the most effective energy solution from both technological and economical point of views. Using economic and environmental indicators, the outcomes show that the implementation of a hybrid storage system with batteries and electrolyser can be an adequate and reliable option for increasing energy independency of small island and decarbonizing transport sector optimizing economic and environmental sustainability.

1. Introduction

Currently, the energy supply in small islands is a key challenge all over the world, both for researches and local applications. All islands have to face the common challenges of security of supply, system stability, local carbon dioxide (CO_2) emissions [1] and high energy costs [2] with the additional issue of a strong seasonality of energy loads in most of them. The islands not connected to the national grid are particularly sensible to these issues. As a matter of fact, production systems rely mostly on fossil fuels imported from the mainland, making them vulnerable both to oil price fluctuations [3] and weather conditions that may let islands isolated for weeks. In this framework, Renewable Energy Sources (RES) integrated into smart grids are an indispensable tool to drive islands' transition into smart islands with autonomous, clean and low-carbon energy system. Many are the examples of islands around the world that bet on RES penetration. Kuang et al. [3] demonstrates that a 10% RES share is an advisable value in most cases. Nonetheless, there are several studies aiming to reach a 100% RES penetration, in Mauritius islands [4], in the Åland Islands [5], as well as in the whole Canary archipelago [6] with particular focus to the island of La Gomera [7], but few are the existing examples of 100% renewable energy islands, like the islands of Samso in Denmark and Pellworm in Germany [8].

Some Mediterranean small islands are following that trend and different projects were developed such as Giannutri and Giglio islands. Referring to Palone et al. [9], the introduction of a PV-Battery Energy Storage (BES)-Hydrogen Energy Storage (HES) hybrid system in Giannutri's power grid were designed while in [10] the installation of large scale PV plants and distributed PV systems in the island of Giglio has been analysed.

Moreover, many other studies were developed investigating different solutions to reduce GHG emissions on islands; among them, the introduction of district heating/cooling networks supplied by cogeneration and RES [11] such us with bioenergy from short chain [12], application of different energy storage technologies [13] low-energy service buildings in touristic islands [14], geothermal and desalination plants [15], wave energy converters [16], the renovation of the transportation sector [4] as well as intervention aimed at improving and

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coupling different sectors [17]. According to Bruschi and Berghi [18] transportation sector represents a great portion on the total Italian final energy consumption that is equal to 31.8%. However, in most cases it is not considered in Sustainable Energy Action Plans.

As regard the mobility sector, the interest in Hydrogen and Fuel Cell Electric Vehicles (FCEVs) is growing [19] and currently all the most important manufacturing companies have already brought into the market or announced the year of commercialization of their models [20]. The technology is now almost mature; around 550 vehicles are running in demonstration projects around the world and 192 of them are located in Europe [21]. It has been stated that fossil fuel vehicles could be completely replaced by FCEVs by 2050 [22]. In detail, many research projects proved the efficiency of using FCEVs in public transport sector [23], using hydrogen from wastewater [24] and analysing particular case studies [25]. Furthermore, methane-hydrogen [26] fuelled spark ignition (SI) engines buses have been proved to be a valid option too [27] Compared to CO2-Based Methanol Synthesis [28].

In this framework, this paper aims to compare economic and environmental indicators of using BESs and HESs [29] in order to increase RES share and energy independence of small islands by means of designing different hybrid systems composed by PV arrays applied to a pilot case in the island of Favignana (Italy) [30].One of the main novelties of this research, compared to the current state of the art briefly mentioned in the above paragraphs, is to integrate hybrid energy systems using BESs and HESs analysing at the same time the introduction of either FCEVs' fleet or a Hydrogen Compressed Natural Gas (HCNG) fuelled one to renew the local public transport services of an island. This new approach allows a comparison of economic and environmental indicators of BES and HES in insular contexts assessing at the same time the feasible use of the stored hydrogen for decarbonizing local public transports considering both FCEV or HCNG buses.

2. Materials and methods

The HOMER simulation tool has been used to optimize and examine the energy scenarios from both, technical and economical point of view in the pilot area of Favignana. The present research has been carried out within an international project called PRISMI (*Promoting RES Integration for Smart Mediterranean Islands*), funded by Interreg-MED EU programme, aimed to support the transition of small Mediterranean islands to autonomous, cleaner, secure, low-carbon energy systems, in line with the overall EU Energy Union package and EU2020 Strategy, through the development of an integrated trans-national approach to assess and exploit the use of RES locally available.

Preliminarily, a methodology for RES potential assessment developed in PRISMI project [31] specifically for Mediterranean small islands has been applied for designing the baseline scenario of each considered small island. The method consists of three separate steps: assessing island needs and legislative framework; assessing the RES potential; designing and dynamically modelling foreseeable scenarios able to exploit available resources to meet the island energy needs.

Thus, in the first step the island legislative constraints, the energy needs and current mix of production, have been analysed. Mapping all the needs of the considered island implied studying the electric load profile, water needs, waste management and public transport services [31]. Thus, the most important energy sectors were identified, and the baseline scenario has been built in details. Furthermore, this context knowledge is indispensable to assure an awareness of territory's issues and then to choose the most relevant interventions that have to be implemented. Thereafter, an investigation on the potential seasonality needs is required to find the most profitable technical solution. The second step consisted of assessing the RES potential on the considered island. Subsequently, the best fitting scenarios were designed with the goal of improving the energy independence of the island as well as reducing GHG emissions and improving inhabitants' quality of life. The last step was to analyse the scenarios using HOMER software to this purpose. HOMER is an optimization software, developed by the U.S National Renewable Laboratory (NREL) to help the design and to study the feasibility of micro-power systems through comparison of the chosen technologies, accounting for the power systems physical behaviour and their technical life cost. It is widely used for micro-grid [32] and for bigger systems like island grids [33]. HOMER permits to analyse off-grid systems [34] or grid connected ones [35] and allows the user to set the time step of the analysis. In this paper an hourly time step was considered related to the pilot case study of Favignana island.

In order to evaluate the solar potential of each considered island, the incoming yearly solar radiation should be estimated. It derives from a raster Digital Surface Model (DSM) by means of the ArcGIS tool "Solar Area Radiation".

Regarding renewable technologies integration into the power system, the pilot analysis has been focused on PV systems since this clean technology is the most feasible for the case study of Favignana. However, the same approach should be applied analysing wind, biomasses or other RES available in other small islands. The hourly solar radiation data are provided by the HOMER software utility that is linked to the "NASA surface meteorology and solar energy dataset" [36]. Similarly, temperature data have been obtained by the same data source.

In the particular case of the selected pilot island, the PV size considered in the scenarios has been chosen based on Favignana's expectation, defined by the Ministerial decree "Energy to small islands" for 2020, it means an overall PV power of 900 kW_p, 500 kW_p of which related to a single power plant, while and the remaining modules will be integrated on existing buildings [37].

In order to compare BESs and HESs, the simulated energy scenarios took into account a Trojan AGM 31 battery. On the other hand, the scenarios with hydrogen storage considered two options to exploit the hydrogen produced, both aiming to renew the public transport sector by the introduction of a FCEV fleet or HCNG-fuelled buses one.

The average fuel consumption related to a single diesel bus has been assumed equal to 0.177 l/km, while for a hydrogen-driven one is 0.089 kgH_2/km [23]. Those values are used to evaluate the annual diesel consumption, the hydrogen needed to run the FCEVs fleet and the HCNG-fuelled bus.

The required hydrogen to run HCNG-fuelled buses can be calculated by Equation (1).

$$V_g = V_d \times \frac{LHV_d \cdot \eta_d}{LHV_g \cdot \eta_g} \quad (1)$$

Where:

V_g [Nm^3/km] is the average gas fuel consumption.
V_d [dm^3/km] is the average diesel fuel consumption.
LHV_d [kJ/dm^3] is the Lower Heating Value of diesel fuel.
LHV_g [kJ/Nm^3] is the Lower Heating Value of blends fuel.
η_d is the compression ignition energy efficiency.
η_g is the SI energy efficiency.

The hydrogen content in the mixture for simulations is 20% vol. since it is an optimum value as reported in literature [38]. Moreover, the Lower Heating Value (LHV) of hydrogen enriched natural gas blend at 20 vol.% is 30.713 MJ/Nm^3 [38].

The total CO_2 emissions of diesel buses have been evaluated by Eq. (2) [23].

$$CO_2 = Diesel\ \ consumption \cdot CC_d \cdot \frac{44}{12} [tonCO_2/y] \quad (2)$$

where CC_d [%] is the fuel carbon content and *Dieselconsumption* is considered in ton/y.

Finally, in order to calculate the carbon avoidance related to the introduction of HCNG-fuelled buses, a value of 51.13 $kgCO_2/GJ$ has been assumed [38] as the carbon intensity of blended fuel.