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Combined production of electricity and hydrogen from solar energy and its use in the wine sector

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A B S T R A C T

In the present research, the energy demanded by the wastewater treatment plant of a winery and the pumping station of the irrigation system of a vineyard is supplied by a stand-alone renewable energy system formed by three photovoltaic arrays connected to a microgrid. A relatively small battery maintains the stability and quality of the energy supply acting as a short-term energy storage. Hydrogen is generated in a production and refueling plant specifically designed for this project, and it is eventually used in a plug-in BEV properly modified as a hybrid vehicle by adding a PEM fuel cell. On the one hand, the technical and economic feasibility of the on-site electricity production for the winery and vineyard, compared to the commercial electricity from the grid and diesel gensets, is demonstrated. On the other hand, the diesel savings by the hydrogen generated on site are assessed. The electricity (72 MWh) and hydrogen (1214 m^3) produced in the first year have saved the emission of around 27 tons of equivalent CO_2.

1. Introduction

Increasing the use of renewable energy sources (RES) in the energy mix has become a challenge for power engineers and scientists all over the world. Even when hybrid power systems based on RES (HRES) have attracted the attention of the sustainable energy market, the optimal use of either solar photovoltaic (PV) or wind power is difficult, specifically in local power grids. This is because of their fluctuating and intermittent nature, due to the dependence on meteorological conditions. Thus, standalone renewable energy sources cannot guarantee a reliable power supply. A typical solution to this problem is the use of HRES combining both short-term energy storage options (batteries, capacitors, flywheels, or compressed air) and long-term ones with hydrogen as energy storage. Hydrogen is considered the energy vector of the future, especially if it is produced from RES [1–5]. Different energy storage systems have been used to optimize the energy management of power systems based on single or multiple RES in the household sector, in applications such as plug-in battery electric vehicles (BEV) [6] or fuel cells [7–10].

In remote rural areas, the energy demand can be actually satisfied using HRES, but their introduction has been limited by the lack of economic viability and technical adaptation. Aerial power lines, which are very expensive, are normally extended in natural areas to distribute commercial electricity to the consumers. These infrastructures have a severe environmental impact affecting the skyline and, what is more important, killing both native and migratory birds, something especially serious in the case of endangered species. In the particular case of the wine industry, energy demands (irrigation, farming machinery, thermal processes, mobility, etc.) present strong seasonal cycles not only throughout the year but also during the day. Besides, fossil fuels are massively used both in transportation and on-site power generation, emitting CO_2 and other pollutants. Thus, in order to achieve standalone HRES with high reliability, which would contribute to their massive use in the wine sector, both short-term and long-term energy management systems must be considered [11,12].

In this research, a part of the energy demanded in a winery is supplied by the power produced from a PV energy system.

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Nomenclature

Acronyms

ATEX	Anti-explosion elements
BEV	Battery electric vehicles
CO_2-e	equivalent CO_2
ECU	Electronic control unit
EM	Electric machine of the BEV
EMS	Energy Management System
FC	Fuel cell
FCHEV	Fuel cell hybrid electric vehicles
GSS	Gas storage system
HEV	Hybrid electric vehicle
HPP	Hybrid power plant
HRES	Hybrid renewable energy systems
IRR	Internal rate of return (%)
NI	National Instruments
NPV	Net present value (€)
OS	Operative system
PEM	Polymer electrolyte membrane
PLC	Programmable logic controller
PV	Solar photovoltaic
PWM	Pulse-width modulation
RES	Renewable energy sources
SOC	State of charge of the battery
TAC	Total annual costs
WWTP + IS	Waste water treatment plant and irrigation system

Latin symbols

AE	Annual expenses (€)
C	Cash-flow
CoE	Energy cost (€)
CoL	Cost due to lifetime (€)
CoP	Power cost (€)
E	Energy consumed (kWh)
I_o	Initial investment costs (€)
Inf	Inflation (%)
K	Discount rate
P	Power consumed (kW)

Subscript

Bat	Battery system
CE	Commercial energy
DG	Diesel generation set
Gen	General
Inv	Inverters
PV	PV solar plant

Specifically, it includes the power consumed by the wastewater treatment plant (aerators), the pumping system for sludge, filtering and irrigation processes, a hydrogen production and refueling station, and the recharge of the battery system of an electric vehicle. To the authors' knowledge, this is the first time that such challenge is assumed in this specific sector, which is very relevant for the European countries of the Mediterranean area (Italy, France, Greece, Spain, Portugal, etc.). The research describes in depth the design and operational tests performed during the demonstration period of the PV system and the hydrogen production and refueling station. Besides, the performance of a BEV suitable modified into a hybrid electric vehicle (FCHEV) equipped with a polymer electrolyte membrane fuel cell (PEMFC) is also discussed.

2. Description of the different facilities

This research is part of the project "*Profitable Small Scale Renewable Energy Systems in Agrifood Industry and Rural Areas: Demonstration in the Wine Sector*" [13], funded by the European Union under the LIFE program.

The project facility is placed at Viñas del Vero winery, which is located in the Somontano region, in the north of Aragon (Spain). As depicted in Fig. 1, this power-to-gas power plant is formed by two main facilities: the electricity production section (upper row) and the hydrogen production and storage units (lower row). They are interconnected by a main cabinet where all the control and safety software are installed. The surplus electricity produced by a solar PV plant is converted into hydrogen by water electrolysis. The hydrogen produced is stored in pressure cylinders and is further reconverted into electricity in a PEMFC that is the secondary power source of the hybrid power plant of a FCHEV.

2.1. The electrical facility

The energy consumed by the wastewater treatment plant and the irrigation system (WWTP + IS), which was originally connected to the main winery electric grid, has been replaced by a solar PV plant and a microgrid formed by battery storage system. As depicted in Fig. 1, the stand-alone electrical facility is formed by the PV plant, a battery that acts as the short-term energy storage system, different inverters to properly use the electricity, and the consumer elements. The water used for irrigation is recycled from the wine production processes. The wastewater is accumulated in an aeration pond where it is treated, and is sequentially moved using centrifugal pumps to the filtration sandbox and to the irrigation pond. The vineyards to be irrigated have an area of 10 ha, and the annual water volume used for this purpose reaches 10,000 m^3 [14]. The power consumed and tasks performed by the different consumers are summarized in Table 1.

Among the different possible RES, only solar and wind power were initially considered, since there are no other reliable resources in the area. However, wind power was discarded due to the small average air velocity ($1.66\ m\ s^{-1}$) measured during on-site measurement campaigns [15]. On the contrary, solar power is a very reliable option due to the high average solar irradiance in Spain [16]. The average value corresponding to the exact location of the winery, obtained from the Photovoltaic Geographical Information System (PVGIS) of the European Union [17], is $4.73\ kWh\ m^{-2}\ day^{-1}$, as can be observed in Fig. 2. The maximum value takes place in Summer, concurring with the irrigation season, and it is well above $7.5\ kWh\ m^{-2}\ day^{-1}$. In addition, optimal inclination according to PVGIS varies between 9° in June and 66° in December, with an annual average value of 37°.

2.1.1. The solar photovoltaic system

The use of solar energy within the energy mix is common in many countries all over the world [18–23]. However, the indisputable role of solar energy in the Twenty-first Century is overshadowed by the intermittent nature of its power production. This problem can be addressed by the use of both short-term and long-term energy storage systems [24–29]. Although conventional stand-alone solar systems often use a DC bus architecture, it was