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Hydrogen production system from photovoltaic panels: experimental characterization and size optimization

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ABSTRACT

In this paper an approach for the determination of the optimal size and management of a plant for hydrogen production from renewable source (photovoltaic panels) is presented.

Hydrogen is produced by a pressurized alkaline electrolyser (42 kW) installed at the University Campus of Savona (Italy) in 2014 and fed by electrical energy produced by photovoltaic panels. Experimental tests have been carried out in order to analyze the performance curve of the electrolyser in different operative conditions, investigating the influence of the different parameters on the efficiency. The results have been implemented in a software tool in order to describe the behavior of the systems in off-design conditions.

Since the electrical energy produced by photovoltaic panels and used to feed the electrolyser is strongly variable because of the random nature of the solar irradiance, a time-dependent hierarchical thermo-economic analysis is carried out to evaluate both the optimal size and the management approach related to the system, considering a fixed size of 1 MW for the photovoltaic panels. The thermo-economic analysis is performed with the software tool W-ECoMP, developed by the authors' research group: the Italian energy scenario is considered, investigating the impact of electricity cost on the results as well.

1. Introduction

The issues related to environmental rules defined in the last years have moved researchers to increase the interest in innovative fuels able to produce low (or zero) emission conditions. In this scenario, hydrogen is considered interesting because it is a fuel able to avoid any CO_2 emission during combustion [1]. However, since hydrogen is not a natural fuel, it is necessary to produce it throughout chemical, electrochemical or different approaches. An interesting option for its production is water electrolysis employing electricity from renewable sources [2,3]. Since renewable sources can produce significant uncontrollable variations during generation, the electrical energy total available amount can be significantly higher than the demand values during peak production. Considering these aspects, an interesting solution is related to hydrogen production (using the exceeding energy) performing a sort of chemical electricity storage. The produced hydrogen flow can be used for electrical energy generation at high efficiency conditions toward fuel cells and hybrid systems [4]. Even if previous works were carried out on hydrogen generation from renewable sources considering electrolysers [5–7], usually just nominal performance data are available for these kinds of reactors. So, in this paper the problem was started from a wide experimental campaign producing electrolyser off-design data not published by manufacturers' communication documents. Hydrogen generation from renewable sources and the related storage/utilization aspects (considering both efficiency and cost issues) have to be considered starting from calculations [8,9]. Even if several optimization tools were applied at different cases [8,9] (both conventional or advanced methods [10–14]) an experimental support is essential for defining real optimized size and management for real plant applications. So, in this paper a real test case (considering the experimental electrolyser curves) was carried out on solar power source referred to the campus located in Savona (geographical coordinates: 44°18′28.71″N 8°28′51.66″E), Italy.

The Italian generation related to renewable sources is close to 112 TWh: even if the largest amount (52.7 TWh) is produced by hydroelectric plants, the impact of other renewable sources has significantly increased. Considering the generation based on renewable sources related in 2000 [15], a strong increase can be highlighted (from 51 TWh to 112 TWh), mainly for solar energy system installations (+21.6 TWh), wind power plants (+14.3 TWh) and biogas/biomass based systems (+15.6 TWh), while generation by hydroelectric and geothermal are almost constant. Among the renewable source based plants installed in Italy, 591,029 systems

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Nomenclature

Abbreviations

AEC	Alkaline Electrolytic Cell
CCS	Carbon Capture and Sequestration
DPBP	Discounted Pay Back Period
IRR	Internal Rate of Return
NPV	Net Present Value
PEC	Purchased Equipment Cost
TCI	Total Capital Investment
TPG	Thermochemical Power Group
W-ECoMP	Web-based Economic Cogeneration Modular Program

Symbols

C	cost (€)
F	Faraday constant (C/mol)
HHV	High Heating Value (MJ/kg)
I	current (A)
M	mass flow rate (kg/h)
P	power (kW)
p	pressure (Pa)
Q	flow rate (m^3/s)
R	gas constant (J/kg K)
T	temperature (K)
V	voltage (V)

Subscripts

0	standard conditions
f	fuel
fix	fixed
inst	installed
rev	reversible

Greek symbols

η	efficiency
ρ	density (kg/m^3)

are photovoltaic plants [15]. They represent a significant number in comparison with wind power plants (1386), hydroelectric systems (3250) and biogas/biomass power plants (2409). So, considering these aspects related to the Italian scenario, photovoltaic technology was taken into account as renewable source based electrical input for the hydrogen generation evaluated in this paper.

The results presented in this paper were obtained in the Research Project named ***IDRO-RIN TRAN-GENESI*** and by the Italian government. It was related to development of innovative technologies for hydrogen generation from renewable sources (large size plants) and the utilization of this fuel in both land and naval transportations. The main topics related to this project, presented in Fig. 1, were: (i) H_2 production from renewable sources using water electrolysis [16,17]; (ii) H_2 storage devices and management considering both traditional and innovative approaches; (iii) hydro-methane generation from H_2 and CO_2 from biomass gasification or Carbon Capture and Sequestration (CCS); (iv) thermo-economic optimization of plants for generation of hydrogen and hydro-methane, storage systems and utilization devices, considering the availability aspects and the economic conditions.

In this paper, the experimental results of the test campaign performed on the alkaline electrolyser installed at the University of Genoa campus in Savona are presented and discussed, investigating the influence of the different parameters on the performance. In the test campaign, the electrolyser is fed by electricity from the national grid and the performance of the device at different load conditions is evaluated. Then, a thermo-economic analysis is carried out, considering to feed the electrolyser by time-dependent renewable energy, provided by photovoltaic panels, eventually purchasing electrical energy from national grid when solar energy is not sufficient. The thermo-economic analysis is performed considering the real irradiance curves of Savona and using the in-house software **W-ECoMP** (Web-based Economic Cogeneration Modular Program) for system optimization to define the optimal plant size and the best management approach for the electrolyser, minimizing costs as well.

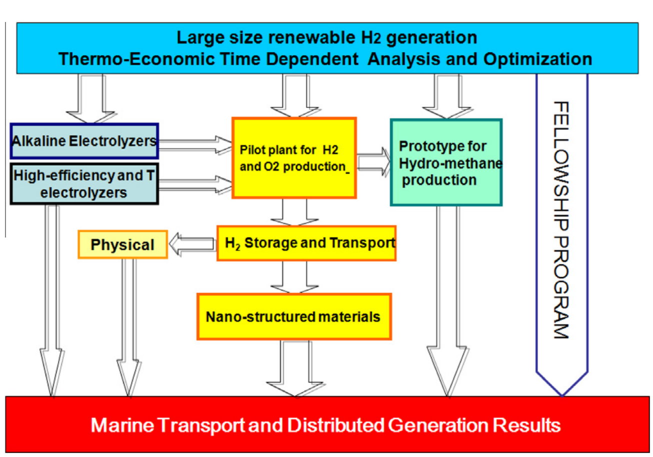

Fig. 1. IDRO-RIN TRAN-GENESI project: main topics.

2. Plant layout

The plant considered in this work is an experimental facility developed to operate tests on electrolysers. It is a simple test bench (Fig. 2) able to measure electrolyser main properties (voltage, current, temperature) and hydrogen flow characteristics (pressure, temperature and mass flow rate). All the probes have a ±1% accuracy, except temperature sensors which are affected by a ±0.3 K accuracy performance. The rig is also equipped with outlet valves on both hydrogen and oxygen sides to operate pressurised tests. Moreover, a dryer was installed on the hydrogen line to avoid water drops inside the mass flow rate probe. While oxygen produced by the electrolyser is simply vented, hydrogen is burned in a torch (see Fig. 2).

2.1. Electrolyser

The electrolyser (Fig. 3) tested in this work is the Piel "DODICIMILA" device (since now the production has been changed,

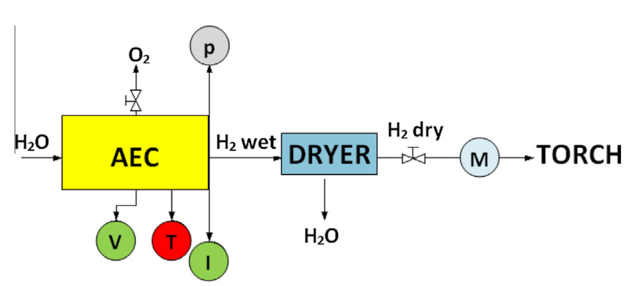

Fig. 2. Plant layout.