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Modeling and optimization of an energy generation island based on renewable technologies and hydrogen storage systems

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ABSTRACT

The widespread use of renewable energy sources is hindered by their intermittent and unpredictable nature. This problem can be overcome with a storage system which manages the time mismatch between energy production and load requirements.

The aim of this work is to develop a simulation tool for evaluating energy and economic performance of renewable energy islands, including various electricity generation technologies (photovoltaic modules, wind turbines and micro-hydroelectric plants), integrated with a hydrogen storage system, comprising an electrolyzer, a hydrogen storage tank and a fuel cell. After a brief description of the simulation tool structure, the attention is focused on energy and economic models of system components. Then an innovative approach for optimizing the energy island is proposed; it is based on a hybrid genetic-simulated annealing algorithm and aims to minimize the unit cost of electricity. Finally a generation island that provides electricity and hydrogen to a farm in central Italy is designed and optimized, comparing configurations based on different renewable technologies.

1. Introduction

The progressive depletion of fossil fuel resources and the environmental issues related with their burning have generated growing interest in renewable energy sources. However, an essential feature of most renewable energy sources is their intermittency, that conflicts with the reliability of electricity supply. One way of overcoming this problem is to use an appropriate storage system. In recent years hydrogen-based storage systems are receiving much attention [1–4]. Hydrogen is an energy carrier that can stabilize the flow of intermittent renewable energy enabling these sources to be used for transportation and stationary applications in industrial and residential sectors [5].

The focus on stand-alone renewable energy systems is highlighted by a major and extensive research effort, which has resulted in numerous experimental projects and in the development of several simulation models. Li et al. [6] developed a dynamic model to compare energy and economic performances of different configurations of stand-alone photovoltaic systems, based on battery bank and/or hydrogen storage. Examining the same systems, Avril et al. [7] suggested a design tool based on particle swarm optimization, with the purpose of both minimizing the cost and obtaining a stable connection to the grid.

The potential of wind-hydrogen system were explored by Aguado et al. [8], through the development of WindHyGen computer tool, based on a management policy optimized to get

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Nomenclature

A_{PVm}	number of photovoltaic modules
C_p	specific heat at constant pressure, kJ/(kgK)
DOD	depth of discharge
E	energy, kWh
E_{REN_p}	primary renewable energy source, kWh
g	gravity, m/s^2
H	incident radiation, kWh
I	current, A
J	current density, A/cm^2
J_{max}	maximum current density, A/cm^2
k	specific heat ratio
L	load, kWh
$\bar{L}_{EL}$	mean annual electrical load, kWh
$\bar{L}_{H_2}$	mean annual hydrogen load, kWh
M	margin coefficient
$\dot{M}_{H_2}$	mass flow of hydrogen per unit of electrolyzer power, kg/kJ
n	plant lifetime
p_{H_2}	partial pressure of hydrogen, atm
p_{O_2}	partial pressure of oxygen, atm
p_1	pressure at compressor inlet, MPa
p_2	pressure at compressor outlet, MPa
P_{max}	maximum electrical power flowing through the electrolyzer, kW
R	gas constant, kJ/(kmolK)
R_{elec}	resistance to electron transfer in the collector plates and electrodes (ohm)
R_{prot}	resistance to proton transfer in the solid polymer membrane (ohm)
T	temperature, K
T_1	temperature at the compressor inlet, K
V	voltage, V

Greek letters

η	efficiency
$\bar{\eta}$	mean annual efficiency
ρ	water density, kg/m^3
ρ_b	molar density of the bulk, mol/l
ρ_i	molar density of the *i*th layer, mol/l
ρ_{max}	molar density at the maximum capacity, mol/l
ρ_s	adsorbent density, g/cm^3
ε	adsorbent porosity

Subscripts

c	cell
c_i	ith system component
CP	compressor
DC–DC	DC–DC converter
EL	electrical, electrolyzer
FC	fuel cell
HT	hydrogen tank
I	investment
inc	incident
inv	inverter
m	module
MH	micro-hydro
MPPT	maximum power point tracker
O&M	operation and maintenance
PV	photovoltaic
R	replacement
REN	renewable
rev	reversible
W	wind power

Acronyms

COE	cost of electricity, €/kWh
COH	cost of hydrogen, €/Nm^3

a maximum efficiency in the use of the different devices and a maximum profit from the energy sales. The integration of photovoltaic and wind technologies were studied by Mills and Al-Hallaj [9], using a probabilistic model integrated in Hybrid2 software, and by Krajacic et al. [10], which describe the potential of the H2-RES software, as a tool for performing economic and environmental planning of hybrid energy systems. Santarelli et al. [11] proposed a simulation model to compare performance and cost of stand-alone hydrogen systems based on solar, wind and hydraulic resources. For the design of these systems, eventually integrated with diesel engine, Lopez and Agustin [12] developed a software in C++ (HOGA), that enables the minimization of net present cost, CO_2 emissions and unmet load, through a multi-objective genetic algorithm. Hence, many investigations have dealt with renewable systems integrated with hydrogen production; however, they are often aimed at deepening the aspects related to the time differences between the production and use of electricity and almost never take into consideration the management of the integrated system when hydrogen is not only used as a means of accumulation but also in the industrial and transport sectors.

The aim of this work is to develop a computer code capable of evaluating the energy and economic benefits of renewable energy islands integrated with a hydrogen production system, used as electrical energy storage, as well as for meeting the hydrogen demand for different types of users. The implementation of the simulation tool has required the creation of databases for characterizing the energy sources, technologies and electricity and hydrogen load profiles. The renewable energy sources database provides the input to models developed for estimating the hourly availability of solar, wind and hydraulic power sources, depending on site location. The technologies database characterizes the system components in terms of efficiency and specific cost, thus enabling the development and application of appropriate energy and economic models.

The energy analysis of the integrated system requires implementation of an appropriate energy flow control strategy, in order to determine energy exchange between power systems, storage facilities and utilities. Moreover, the economic analysis of the whole system, based on investment, operating and replacement costs of each component, enables to evaluate the unit cost of both electricity and hydrogen.

System optimization is achieved through an innovative approach for defining the objective function and the minimization algorithm. The objective function proposed is a cost function that, using a unified approach, is able to estimate the unit cost of energy for both grid-connected and stand-alone power systems.