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Modelling and optimisation of a hydrogen-based energy storage system in an autonomous electrical network

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HIGHLIGHTS

- Development of a complex model for simulating a H_2-based energy storage system.
- Optimum sizing of a H_2 system supplied from RES curtailments in an autonomous grid.
- Calculated water electrolysis efficiency exceeds 60%, based on HHV of hydrogen.
- H_2-based energy storage system can increase RES energy penetration in autonomous grid at least 30%.
- RES-H_2 can support "green" mobility in small autonomous islands.

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ABSTRACT

The European Union's 2020 climate and energy package (known as "20–20–20" targets) requests, among other key objectives, 40% of the electricity production in Greece to be supplied from Renewable Energy Sources by 2020. The main barriers for reaching this target is the intermittency of renewable energy sources combined with the penetration limits in the local electrical grids and the high seasonal demand fluctuations. In this context, the introduction of energy storage systems, comprises one of the main solutions for coping with this situation. One of the most promising technologies for storing the excess energy, that would be otherwise lost, is the production and storage of hydrogen through water electrolysis. Hydrogen can be used for supporting the electricity grid during periods of high demand but also as transportation fuel for hydrogen-based automobiles (e.g. fuel cell vehicles). For this purpose, a simulation algorithm has been developed, able to assess the specifications of the optimum sizing of hydrogen production storage systems. For the application of the algorithm, the area of the Aegean Sea has been selected, owed to the considerable renewable energy sources curtailments recorded in the various non-interconnected islands in the region. More specifically, the developed algorithm is applied to an autonomous electricity network of 9 islands, located at the SE area of the Aegean Sea and known as the "Kos-Kalymnos" electricity system. The results obtained designate the optimum size of the hydrogen-based configuration, aiming to maximize the recovery of otherwise curtailed renewable energy production.

1. Introduction

During the last century, the profligate exploitation of finite energy sources resulted to a negative effect on environmental, financial, and geostrategic aspects. Since the 1970s, there have been efforts to adopt a 'greener' way for covering our energy demand. Nowadays, Renewable Energy Sources (RES) based mostly on wind, solar and hydro power, are used in most developed countries, contributing significantly in the global electricity production, reaching a share of 23.7% in 2016 [1]. Particularly, in the European Union, the EU Climate Change Package, released in 2008, aims to ensure the 20–20–20 targets, meaning a 20% reduction in greenhouse gas emissions, a 20% improvement in energy efficiency, and a 20% share for renewables in the EU energy mix by the year 2020.

Specifically, the target for 2020 concerning the electricity production, includes an increase of the RES installed power share to 35–40% of the total electrical power installations [2].

However, the efficient exploitation of RES presents drawbacks concerning mostly their penetration in weak electrical grids. According to Kaldellis (2008) [3], wind energy and solar energy exhibit a stochastic and variable availability respectively, enhancing the mitigation of the RES maximum penetration during the daily and seasonal

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Nomenclature

Greek letters

a_x	coefficient which relates the hydrogen concentration and hydrogen flow rate, kg
ΔH	enthalpy of reaction, kJ/kg
η_F	Faraday's efficiency

Symbols

A	electrode's area, m^2
A_{VH}	Van't Hoff parameter A
B_{VH}	Van't Hoff parameter B
C_{cw}	thermal capacity of cooling water, J/K
C_t	electrolyzer's overall thermal capacity, J/K
C_{tank}	Metal Hydride (MH) total heat capacity, kJ/K
c_{H2}	hydrogen specific heat capacity, J/(kg K)
c_{H2O}	water specific heat capacity, J/(kg K)
c_{O2}	oxygen specific heat capacity, J/(kg K)
c_p	hydrogen specific heat at constant pressure, kJ/(kg K)
c_v	hydrogen specific heat at constant volume, kJ/(kg K)
E_a	activation energy, J/mol
E_{abs}	absorbed energy by the electrolyzer, kWh
E_{cool}	thermal energy removed from electrolyzer's cooling system, kWh
E_{H2loss}	faradaic losses, kWh
E_{loss}	thermal energy lost to environment, kWh
E_{sens}	sensible heat to fluids, kWh
E_{stored}	stored energy in the electrolyzer's mass, kWh
F	Faraday's constant, 96484.6 C/mol
f_1	parameter related to Faraday's efficiency, $mA^4\ cm^{-4}$
f_2	parameter related to Faraday's efficiency
f_{hys}	hysteresis factor
f_{ps}	plateau slope factor
I	electrolysis current, A
$k_{0,a}$	kinetic rate coefficient, sec^{-1}
$[MH]$	number of atoms in hydride molecule
$\dot{m}_{H2}$	mass flow rate of hydrogen, kg/s
$\dot{m}_{H2O}$	mass flow rate of water, kg/s
$\dot{m}_{O2}$	mass flow rate of oxygen, kg/s
N_0	initial storage level of buffer tank, mol
N_{H2}	final hydrogen stored in buffer tank, mol
$N_{H2,a}$	absorbed quantity of hydrogen in MH, mol
N_{out}	hydrogen exiting buffer tank, mol
n	number of electrons to split each molecule of water
$\dot{n}_{H2}$	hydrogen production rate, mol/s
n_c	number of cells in series
P_{in}	input power of electrolyzer, kW
P_{max}	maximum power of electrolyzer, kW
PM_{MH}	MH molecular weight, g/mol
p_0	initial pressure in buffer tank, bar
p_{bf}	pressure inside buffer tank, bar
p_{eq}	equilibrium pressure, bar
p_{H2}	partial pressure of hydrogen, N/m^2
p_{H2O}	partial pressure of water, N/m^2
p_{in}	entering hydrogen pressure in MH, bar
p_{O2}	partial pressure of oxygen, N/m^2
$\dot{Q}_{cool}$	auxiliary electrolysis cooling demand, W
$\dot{Q}_{gen}$	electrolysis generated heat flux, W
$\dot{Q}_{loss}$	heat loss flux to environment, W
Q_{MH}	MH absorption denerated heat, kJ
$\dot{Q}_{sens}$	heat flux with H_2, O_2, H_2O streams, W
$\dot{Q}_{store}$	stored heat flux in the electrolyzer's mass, W
R	universal gas constant, 8.314 J/kmol
R_t	overall thermal resistance of electrolyzer, K/W
r_1	empirical ohmic parameter 1, Ωm^2
r_2	empirical ohmic parameter 2, $\Omega m^2/°C$
s_1	anode overvoltage parameter 1, V
s_2	anode overvoltage parameter 2, V/°C
s_3	anode overvoltage parameter 3, $V/°C^2$
T_a	ambient temperature, K
$T_{cw,in}$	inlet temperature of cooling water, K
$T_{cw,out}$	outlet temperature of cooling water, K
T_{el}	electrolysis temperature, K
T_{H2}	hydrogen temperature entering buffer tank, K
$T_{H2,in}$	hydrogen temperature entering MH, K
T_{H2O}	temperature of entering water in electrolyzer, K
tga	plateau slope of absorption
t_1	cathode overvoltage parameter 1, m^2/A
t_2	cathode overvoltage parameter 2, $m^2\ °C/A$
t_3	cathode overvoltage parameter 3, $m^2\ °C^2/A$
U_{cell}	electrolytic cell voltage, V
U_{el}	electrolysis voltage, V
U_{rev}	reversible voltage, V
$U_{rev,T,P}{}^o$	reversible voltage at standard conditions, V
U_{tn}	thermoneutral voltage, V
V_{max}	maximum volume of buffer tank, m^3
W_{MH}	metal hydride mass, kg
X	hydrogen to metal ratio in MH tank
z	compressibility factor

electricity demand fluctuations. So, it is obvious that even in the case of high wind or solar potential, the produced energy cannot be absorbed from the electrical network, resulting in a waste of energy and monetary losses for the RES investors. Furthermore, the fact that there are several remote locations (even in Europe), especially in island regions (e.g. the case of the Aegean archipelago islands) where the grid is unstable and is based on high operating cost oil-fired generators, indicates the necessity of arrangements which will contribute to higher RES systems' penetration [3].

Hence, it is essential to mitigate the intermittent nature of RES installations in order to maximize their integration both in electrical networks and in isolated off-grid consumers. Schroeder (2011) [4] suggests that there are two effective concepts to encounter with the variable outputs of RES: demand side management by using 'smart metering' including demand response and direct load control, and energy storage by using specific arrangements in order to store excess energy whenever this is available [5]. Fig. 1 indicates the most common energy storage technologies based on their autonomy period and power rate [6].

One of the most promising technologies for storing excess energy from RES systems during off-peak hours is the production and storage of hydrogen. Hydrogen energy storage technologies present a power rate range in the order of 10 MW and are suitable for a long term storage (see Fig. 1). Thus, hydrogen can be used in almost all applications where today fossil fuels dominate, without the harmful emissions of the latter ones [7]. Hydrogen production via renewable sources can be accomplished with several methods. However, the most widely accepted method is the water electrolysis, where water splits into H_2 and O_2 through the application of direct current (DC) electricity. The most significant water electrolysis technologies include the alkaline, the proton exchange membrane (PEM) and the solid-oxide electrolysis. Large-scale alkaline electrolysis units comprise a mature technology in the industrial sector, able to produce up to 200 Nm^3/h of hydrogen. These alkaline electrolyzers use an aqueous solution of sodium or