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Analytical hydrogen production and storage simulation for the "Kos-Kalymnos" system

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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 (RES) by 2020. The main barriers for reaching this target is the intermittency of RES 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 (ESSs), 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 and as transportation fuel for H_2-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 RES 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 RES production.

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Keywords: RES curtailments, autonomous networks, hydrogen production-storage, "Kos-Kalymnos" system, alkaline electrolysis, metal hydride storage.

1. Introduction

Nowadays, the contribution of RES production in the non-interconnected islands of Greece reaches 21.8% [1], which is indicative of the quality of the local RES resources and also of the potential to support the accomplishment of the 40% RES target by 2020, this time at the national level [2]. To this end, the Kos-Kalymnos autonomous grid (see Fig. 1), comprising of 9 islands covers a big part of the Dodecanese complex, featuring excellent wind and solar potential and thus suggesting an area of major interest for harvesting RES resources. Despite the high-quality RES potential of the area however, the Kos-Kalymnos system is currently based on thermal power generation, with its average contribution per annum being in the order of 84% [3]. The conventional power stations comprise two oil-based plants of around 120 MW, one in Kos (102 MW) and one in Kalymnos (18 MW). On the other hand, installed RES capacity includes mainly wind and photovoltaic (PV) power installations. Wind and PV power capacity reaches 15.2 MW and

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8.78 MW respectively [1].

In this context, Fig. 2 presents the monthly electricity generation in the "Kos-Kalymnos" system for 2013, where it is obvious that the RES share in the local generation mix is much lower than the respective of the conventional thermal power plants. To this end, it is necessary to mention that local RES stations must comply with the minimum residual load deriving from the dynamic penetration limit set by the local operator (i.e. 30% over the instantaneous load demand) on the one hand, and from the technical minima of local thermal power stations on the other [4]. This situation suggests that although the RES potential of the region is high, RES curtailments during the year are frequent and discourage the implementation of new RES projects (see Fig. 3). At the same time, it is important to note that the use of imported oil for the operation of the thermal power stations results to increased electricity production cost and local air pollution phenomena [5], [6].

In this regard, it is believed that the "Kos-Kalymnos" system would benefit from the integration of solutions that enable high RES penetration. This in turn is expected to reduce current electricity production costs and also mitigate environmental impacts of the conventional power units. Such solutions may include Demand Side Management and Energy Storage Systems [7].

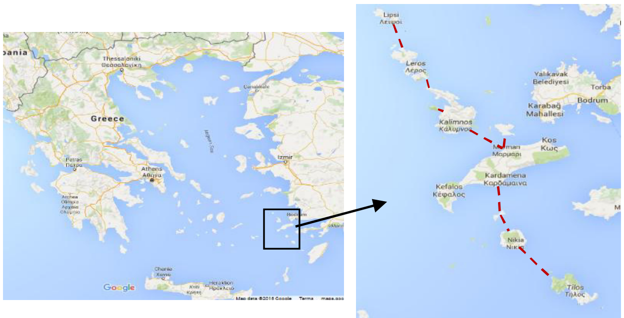

Fig. 1. The "Kos-Kalymnos" system interconnection (9-island complex)

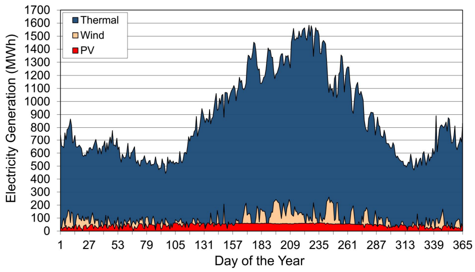

Fig. 2. Electricity generation in "Kos-Kalymnos (2013)

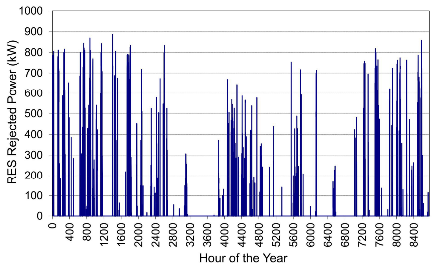

Fig. 3. RES curtailments in "Kos-Kalymnos" (2013)

2. Proposed Configuration and Devices

Among different energy storage technologies, hydrogen based systems present a growing interest as their potential for grid stabilization and balancing services is evident [8]. Hence, contribution of hydrogen storage systems in weak electricity networks (such as island grids) can be considered as a solution worth examining, aiming to mainly support increased RES penetration by recovering RES curtailments.

The most appropriate method for producing hydrogen from RES energy is through water electrolysis, where water splits into H_2 and O_2 through the application of DC voltage. Large-scale electrolysis units comprise a mature technology in the industrial sector, able to produce up to 200 Nm^3/hr of hydrogen. These alkaline electrolyzers use an aqueous solution of sodium or potassium hydroxide (i.e. NaOH, KOH) as electrolyte, where two nickel-coated steel electrodes emerge. The two electrodes are separated via a porous membrane that only allows OH^- to pass, while hydrogen is generated at the cathode and oxygen at the anode [9-10].

Storage of hydrogen can be accomplished with three methods. Using compressed gas cylinders, special tanks, or metal hydride canisters. The first two methods, being quite land intensive, present additional disadvantages such as the high energy cost for compression and liquefaction respectively [11]. On the other hand, metal hydride storage is based on metal alloys' ability to reversibly absorb hydrogen at low pressure and temperature [12].

Acknowledging the above, Fig. 4 presents the proposed configuration for the hydrogen production-storage system. The system includes the existing RES installation which comprises of 4 wind farms (15.2 MW total installed capacity) and 92 small-scale PV power plants of 8.78 MW total capacity, along with the hydrogen system which includes:

- An alkaline electrolyzer of maximum operational power "P_{max}" that operates at 15 bar and produces hydrogen of 99.999% purity. The electrolyzer is supplied from RES curtailments.
- A hydrogen storage unit that includes a buffer storage tank of 200m^3, which stores the produced hydrogen temporarily and then delivers it to the metal hydride storage system, where each of the canisters contain the alloy $MmNi_{4.5}Al_{0.5}$.
- The balance of system components such as control units, water supply, piping and auxiliary cooling systems.

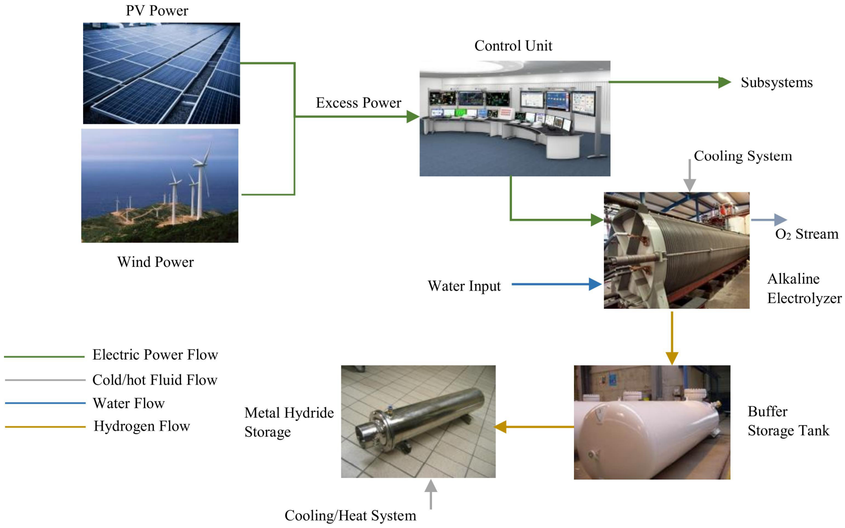

Fig. 4. Description of the hydrogen production-storage system

3. Methodology

In order to designate the optimum size of the electrolyzer and therefore the system's additional parameters (e.g. hydrogen production, efficiency), an integrated algorithm was developed based on a set of equations describing the electrolysis and the hydrogen storage processes.

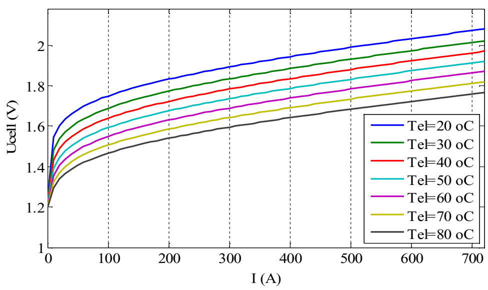

Fig. 5. Electrolysis cell voltage-current curves

Initially, a combination of empirical equations [10, 13-16] were used to develop a model for the calculation of the produced hydrogen, based on the electrochemical and thermal behaviour of the alkaline electrolyzer. The model calculates the maximum hydrogen production that can be achieved for a given range of electrolyzers. The capacity of the investigated electrolyzers was based on the cell voltage-current curves, the available power input and the operational temperature (see Fig. 5), which determined the required number of electrolytic cells. The storage procedure was developed also through empirical equations [17-18] which describe the mass transfer of hydrogen inside the metal hydride tanks, and the thermal phenomena that occur during the absorption of hydrogen.

The flowchart in Fig. 6 presents the algorithm used for the calculation of the electrolysis-storage parameters. The upper left part explains the estimation of the current-power equations at different operational temperatures, between 20ºC and 80ºC, for different values of current ranging from 0 A to 720 A. The upper right section concerns the absorbed power by the electrolyzer depending on the latter operational power range (e.g. 10% to 100%) and the respective available input. The electrolysis simulation is schematically presented at the lower right part and finally the storage procedure is depicted at the lower left section.

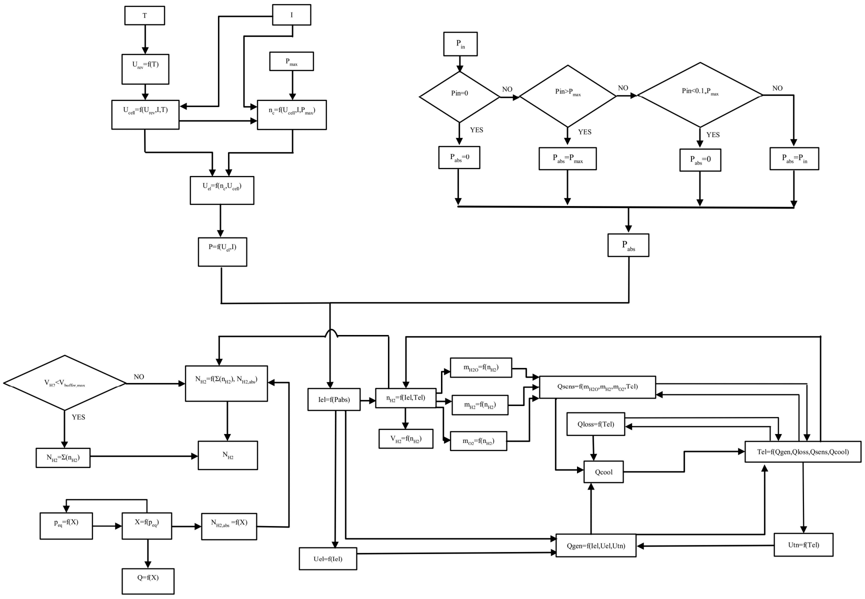

Fig. 6. Electrolysis-Storage developed algorithm

4. Results and Discussion

It was mentioned previously that the installed RES plants of the "Kos-Kalymnos" system face substantial curtailments due to the local grid limitations (Fig. 3). In order to evaluate the characteristics of an optimum hydrogen production-storage configuration, the above described algorithm was used. As an input to the model, the rejected power profile (curtailments), presented in Fig. 3, was introduced. To this end, Fig. 7 illustrates the percentage of the stored energy estimated for different electrolyzers through the model.

According to Fig. 7 an electrolyzer of 1.26 MW capacity is able to absorb the maximum rejected RES energy (i.e. around 71%). It should be noticed that although the maximum RES power reaches 900 kW, the capacity of the optimum electrolyzer is much higher due to its operational power limits, which range between 10% and 100% of its nominal capacity.

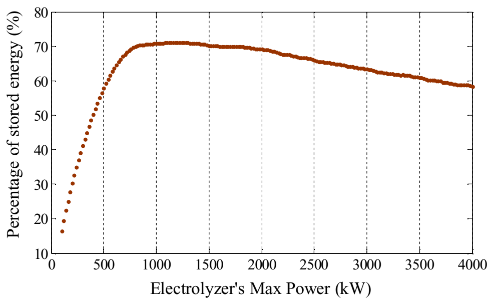

Fig. 7. Percentage of stored energy at different values of electrolyzer's capacity

In Fig. 8, the produced hydrogen mass rate is depicted, while Fig. 9 shows the energy balance during the annual operation of the electrolyzer.

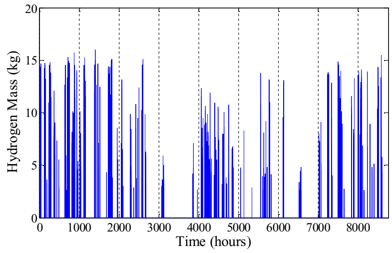

Fig. 8. Hydrogen production rate

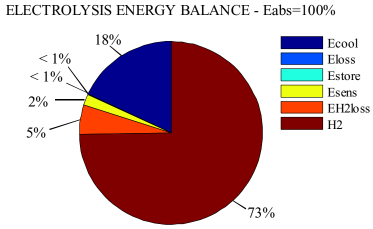

Fig. 9. Electrolysis energy balance

The electrolysis energy balance (Fig. 9) indicates that 73% of the absorbed energy (E_{abs}) is stored as hydrogen (H_2). The rest 22% represents the generated heat during the operation of the system, which is further divided in the thermal energy removed via the auxiliary cooling (E_{cool}) system, the thermal energy lost to the environment (E_{loss}), the thermal energy stored in the mass of the electrolyzer (E_{stored}), the sensible heat leaving the system with the hydrogen-oxygen streams and the thermal energy transferred to the incoming water (E_{sens}). Finally, E_{H2loss} represents the last 5% of the absorbed power and expresses the faradaic losses occurring during the operation of the device.

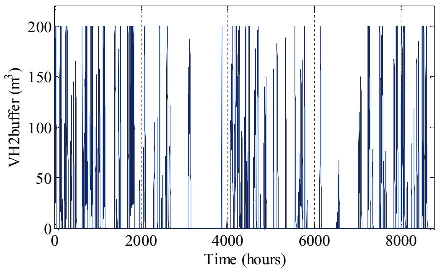

Fig. 10. Hydrogen volume in buffer tank

The produced hydrogen via the electrolysis process is stored in the 200 m^3 buffer storage tank prior to its storage in the metal hydrides. Fig. 10 illustrates the variation of the hydrogen volume inside the buffer storage tank. It is obvious that in periods of zero H_2 production, the hydrogen quantity inside the tank is used for filling the metal hydride canisters until its full depletion. The storage capability of each metal hydride canister is calculated to 320mol/640gr (Fig. 11) of hydrogen at an equilibrium pressure of around 4.2 bar. Fig. 12 indicates the relationship between the equilibrium pressure and the absorbed hydrogen in the metal hydride canister. Equilibrium pressure at the beginning equals to around 3.85 bar. As concentration of hydrogen increases, equilibrium pressure increases as well, resulting in a reduced rate of absorption (Fig. 11). A summary of the results of the H_2 production-storage simulation is given in Table 1.

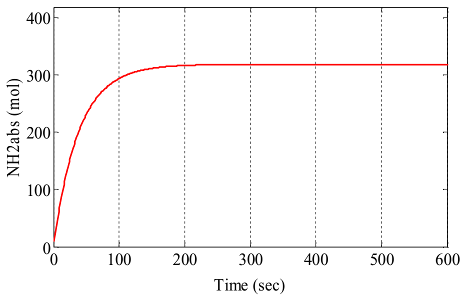

Fig. 11. Absorption capability of metal hydride tank

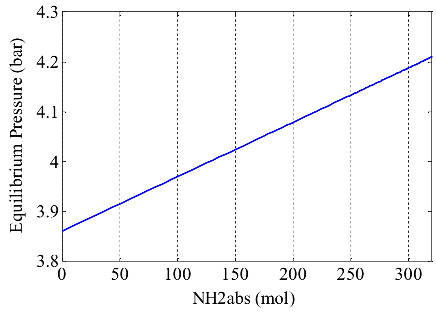

Fig. 12. Equilibrium pressure during metal hydride storage

Table 1: Simulation application results for the "Kos-Kalymnos" electric network

Annual Operation of the Hydrogen Production – Storage System		
Parameter	**Value**	**Units**
Maximum Operational Power	1.26	MW
Minimum Operational Power	126	kW
RES Rejected Energy	398	MWh
Total Absorbed Energy	385	MWh
Annual Hydrogen production	7226	kg
Total Storage Capacity of Metal Hydride Canisters	3.58×10^6	mol
Average Electrolysis Electrochemical Efficiency	72.9%	-
Average Electrolysis Overall Efficiency	62.9%	-
Average Storage Efficiency	89.7%	-
Average Total Efficiency (production-storage)	56.4%	-

5. Conclusions

An integrated algorithm has been developed in MATLAB software platform in order to estimate the optimum solution of a hydrogen based energy storage system in terms of maximum recovery of RES curtailments. Next, the analysis of the "Kos-Kalymnos" autonomous network provided the necessary data concerning the operation of such a system, and suggested that a considerable amount of hydrogen can be generated from the curtailments of RES power plants located in the specific region, with an average efficiency higher than 56%. In this respect, RES energy can be recovered via hydrogen generation and used either to support the grid (with the employment also of fuel cells) or for transportation purposes. On the other hand, new RES investments would become more cost-efficient due to the minimisation of curtailments. To this end, further research is needed to also take into account financial aspects of the problem investigated, evaluating the economic viability of such a hydrogen storage system.

Acknowledgements

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Biography

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