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Performance Assessment and Afficiency of a Renewable Hydrogen Production Station Based on a Supervisory Control Methodology

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The proposed work explores the operational performance of a stand-alone renewable hydrogen production station located at Thessaloniki, Greece where the hydrogen is produced via water electrolysis and it is stored in high pressure cylinders. The required power is provided by a lead-acid accumulator which is charged by a photovoltaic (PV) array while the electricity flow is controlled by a smart microgrid. The station operates unattended and it is monitored remotely using an industrial supervisory control and data acquisition system (SCADA). A decision making process is realized by a flexible energy management strategy (EMS) using a finite state machine approach. The proposed study assesses the performance of the station in the context of an efficient hydrogen production and investigates the way that a number of energy saving actions affect the long-term hydrogen inventory and station autonomy. Overall the experimental results are used to reveal the potential of the station and present the excellent synergy among the various heterogeneous subsystems.

1. Introduction

The shift towards a low carbon, efficient and secure economy requires targeted deployment of innovative technologies and increased exploitation of renewable energy sources. Although a number of diverse technologies exist that aim at the same target, the synergy between the increased use of renewable energy sources, renewable hydrogen and electricity from fuel cells represent a promising way to realize sustainable energy. These technologies can simultaneously address the environmental concerns and the issues of security in energy supply and are considered as an interesting alternative approach (Wulf and Kaltschmitt, 2012). Hydrogen as an energy carrier can create links between a multitude of production methods and sources to various applications including fuel cell systems. But its usefulness is not limited to those. It offers an interesting solution for both short and long-term storage in small or bulk quantity. In cases where the supply is more than the demand, the excess of energy can be transformed into hydrogen that can be easily transported or remain onsite and serve the needs for power on demand (Winter, 2009). Although hydrogen can be produced by a number of different processes, when the production method is based on renewable energy would increase the benefits from its usage.
Nowadays, the hydrogen distribution network is under design and it constitutes a major challenge for the availability of hydrogen worldwide and the penetration of fuel cells in the transportation sector (0. The scope of the presented work is to explore the behavior of a station that currently operates at CERTH and the produced hydrogen is mainly used by a process that converts used cooking oil to 2nd generation biofuel through catalytic hydrotreatment (Bezergianni, 2012) and a number of small-scale PEM fuel cell units. Furthermore, this paper analyzes the effect that minor actions related to the deactivation of certain devices

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for specific period of time have, to the overall energy consumption within the station and to its long-term autonomous operation.

2. Description of the renewable hydrogen production station

The autonomous station consists of several subsystems that are integrated to produce hydrogen via water electrolysis and solar energy. A 10 kWp peak power photovoltaic array (PV) supplies energy for a PEM electrolyzer that is rated at maximum of 7.5 kWp supplying up to 7 bar of hydrogen. The produced hydrogen is initially stored at a low pressure cylinder and subsequently through a compressor to a high pressure cylinder. A lead-acid accumulator is used as energy storage (1,000 Ah/24 V) which is utilized to address the weather fluctuations and to maintain the operation of the station during the night time. A smart microgrid controls the transmission and distribution of the electricity flow, whereas its topology is based on a AC-Bus bar. Figure 1 presents the connection of the subsystems of the station.

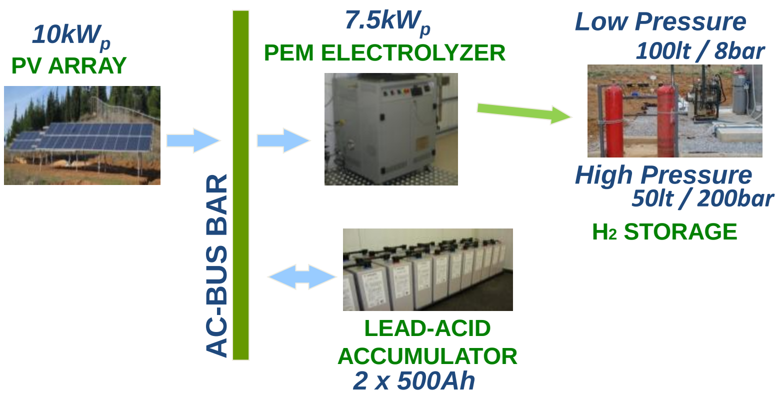
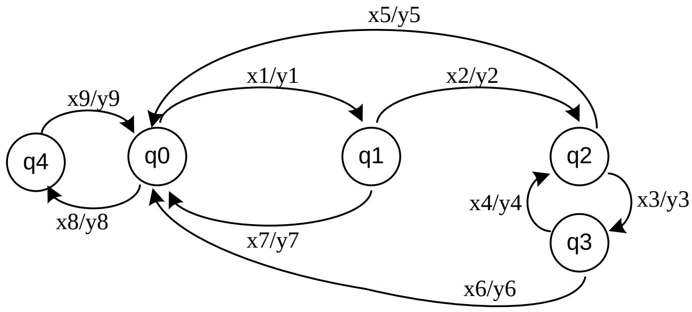


Figure 1: Subsystem's interconnection

The main challenge for the overall control system is to guarantee that power will be available whenever needed, without compromising reliability and maintain system operation both for the hydrogen production period as well as for the part of the day with no insolation, as the system is autonomous. Driven by this incentive it is important not only to produce hydrogen in an optimum manner but also to reduce the power consumption of the various components of the station to the least required. To achieve these main objectives, a Supervisory Control and Data Acquisition (SCADA) system is utilized.
The monitoring and control of the station is performed by this SCADA system, whereas the complex interactions among electrical and chemical subsystems are addressed by the automation infrastructure. Each subsystem of the station serves a unique purpose, nevertheless they are also interconnected to form an integrated hybrid system and they operate towards a common objective which is the optimal production of the renewable hydrogen. Therefore, the SCADA considers not only the handling of each subsystem independently but also the overall objectives of the station. Various network and industrial protocols (CANbus, Profibus, RS485, TCP/IP etc.) are used to integrate the system devices into one central control entity, managing this way the heterogeneity between the chemical and electrical subsystems (Ziogou et al., 2012).

3. Energy management and logical rules representation

The operation of the interconnected subsystems of the station is managed through an Energy Management Strategy (EMS). In general the EMS consists of set of operating rules that dictate a series of switching actions in order to drive the system from an initial state to a desired target state while satisfying device specifications and associated constraints. The scope of the EMS is to control the operation of each subsystem of the station and it is represented by a Finite state machine (FSM) which is a dynamic approach that describes the evolution in time of a set of discrete and continuous state variables. A FSM M is defined by a tuple $(Q, q_0, \delta, \lambda, \mathrm{X}, \mathrm{Y})$ in which Q is a finite set of states, $q_o \in Q$ is the initial state, δ is the state transfer function, λ is the output function, X is the finite input alphabet; and *Y* the finite output alphabet. The FSM represents all feasible states of the station and the logical rules that trigger the transitions between the states.



q0: Station standby
q1: Preparation for H_2 production
q2: Produce H_2
q3: Compress H_2
q4: Use backup to self-sustain the station

Figure 2: Finite State Machine for the operation of the station

If M receives input $x \in X$ while in state q it produces output $y = \lambda(q, x)$ and moves to state $q' = \delta(q, x)$. This defines a transition $(q, q', x / y)$. Therefore, the transition between the states is performed according to a set of rules that define the input alphabet (*X*) of the FSM (Ziogou et al., 2012). More specifically, the output function (*y=λ(q,x)*) can initiate or terminate the operation of a subsystem (e.g., EL, CP, WT) based on mass and energy inventory levels in the three subsystems namely the accumulator (BAT), low-pressure hydrogen buffer tank (BF) and high-pressure final tank (FT). The set of actions defines the FSM output alphabet (*Y*) representing the feasible states of the renewable hydrogen station.

3.1 Logical representation of the operation rules

The operating rules are represented via a propositional-based logic approach using a combination of logical operations ($AND : \wedge, OR : \vee, NOT : !$) and a set of Boolean variables (*β*), which are related to the status of each component of the station. Thus, the complete set of rules is derived by the operation of the unit's subsystems and their constraints. Each rule is associated with a transition at the FSM. For example Table 1 presents the variable (β_{WT}) that monitors the water quality based on the measured resistivity of the water and the rule that activates the hydrogen production (x_2).

Table 1: Buffer Tank Status Variable

Variable status	Description
$[\beta_{WT} = 1] \leftrightarrow [WT_{\mathrm{Res}} \geq WT_{\mathrm{Res},high}]$	Variable β_{WT} is true (=1) if and only if (iff) the water resistivity is greater/equal to $WT_{\mathrm{Res},high}$ (2.2MΩ)
$[\beta_{WT} = 0] \leftrightarrow [WT_{\mathrm{Res}} < WT_{\mathrm{Res},low}]$	Variable β_{WT} is false (=0) iff the water resistivity is below $WT_{\mathrm{Res},low}$ (2.0 MΩ)

Operation rule	Description
$x_2 : \beta_{WT} \wedge \beta_{ELon} \wedge ! \beta_{FT}$	The water resistivity is at the required level (>2 MΩ) and the accumulators are charged to the point where the electrolyzer is allowed to operate while the final tank pressure is lower than its maximum level (200 bar)

In a similar way the rest of the elements of the a set of Boolean variables are defined for every subsystem (EL, BF, FT, CP). It is observed that these rules include a set of parameters such as the upper and lower values for the activation of a subsystem or the level where a component should operate. For example the upper and lower level of SOC where the electrolyzer is allowed to operate, is expressed by two parameters ($SOC_{el,on}$, $SOC_{el,off}$). In order to enhance the overall behavior of the station we need to optimally determine the values of the parameters that make a Boolean variable to change its value, either true or false. Thus, a model based framework is employed that minimizes offline a properly formulated performance index and the results are applied online to the parameters of the station.

3.2 Optimization of the station operation

Besides the decision making process which is implemented by the EMS through the FSM and the logical rules, the value of the parameters and the levels of operation needs to be defined. From a sensitivity analysis it was derived that the operation parameters that mainly influence hydrogen production and operation of the station are the SOC levels $(SOC_{el,on}, SOC_{el,off})$, a prerequisite to initiate and stop hydrogen production, the maximum allowable power drawn from the accumulator $(P_{bat,\max})$ and the minimum power for the operation of the electrolyzer $(P_{el,\min})$. Thus, the optimization framework determines the optimal values for these parameters (Ziogou et al., 2013) and the resulting values of these parameters are applied to the SCADA system. Overall the operation of the station is controlled by the aforementioned EMS according to the predefined set of decision making rules and its behavior is monitored by the SCADA system. The next step involves the exploration the online behavior of the station under different time period and with respect to the overall power consumption of the various components.

4. Assessment of the behavior of the station

The operation of the station is presented through the results of two typical days during winter and summer that represent the worst case and the best case scenario for hydrogen production. The scope of this analysis is to explore the potential of the station for hydrogen production under the same conditions which are expressed by the weather conditions. In both case a sunny day was selected. Subsequently an analysis that includes a energy saving approach is presented which is implemented by simple actions and its effect to the long term operation of the station is evaluated.

4.1 Best and worst case scenario for the hydrogen production (daily analysis)

Two indicative days are selected (SD: June 2012, WD: January 2013) for the analysis of the station's behavior. Prior to the operation of the station the results from the optimization study (Ziogou et al., 2013) were applied to the variables of the SCADA system. More specifically, the parameters for the activation/deactivation of the hydrogen production state (q_2) are summarized for each season at Table 2.

Table 2: Operating levels for activation/deactivation of hydrogen production state

Optimization Variables	$SOC_{el,on}$ (%)	$SOC_{el,off}$ (%)	$P_{bat,\max}$ (W)	$P_{el,\min}$ (W)
Winter period	78 %	72 %	780 W	2,800 W
Summer period	72 %	60 %	1,000 W	2,800 W

The station operates unattended and the data are acquired by the SCADA system using a sampling time of 1min. The performance of the station is evaluated in terms of produced hydrogen and efficiency which is derived by the electrical behavior of the electrolyzer and its power supply.

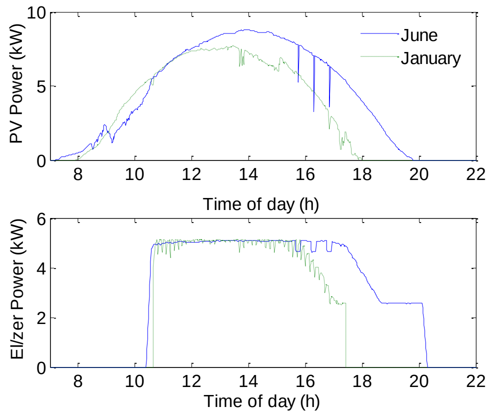


Figure 2: a) PV array and b) Electrolyzer power

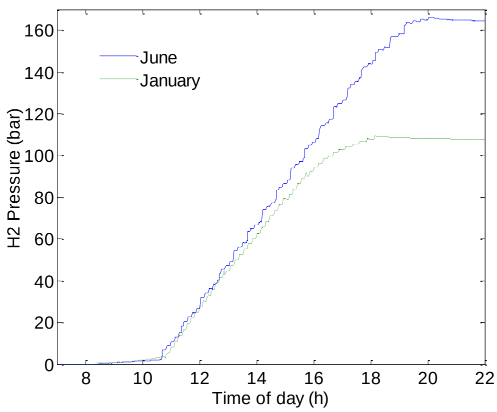


Figure 3: Hydrogen pressure at the final tank

Figure 2a illustrates the comparison of the produced power between the two different days and Figure 2b illustrates the power which is consumed by the electrolyzer. From the hydrogen production point of view, the results from Figure 3 indicate that initially the production rate is similar until 15:00, but as the available PV power decreases so does the production rate during the day in January. On the other hand, the electrolyzer operates for 3.5 h more during the summer day. The interpretation of the results from the comparative analysis is analyzed quantitatively by presenting the average hourly produced hydrogen and the mean electrolyzer efficiency (Table 3).

Table 3: Operation statistics

	H_2 pressure at FT	Produced H_2	Average Produced H_2	Operation Hours	Mean Electrolyzer Efficiency
WD: Winter day	99 bar	8.5 Nm^3	1.53 Nm^3/h	5 h 30 min	69 %
SD: Summer day	165 bar	13.4 Nm^3	1.49 Nm^3/h	9 h	71 %

Based on the above analysis it can be concluded that the performance of the station is similar in both cases. The electrolyzer produces hydrogen with the same efficiency and the only difference is the daily amount of hydrogen, which during the winter day is 63 % compared to the one produced during summer. Another interesting issue which is of major concern for the station is its autonomy. As stated earlier the nominal operation of the station relies on the energy which is stored at the accumulators that are charged only by the PV array. Therefore an analysis that involves the saving of energy by simple actions within the station is explored at the subsequent section.

4.2 Energy saving approach

Due to the fact that the station is not connected to the grid it is of paramount importance to use the available and stored electric energy in the most effective approach. The default way that the station initially operates, provides power (enable the devices but not operated) to all the devices even though some of the involved subsystems do not operate during night-time and when there is not enough energy to produce hydrogen. By these actions the devices are ready to be used regardless of the time of the day or the accumulator's SOC. In an effort to minimize the consumed energy within the station when it is in idle mode, an analysis that included every component was conducted. By a careful examination of the various devices of the integrated station we concluded to those that can be deactivated during nighttime. From this analysis the devices that were selected are:

- The pump for the purification of the water
- The inverter of the compressor
- The power for the device that supplies the power (PWS) for the operation of the electrolyzer

In order to explore the effect of this approach a comparative experimental analysis was performed. The first case (noES) involves the typical operation of the station whereas the second case (ES) involves the application of these energy saving actions. A slight modification was performed at the operational level of the SCADA system to include these actions, whereas at the EMS level these devices are deactivated when the FSM is at the standby state (q_0) and are reactivated at the state (q_1) where the preparation for hydrogen production takes place. The experimental analysis focuses on the decrease of the accumulator's SOC during nighttime and the power that the auxiliaries consume. Table 3 presents the effect of these actions to the station for two days (November 2012).

Table 4: Impact of the energy saving approach to the station

Case study	Depth of Discharge (DOD)	Discharge rate	Station autonomy
noES: Nominal case	29.4 %	2.1 %/h	2.8 d
ES: Energy saving approach	21.5 %	1.54 %/h	3.9 d

The station uses the energy stored at the accumulators for 14 h (from 17:10 to 7:20). During the ES case the consumed power during this period of time was reduced by 0.36 kW/h and a total of 5.04 kW/h were saved. The depth of discharge (DOD) is also an interesting metric which is defined as the difference between the maximum and the minimum measured values of the SOC of the accumulator and it is calculated for the period of time where the discharging takes place. From the metrics shown at Table 3 we observe that the discharge rate is slightly reduced and the DOD was decreased by 8 % compared to the case where the energy saving approach was not employed. Even though this decrease might seam quite low, if we extend these results to a yearly basis we could potentially save up to 1,825 kWh which is a considerable amount of energy that could be transformed into hydrogen or avoid the usage of the backup option for the station into consideration. For example in the case where all the saved energy was converted into hydrogen using a 96 % conversion rate due to losses caused by the power supply, a total of 346 Nm^3 could be produced. This amount of hydrogen is equivalent to the monthly operation of the station. On the other hand, the only side effect of these actions is a small delay which is inserted when the system prepares for the hydrogen production (state q_2) and it is caused by the fact that the water is not continuously purified as the water pump is switched off.

The impact of these simple energy saving actions to the autonomy of the station is also worth mentioning, since this constitutes a significant issue especially for periods where the PV power is limited. During the winter the focus is towards the maximization of the station's autonomy, whereas for the rest of year where the electrolyzer operates, the amount of energy which is saved can be transformed into hydrogen. In order to calculate this metric (station autonomy), we assumed that the accumulators were fully charged. Generally the backup power is activated when the SOC drops below 14 %. Thus, the desired SOC ideally must be above this SOC level. From the results of Table 3 we notice that the autonomy of the station is improved in the case of the energy saving approach by one day.

5. Conclusions

This work presented an experimental comparative analysis of the worst and the best case scenario for the production of hydrogen by the station. The scope of the station is to produce hydrogen in the most efficient way while protecting the lifetime of the subsystems that support the hydrogen production in conjunction with the full utilization of the available renewable energy. Overall the flexibility of the supervisory control methodology that is applied to the station is shown and the behaviour of the station is explored. A sensitivity analysis of the electricity consumption pattern was performed and the results were exploited in order to ensure that the stored energy is utilized in an effective way. As a result of this approach we concluded that during the winter time the proposed energy saving could increase the autonomy of the system, whereas during the summer period the saved energy could be used to increase the amount of produced hydrogen.

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