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Optimal production of renewable hydrogen based on an efficient energy management strategy

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This work presents the development of a flexible energy management strategy (EMS) for a renewable hydrogen production unit through water electrolysis with solar power. The electricity flow of the unit is controlled by a smart microgrid and the overall unattended operation is achieved by a supervisory control system. The proposed approach formalizes the knowledge regarding the system operation using a finite-state machine (FSM) which is subsequently combined with a propositional-based logic to describe the transitions among various process states. The operating rules for the integrated system are derived by taking into account both the operating constraints and the interaction effects among the individual subsystems in a systematic way. Optimal control system parameter values are obtained so that a system performance criterion incorporating efficient and economic operation is satisfied. The resulted EMS has been deployed to the industrial automation system that monitors and controls a small-scale experimental solar hydrogen production unit. The overall performance of the proposed EMS in the experimental unit has been evaluated over short-term and long-term operating periods resulting in smooth and efficient hydrogen production.

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1. Introduction

Hydrogen production from renewable energy sources (RES) is envisioned as an alternative to fossil fuels. This work investigates the operating policies which are implemented in a small-scale hydrogen production unit through water electrolysis from solar power. The primary purpose of the unit is to produce and store high-pressure hydrogen in order to improve the sustainability of a process converting used cooking oil to second generation biofuels through catalytic hydrotreatment\textsuperscript{1}. Renewable hydrogen is considered as a promising energy carrier and provides a three-fold benefit of energy preservation, environmental protection, and economic profits as shown by Shen et al.\textsuperscript{2}. Furthermore, as demonstrated in the extensive reviews and studies of Refs.\textsuperscript{3} and\textsuperscript{4}, the use of RES is always accompanied by hydrogen production and utilization, resulting in this way in integrated hybrid systems. Consequently, it is an essential component for a number of applications such as a) wind exploitation as described by Díaz-González et al.\textsuperscript{5} and wind--photovoltaic (PV) combination presented by Isherwood et al.\textsuperscript{6}, b) electrification of remote off-grid areas\textsuperscript{7}, c) utilization in transportation sector in hybrid vehicles\textsuperscript{8}, and d) direct use in automotive\textsuperscript{9} and so forth. Numerous studies have been published on the area of RES based power generation and hydrogen production systems and cover topics of energy policies\textsuperscript{10}, operating issues, mathematical modeling and effective control strategies\textsuperscript{11}. Systems that operate based on RES in conjunction with hydrogen production can be found among others in Germany\textsuperscript{12}, in Spain\textsuperscript{13}, in Switzerland\textsuperscript{14}, and most recently in France\textsuperscript{15}.

In order to efficiently and safely operate autonomous RES based hydrogen production systems it is important to develop flexible energy management strategies (EMSs) that ensure an overall high performance. Early development in this area provided rather primitive strategies based on the realization of heuristic flowcharts that define a set of decisions as exhibited by Voutetakis et al.\textsuperscript{16}. Similarly, Dufo-López et al.\textsuperscript{17} developed similar conventional if-then-else flowcharts that tried to evaluate through dedicated optimization and control studies that were initially promoted by Ulleberg in Ref.\textsuperscript{18}. More specifically, a comparison of different
strategies has been provided by Dursun and Kilic [19], with main concern the control of energy storage states. The applications methodologies that employ multiple “if-else” commands have led to improvements since intelligent control techniques have been adopted in latest developments [20,21].

Such methodologies however, require extensive knowledge of the system features (start/stop signals, operating limits etc.) Further on, a rather ignored feature in RES units that also needs to be addressed is the analysis of auxiliary electronic systems that complement RES–hydrogen systems. All necessary connections were sufficiently described in conjunction with the monitoring system, but the applied power management strategy was not thoroughly explored. Koutroulis and Kalaitzakis [23] also developed an integrated data acquisition system for RES plants and the proposed method was based on an easy-to-use graphical environment, for processing, displaying and storing the collected data.

The development of energy management in integrated hybrid systems is of paramount importance for adequate performance. However, there is a lack of a systemic approach to the formulation of such an energy management strategy. The areas that require further attention refer to: a) optimum operating patterns among the interconnected subsystems and b) safe operation of the equipment away from critical process limits (e.g., high charging rates, high hydrogen storage and so forth). The main focus of
previous research work dealt a) with the concept of developing model-based energy management strategies for integrated systems that utilize RES (solar and wind energy) and energy storage systems for stationary applications in Xanthi Greece [16], and b) with the delicate issue of promoting advanced infrastructure facilities (both software and hardware) for the safe and remote operation of a similar hybrid unit [24] in Thessaloniki, Greece. This paper aims to enhance the operation of a renewable hydrogen production unit which was designed and constructed at Centre for Research and Technology Hellas (CERTH) by proposing a novel and flexible method for applying a set of real-time decisions in the form of operating rules that consist an energy management strategy (EMS). Several methodologies that can describe an EMS, such as if-then rules [16], fuzzy logic [25], Petri nets, state-flow charts [26] and automata [27] or finite-state machines [28] have been employed. This work proposes a methodology that uses a finite-state machine (FSM) which can be naturally deployed to the automation systems that monitors and controls the unit. The derived rules are used for the operation of the unit’s subsystems and are able to drive the system from an initial state to a desired target state, taking into consideration the device specifications and the respective constraints. Overall the operation of the unit is based on a methodology which is designed and implemented with sustainability considerations in mind. The resulting low complexity algorithm has negligible computational requirements and it is used to improve the overall energy efficiency of the system, thus, it is considered as an energy-aware methodology.

This paper is structured as follows: in Section 2 the renewable hydrogen production unit is described. In Section 3 the proposed energy management strategy based on a finite-state machine using propositional-based logic is presented. Section 4 presents the results of an optimization study that is subsequently implemented in the system. Finally the daily and the long-term operation of the system is presented along with its efficiency.

2. System description

Renewable hydrogen lays the ground for a sustainable energy economy since it constitutes an environmentally friendly, cost-effective, zero-emission energy solution. In the current work hydrogen is produced via water electrolysis and the required power for the electrolysis is provided by a lead-acid accumulator which is charged by a PV array in an autonomous way. In order to construct such a system several subsystems are required to be integrated in order to formulate an autonomous system able to operate unattended. At the core of the infrastructure a smart microgrid is formed that generates, distributes and regulates the flow of electricity to the electrolyzer and to the system utilities. This microgrid is based on an AC-bus topology, meaning that all transfer of energy is made through a three-phase bus bar. A 10 kWp peak power photovoltaic array (PV) supplies electric power for a polymer electrolyte membrane (PEM) electrolyzer that is rated at 7.5 kWp and is able to provide up to 8 bar hydrogen. The produced hydrogen is stored in tanks at high pressure using a compressor between a buffer tank connected to the electrolyzer and the final storage tank. In order to maintain a smooth operation despite weather fluctuations, a 1000 A h/24 V lead-acid accumulator stores temporarily electrical energy and dispatches it when needed in a controlled way [24], Fig. 1 presents the connectivity of the subsystems.

2.1. Data sampling and measurement accuracy

The monitoring and control of the unit is implemented through a supervisory control and data acquisition system (SCADA), whereas the interactions among the electrical and the electro-chemical subsystems are addressed by the automation infrastructure. Various network and industrial protocols (CANbus, Profibus, RS485, TCP/IP (transmission control protocol/internet protocol) etc.) are employed in an effort to integrate the system devices into one central control entity, managing this way the heterogeneity between the electrochemical and electrical subsystems [29]. Fig. 2 shows the electrical interconnection of the subsystems.

The operating decisions for each subsystem are based on the data acquired by the I/O field. Therefore, it is important to rely on precise measurements in order to be able to make the optimal decisions for the operation of the unit. The variables acquired from the field are related to pressure, temperature, conductivity, power, current and voltage. The transmission of the analog measurement signals is made through the input terminals to the automation system. The sensor signals are wired to the I/O terminals which are connected in a centralized way to the bus coupler. These I/O terminals transform the sensor signals (4.20 mA) with a 12 bit resolution into digital data which are subsequently processed by the SCADA system. The measurement error is less than ±0.3% of the full range scale and each input signal is represented by 16 bits. The sampling time of each measurement is set to 1 s and the data are archived without compression. The produced hydrogen is measured through the pressure indication at the final tank. Hence,

![Fig. 1. Subsystem’s interconnection.](image-url)
a calibrated pressure transducer is used for accurate measurements of the produced hydrogen. The calibration error of the transducer has been estimated in the range of $\pm 0.25\text{ psig}$.

The main challenges for the integrated system are to guarantee the availability of power without compromising system reliability and to maintain system integrity and safety both for the hydrogen production period as well as for the part of the day with no isolation, as the system is fully autonomous.

3. Energy management strategy development framework

The operation of the various interconnected subsystems affects the overall behavior and life of the unit. Therefore, an Energy Management Strategy (EMS) is required in order to exploit the intrinsic features of the system into consideration. A suitable EMS enables the optimal use of the devices within safety limits that constitute the unit while taking into consideration the strong interactions among the individual subsystems. This is basically achieved through the close supervision of the operating state of each subunit [29]. In general the EMS consists of sets 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. These rules are derived by the necessary actions that describe the operation of each subsystem, namely the electrolyzer (EL), the hydrogen compression (CP) subsystem and the water purification subsystem (WT).

A finite-state machine (FSM) approach is employed to represent the operation and the main decision making mechanism for the unit. The selection of the FSM is supported by the flexibility of the approach to accommodate simulation and offline optimization studies and its compatibility to SCADA based control systems.

3.1. System representation

A finite-state machine (FSM) or finite-state automaton is a theoretical framework that describes state contents and transitions that are widely applied to computer science (e.g., for parsing, compiler design and formal verification) and to the design of digital logic circuits [27]. In general the FSM theory deals with the transition and behavior between states which can be applied to any specific or abstract system. An FSM can be used to describe the behavior of a specific subsystem, an entire integrated system or a number of systems connected to each other. Indicative examples of each case with respect to energy systems are:

- **Subsystem level**: The water purification subsystem where various components are involved (e.g., valves, water pump, conductivity measurement and so forth).
- **System level**: A renewable hydrogen production unit consisted of a number of subsystems (e.g., water purification, hydrogen production and hydrogen compression subsystem).

- **Network level**: Grid independent systems that distribute energy among them in order to serve a common load demand and produce hydrogen with the excess of the available energy.

Overall an FSM, $M$, is a dynamic approach that describes the evolution in time of a set of discrete and continuous state variables and is defined by a tuple $(Q, q_0, \delta, \lambda, X, Y)$ in which:

- $Q$ is a finite non-empty set of all possible states of $M$
- $q_0 \in Q$ is the initial state of $M$
- $\delta$ is the state transfer function
- $\lambda$ is the output function
- $X$ is the finite input alphabet
- $Y$ is the finite output alphabet

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 $(q, q', x/y)$. This transition function determines the next state for every feasible combination of input alphabet and state. The alphabet $X$ is a non-empty set of symbols that represents the operating rules to be explained in the following section. There are several steps in creating an FSM which are common to every level of application (subsystem, system or network wide):

1. Create the structure by determining the number of states and the initial or nominal state of operation.
2. Define the logical behavior of the system by specifying the triggers that enable the transitions between the states.
3. Determine the actions which are performed within the system during the various operating states.
4. Assemble the system and verify its behavior.

In this work an FSM is used at the system level to describe the realization of the EMS for the operation of a stand-alone renewable hydrogen production unit. Particularly, an FSM can be extremely helpful in the study of the behavior of the autonomous renewable hydrogen production unit due to its inherent hybrid structure. The operation of the subsystems exhibits either discrete (e.g., starts or stop of the compressor and the electrolyzer) or continuous (e.g., state of charge (SOC) of the accumulators) dynamics. The state interaction between the discrete and the continuous operating states motivates the use of the hybrid approach and thus, the FSM appears as an appropriate and powerful representation and analysis tool for the realization of a generic EMS.

The operation cycle of the renewable hydrogen production unit in CERTH is approximated by five discrete states $Q = [q_0, q_1, ..., q_4]$ as shown in Fig. 3 and described afterward in detail (it is noted that the numbers $0, ..., 4$ do not denote a series of consequent actions):

- $q_0$: System standby.
- $q_1$: Preparation for hydrogen production.

![Fig. 2. Information flow.](image)

![Fig. 3. Finite-state machine for the operation of the system.](image)
\[ q_2: \text{Hydrogen production.} \]
\[ q_3: \text{Hydrogen compression.} \]
\[ q_4: \text{Use backup to self-sustain the system.} \]

The nominal state of the system is \( q_0 \) that corresponds to the actual electrolyzer operation, whereas the initial state (or starting state) of the system is considered to be \( q_0 \). Since the RES system is a stand-alone application unit, the backup state should also be considered and denoted as \( q_4 \). Prior the initiation of hydrogen production, a number of preparatory steps are performed that are mainly related to water purification subsystem denoted with the state \( q_3 \). Also, since the produced hydrogen is subsequently compressed up to 180 bar, it is important to include state \( q_3 \), which is related to hydrogen compression from the low-pressure to the high-pressure cylinder.

The transition between the states is performed according to a set of rules (see Section 3.2) that define the input alphabet \( X = \{x_1, x_2, \ldots, x_n\} \) of the FSM. The output function \( (y = f(q, x)) \) can engage or disengage (i.e., initiation or termination of operation, respectively) 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 define the FSM output alphabet \( Y = \{y_1, y_2, \ldots, y_m\} \) representing the feasible states of the renewable hydrogen unit, therefore, the FMS guarantees that every possible realization related to the operation of the unit is included and not omitted. The next step involves the determination of the rules and actions that take place during the transitions among the states.

3.2. System operating rules

State transitions along with the respective actions (triggered by those transitions), require the definition of a set of operating rules implemented via a propositional-based logic approach. The scope of the propositional logic is to present a systemic and generalized approach of the operating rules that constitute the input alphabet \( X = \{x_1, x_2, \ldots, x_n\} \) of the FSM. Generally, each rule corresponds to one state transition and for each input, or propositional rule, there exists one output action which is related to the output alphabet \( (Y = \{y_1, y_2, \ldots, y_l\}) \) of the FSM. The propositional rules are logical expressions that are formed using a combination of logical operations (AND:, OR:, AND NOT: !) and a set of Boolean variables \( B = \{\beta_{\text{var1}}, \beta_{\text{var2}}, \ldots, \beta_{\text{varn}}\} \), where \( r \) is the number of variables that are used to define the status of a subsystem or to define a range of a subsystems operation. The semantics behind this variable-based representation make propositional logic very appealing for systems whose operation involves simple actions based on a combination of simple conditions. The status of each subsystem or the level of stored energy can be subsequently compared to a predefined level using the appropriate operand (Greater: >, Less: <, Equal: =). Furthermore a hysteresis band [16] that prolongs or delays device operation is used in the boundary limits of the accumulator to avoid irregular operation (elimination of frequent start-ups and shutdowns). The SOC of the accumulator, the quality of the water and the level of the hydrogen storage tanks are the main factors that drive the operating decisions concerning the electrolyzer, the compressor and the water purification system. As an example, the operation of the compressor (CP) depends on the level of \( H_2 \) pressure in the BF. Specifically, high (\( P_{\text{BF, high}} \)) and low (\( P_{\text{BF, low}} \)) pressure levels are selected that determine the system state range where the compressor is allowed to operate or not (Fig. 4). Fig. 4 shows that when the pressure in the buffer tank reaches \( P_{\text{BF, high}} \) the compressor starts to operate and it stops only when the pressure drops to \( P_{\text{BF, low}} \). This operation is represented by a Boolean variable (\( \beta_{\text{BF}} \)) that can be true or false based on the predefined pressure limits according to the example given in Table 1.

Similarly, a set of Boolean variables are defined for the water purity (\( \beta_{\text{W}} \)), the pressure at the final tank (\( \beta_{\text{F}} \)) and the SOC of the accumulator (\( \beta_{\text{SOC, low}}, \beta_{\text{SOC, high}}, \beta_{\text{SOC, max}} \)). The critical levels where the value of each Boolean variable changes (from true to false and vice versa) are optimally selected by the satisfaction of a performance criterion for the integrated system as will be discussed in the following section or heuristically utilizing engineering knowledge attained from experience regarding the operational characteristics of similar subsystems. For example, the level of the SOC where the electrolyzer operation is initiated or terminated (\( \beta_{\text{SOC, low}}, \beta_{\text{SOC, high}} \)) is determined in an offline optimization step, whereas the pressure level (\( \beta_{\text{BF}} \)) where the compressor stops, is determined by the device manufacturer.

In order to define the input alphabet \( X \) and subsequently the transfer functions \( f \) of the FSM these variables are combined in order to form the propositional rules. The resulting set of these rules describe the reasoning for the operation of each subsystem \( (X = \{x_1, x_2, \ldots, x_l\}) \). Specifically in the system into consideration the variables which are used to form the propositional rules are described in Table 2.

Table 3 presents a subset of the FSM input alphabet that corresponds to the transitions for the hydrogen production from the preparation state \( (q_1, q_2, x_1/y_2) \) and the start of the hydrogen compression from the production state \( (q_2, q_3, x_1/y_3) \).

The complete set of rules is derived by the operation of the unit’s subsystems and their constraints. The use of the FSM that realizes the EMS enables the study of the behavior of integrated systems in a flexible way due to its adaptability. Furthermore, this modular approach enables a flexible operation that can be altered according to the system’s state. Subsequently, it can be expanded in order to include more states or to implement failover strategies or scheduled maintenance actions. Overall the proposed EMS is an energy-aware algorithm able to incorporate the various interconnections between the feasible states of the unit and can be applied on the actual system including various operating modes. Additionally, it offers a theoretical context for the analysis and design of complex energy systems involving multiple energy sources and loads.

4. Optimization and system performance

The scope of the system is to produce hydrogen in an 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. Therefore, the analysis of the

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overall performance focuses not only on the unattended operation of the unit but also, in the efficiency of each subsystem as well as the overall hydrogen production efficiency. Based on this motivation the specification of the value of important operating parameters is of paramount importance. An optimization-based framework is therefore used, for the calculation of the optimal values for the control parameters that are part of the defining operating rules.

4.1. Optimal calculation of EMS parameters

The optimization framework which is developed and used dictates the operation of the subsystems in terms of reliability and aims at the increase of their life expectancy. Fig. 5 presents the interconnection of the entities that constitute the proposed framework including the online deployment to the unit.

4.1.1. System models

For each subsystem a mathematical model for the prediction of the system behavior under variable conditions is used. The main equations that describe the operation of each subsystem (photovoltaic array, accumulator, electrolyzer and compressor) are presented whereas a thorough analysis can be found in Ref. [24].

The operation of a PV-cell relies on a current–voltage (I–V) relationship such as:

\[ I_{pv} = I_L - I_0 \left( \exp \left( \frac{V_{pv} + I_{pv}R_s}{\alpha} \right) - 1 \right) \]  \hspace{1cm} (1)

where \( I_{pv} \) denotes the PV current, \( I_L \) and \( I_0 \) denote the light and diode reverse saturation currents, respectively, \( R_s \) the series resistance, \( V_{pv} \) the operation voltage and \( \alpha \) is the curve fitting parameter. Finally, the output power \( (P_{pv}) \) from the PV array is given by:

\[ P_{pv} = V_{pv}I_{pv}\eta_{pv} \]  \hspace{1cm} (2)

where \( \eta_{pv} \) denotes the efficiency as a lumped parameter that combines all electrical parasitic losses. The voltage–current relation of the lead–acid accumulator is given by:

\[ V_{ac} = E_{ac} - I_{ac}R_o \]  \hspace{1cm} (3)

where \( I_{ac} \) is the charging or discharging current, \( E_{ac} \) denotes the source voltage and \( R_o \) is the internal resistance. The SOC of the accumulator refers to the available capacity of the accumulator and is given by a function of time \( (t) \) and operation current and is simply the fraction of the reported capacity of the accumulator at each time instance divided by its nominal capacity:

\[ \text{SOC}_{t+1} = \text{SOC}_t(1 - \sigma_{ac}) + I_{ac}\text{SOC}_t(\Delta t) \]  \hspace{1cm} (4)

where \( \sigma_{ac} \) is the efficiency factor and \( \sigma_{ac} \) is the discharging rate of the accumulator.

The voltage of the PEM electrolyzer \( (V_{elec}) \) is given by a nonlinear parametric equation:

\[ V_{elec} = V_{rev.elec} + \frac{r_1 + r_2 \cdot T}{A_{elec}} \cdot I_{elec} + \left( \frac{s_1 + s_2 \cdot T + s_3 \cdot T^2}{A_{elec}} \right) \cdot \log \left( \frac{t_1 + t_2/T + t_3/T^2}{A_{elec}} \cdot I_{elec} + 1 \right) \]  \hspace{1cm} (5)

where \( V_{rev.elec} \) is the reversible voltage, \( r_1 \) are parameters for the ohmic resistance of the electrolyte, \( s_1 \) and \( t_i \) are parameters for the overvoltage that occurs in the electrodes, \( A_{elec} \) is the electrode area, \( T \) is the temperature of electrolyte and \( I_{elec} \) is the current through the cell.

The production rate of hydrogen in an electrolyzer is given by the Faraday’s Law [19]:

\[ n_{H_2} = n_F \cdot \frac{F \cdot I_{elec}}{n_e \cdot F} \]  \hspace{1cm} (6)

where \( n_{H_2} \) is hydrogen produced in mol/s, \( n_F \) the faraday efficiency, \( n_e \) the cell number, \( n_e \) the number of electrons, \( F \) the Faraday’s constant.

The basic mathematical model (Van der Waals Law) that describes the storage of hydrogen is described by the following equations:

\[ P_T = \frac{n \cdot R \cdot T}{V_T} - \frac{a}{V_T^2} \cdot n^2 \]  \hspace{1cm} (7)

where \( P_T \) denotes the pressure, \( n \) is the number of stored moles of hydrogen, \( R \) is the universal gas constant, \( T \) is the ambient
temperature, $V_T$ is tank volume, $a, b$ are parameters depending on hydrogen critical temperature and pressure. Finally storage under pressure requires the use of a compressor in order to increase the hydrogen pressure. The polytropic work ($\Delta W_{pol}$) for the compression of hydrogen is:

$$\Delta W_{pol} = \frac{k}{k - 1} n_{H_2, \text{comp}} R T \left[ \frac{P_2}{P_1} \right]^{\frac{k}{k - 1}} - 1 \right) / n_{\text{comp}} \tag{8}$$

where $n_{H_2, \text{comp}}$ is the hydrogen flow at the compressor, $P_1$ and $P_2$ the inlet and outlet hydrogen pressure, $k$ the polytropic coefficient of hydrogen and $n_{\text{comp}}$ is the compressor efficiency. These models were experimentally validated utilizing experimental data from the various unit subsystems [24].

### 4.1.2. Optimization problem formulation

The performance criterion involves the utilization pattern for the accumulator and the electrolyzer as these factors determine the frequency of equipment replacement and maintenance requirements and therefore, the operating costs over the lifespan of the overall system [16]. Therefore, the objectives for the optimization study are:

- Maximization of the hydrogen production.
- Protection of the lifetime of the accumulator and the electrolyzer.
- Utilization of the available power from the PV array.

The key parameters that influence hydrogen production and the operation of the system are the SOC levels ($SOC_{el,on}, SOC_{el,off}$) where the electrolyzer operation is initiated or terminated, the minimum power level of the electrolyzer ($P_{el,\text{min}}$) and the maximum allowable power drawn from the accumulator ($P_{bat,\text{max}}$). The latter is selected in order to enable the greatest use of the PV power in the system. These parameters constitute the decision variables of the optimization problem. Therefore, the following constrained optimization problem is formulated:

$$\min_{SOC_{el,on},SOC_{el,off},P_{bat,max},P_{el,\text{min}}} J = \sum_{i=1}^{n} \left( w_{\text{loss}} P_{\text{loss}}(i) + R \left[ \frac{P_{\text{bat,cyc}}}{P_{\text{bat,cyc}}(i)} \right] + w_{\text{bat,cyc}} P_{\text{bat,cyc}}(i) \right) + w_{\text{el,cyc}} P_{\text{el,cyc}}(i)$$

s.t.

$$SOC_{el,\text{on}}^{\text{low}} < SOC_{el,\text{on}} < SOC_{el,\text{on}}^{\text{up}}$$

$$SOC_{el,\text{off}}^{\text{low}} < SOC_{el,\text{off}} < SOC_{el,\text{off}}^{\text{up}}$$

$$P_{el,\text{min}} < P_{el,\text{min}} < P_{el,\text{min}}^{\text{up}}$$

$$P_{bat,\text{max}} < P_{bat,\text{max}} < P_{bat,\text{max}}^{\text{up}}$$

where $P_{bat}$ is the PV power which is not utilized by the system, $O_{bat,cyc}$ is the ratio of operation cycles (the number of charging periods followed by discharging periods) of the accumulator divided by the total maximum number of cycles of operation as provided by the manufacturer, $O_{el,cyc}$ are the operation cycle of the electrolyzer (total time of operation in hours which are transformed into percentage of the overall use) and $H_2,\text{prod}$ is the total amount of produced hydrogen, which is calculated from Eq. (7). For
each term of the objective function a proper weight, \((w_{loss}, w_{bat}, w_{el}, w_{H2,prod})\), is applied. These weights indicate the significance of the specific goals as represented by each term in the objective function \((H_2, prod > (Opel, cyc, Opbat, cyc) > P_{loss})\). Furthermore, these weights are adjusted to the magnitude of the related term in order to have a uniform contribution to the objective function. The optimization is performed on a season basis including three months of operation considering a 5 min sampling period that result to 25,920 time intervals \((n)\).

4.1.3. Optimization results

The optimization problem was solved for two different seasons (Spring, Autumn) and the resulting optimal values of the decision variables are presented in Table 4. It is observed by the results that the EMS parameters attain different optimal values for each season. The variables of SOCel_on and SOCel_off are used in the FSM to define the levels of Boolean variables \(b_{El_on}\) and \(b_{El_off}\) which are part of propositional rules \(x_2, x_5, x_6\). The resulted values derived by the optimization study are embedded to the EMS which is deployed to the unit.

4.2. System efficiency estimation

One of the major concerns in all energy systems and particularly in renewable energy exploitation is the calculation of subsystem efficiency. In the renewable hydrogen unit, the analysis focuses on the evaluation of the operating efficiencies of the PV, the PEM electrolyzer and the lead-acid battery. The efficiency of the PV is calculated based on the ratio of energy coming out to the available energy for conversion:

\[
\eta_{PV} = \frac{P_{PV}}{G_s A_{PV}} \quad (10)
\]

where \(G_s\) the incident solar radiation on the tilted panel and \(A_{PV}\) is the total PV area. The accumulator efficiencies in the cases of charging and discharging are:

\[
P_{bat, tot}(\text{charge}) = P_{PV} - P_{load} \quad \text{and} \quad P_{bat, tot}(\text{discharge}) = P_{load} - P_{PV} \quad (11)
\]

\[
\eta_{bat} = \frac{P_{bat, real}}{P_{bat, tot}} \quad (12)
\]

where \(\eta_{bat}\) is the accumulator efficiency, \(P_{bat, real}\) the accumulator power (derived from the actual measurements of current and voltage), \(P_{bat, tot}\) the total power supply or demand from the AC-bus (derived from the balance of loads and PV power). The electrolyzer efficiency is provided as:

\[
\eta_{elec} = \frac{H_2, real}{H_2, theoretical} \quad \text{where} \quad H_2, theoretical = \frac{n_e I_{elec}}{n F} \quad (13)
\]

where \(\eta_{elec}\) the electrolyzer efficiency, \(H_2, real\) and \(H_2, theoretical\) the real and theoretical hydrogen produced respectively in \(\text{Nm}^3\), \(n_e\) the cell number, \(F\) the Faraday's efficiency, \(I_{elec}\) the operating current and \(n\) the number of electrons. Fig. 6 presents the efficiencies of the above subsystems of the renewable hydrogen unit.
4.3. Short-term system operation

The autonomous system operates unattended every day and the hydrogen is stored in high-pressure cylinders. Therefore, the main concern regarding the daily operation is the availability of empty cylinders. In the following analysis the behavior of each subsystem is analyzed. The data are acquired by the SCADA system of the unit using a sampling time of 1 min. In Fig. 7 the typical daily operation of all subsystems of the unit during a sunny day (May 2012) is shown.

When the pressure reaches the maximum allowable level (180 bar) the high-pressure cylinder is switched over to an empty one. In Fig. 7 a sudden drop of hydrogen pressure illustrates the changeover of the cylinder. During the night time the SOC decreases, as the system has to support its auxiliaries subsystems (air-condition, control and automation infrastructure). Also, a slight drop of hydrogen pressure appears after the sunset which is caused by the decrease of the environmental temperature since the cylinders are placed outdoors. Fig. 8 illustrates the produced hydrogen compared to the theoretical hydrogen while Fig. 9 shows the instantaneous efficiency and the respective moving average of the efficiency calculated based on the ratio of produced hydrogen to the theoretical one.

The electrolyzer operates continuously for 7 h and the required power is adjusted according to the SOC of the accumulators. The electrolyzer operates at a maximum, a variable and finally at a minimum power level. During the first 4 h the electrolyzer operates at its maximum point (5.4 kW) and it is observed that the efficiency is between 62% and 91% with a mean value of 78%. As the power from the PV decreases (4–5.2 h) the amount of produced hydrogen is also reduced. Finally in the afternoon the electrolyzer operates at its minimum point of operation (2.8 kW) until the SOC of accumulators reaches the predefined SOC_{off} level. Fig. 9 shows that the efficiency fluctuates when the electrolyzer operates with the minimum allowed power between 41% and 94% and during this period the mean efficiency is 70%. Although the efficiency varies during the day it is observed that the mean electrolyzer efficiency is 73%. Fig. 10 illustrates the operation of the system during a typical cloudy day (October 2012).

It is observed that the PV power fluctuates and the provided power to the electrolyzed is adjusted accordingly. During a cloudy day the variability of the PV power can greatly affect the hydrogen production. However the operation of the electrolyzer is not interrupted.

Fig. 11 shows the produced hydrogen compared to the theoretically produced and Fig. 12 illustrates the respective hydrogen production efficiency. It is shown that the produced hydrogen is close to the theoretically produced regardless of the input power fluctuations due to the availability of PV power. Overall the electrolyzer operates for 5.5 h and it is observed that the efficiency varies between 29% and 91% with a mean value of 66%. Table 5 shows a comparison between the two days.

Based on the above analysis it can be concluded that the system operates smoothly in both cases (during sunny and cloudy days) and hydrogen is efficiently produced. Also, it is shown that the electrolyzer is able to operate using varying input power and therefore, the unit can take advantage even a limited power available from the PV array.

4.4. Long-term system operation

In the following analysis the operation of the system during one month is presented. Specifically the results are from the operation of March 2012. Fig. 13 illustrates the PV and the electrolyzer power and Fig. 14 shows the hydrogen pressure at the final tank and the accumulator’s SOC.

During the presented period the electrolyzer operated for 23 days and a total of 230 Nm³ of hydrogen were produced with an average of 10 Nm³ per day. A statistical summary of the unit's operation and the absolute measurement error during the one month period of the study is summarized in Table 6.

The depth of discharge (DOD) is defined as the difference between the maximum and the minimum measured values of the SOC of the accumulator. The variables for SOC and DOD are calculated for all days during month, while the rest of the variables of Table 6 are calculated only for the days that the electrolyzer operates. The sampling time of the variables was 60 s and the mean value was computed based all data points.

From the above experimental results it is confirmed that the system can operate unattended for a long period based on the aforementioned energy management strategy and that the hydrogen is produced efficiently regardless of the variation in the environmental conditions and the power requirements of the auxiliary subsystems.

Table 5

<table>
<thead>
<tr>
<th>Period</th>
<th>Produced H₂ (Nm³)</th>
<th>El/zer operation (h)</th>
<th>Mean efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>14.3</td>
<td>6.9</td>
<td>73</td>
</tr>
<tr>
<td>October</td>
<td>9.1</td>
<td>5.5</td>
<td>66</td>
</tr>
</tbody>
</table>

Table 6

<table>
<thead>
<tr>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Absolute measure error</th>
</tr>
</thead>
<tbody>
<tr>
<td>El. voltage [V]</td>
<td>24.8</td>
<td>30.3</td>
<td>26.7</td>
</tr>
<tr>
<td>El. current [A]</td>
<td>21.2</td>
<td>217.3</td>
<td>164.7</td>
</tr>
<tr>
<td>El. power [W]</td>
<td>2620</td>
<td>5955</td>
<td>4418</td>
</tr>
<tr>
<td>El. efficiency [%]</td>
<td>22.6</td>
<td>90</td>
<td>64.8</td>
</tr>
<tr>
<td>El. operation [h]</td>
<td>1.2</td>
<td>7.2</td>
<td>6</td>
</tr>
<tr>
<td>H2 produced [l/min]</td>
<td>5.1</td>
<td>17.3</td>
<td>14.8</td>
</tr>
<tr>
<td>Bat. power [W]</td>
<td>-1216</td>
<td>6383</td>
<td>683</td>
</tr>
<tr>
<td>Bat. SOC [%]</td>
<td>16.5</td>
<td>98.9</td>
<td>61</td>
</tr>
<tr>
<td>Bat. DOD [%]</td>
<td>8</td>
<td>52.4</td>
<td>27</td>
</tr>
</tbody>
</table>
5. Conclusions

An efficient energy power management strategy has been developed and implemented in an autonomous small-scale solar hydrogen production experimental unit. The proposed EMS is based on a finite-state machine in conjunction with propositional-based reasoning, leading to an adaptive and flexible structure that can accommodate complex energy conversion systems. The main advantage of this methodology is that the application domain is defined by the nature of the system and it can be adjusted based on the operating requirements. In that context all the feasible states that represent the logic behind the operation of any device or subsystem can be included considering the numerous connection alternatives. An optimization step allows the suitable selection of the key EMS parameters that would ensure a highly performance operation. Furthermore, an excellent synergy among the various heterogeneous subsystems has been achieved by the proposed EMS resulting to an efficient hydrogen production regardless of the varying weather conditions. The tangible benefits that resulted from the implementation of an optimization approach, instead of using a heuristic one, were the achievement of the goals as defined by the objective function. Experimental results clearly prove the good overall performance of the EMS as indicated by the full utilization of the available PV power without compromising the reliability and integrity of the unit.

Acknowledgment

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References