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Role of energy management in hybrid renewable energy systems: case study-based analysis considering varying seasonal conditions

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Abstract: The recent popularity of alternative energy technologies is mainly promoted by the increasing awareness of environmental concerns as well as the economic impacts of the depleting fossil fuel reserves. Among several alternative technologies, wind- and solar-based energy have been given specific importance with government-based support for providing a cost-effective structure to realize better penetration of such environmentally friendly sources in the energy market. Even these sources are advantageous over the conventional means of energy production from many aspects, a main drawback being the total dependence on the meteorological conditions (wind speed, solar radiation, temperature, etc.) of the wind and solar systems, as they are not fully reliable to satisfy a particular load demand variation at each instant. Thus, some form of backup is always required that will shift the use of the energy from the moments of renewable-based nondispatchable production to the load demand-based dispatchable production. In this study, to ensure the supply of the load in all of the cases, an electrolyzer-fuel cell-based 'hydrogen regenerative' system is applied as main backup, together with a small-sized battery group to pick up transients. Thus, a hybrid structure including wind, solar, and hydrogen energy technologies is provided. The artificial neural network controller approach is selected for the hybrid system's energy management and its performance is examined and evaluated during different case studies that reflect the variations of the meteorological conditions in different seasons. It is aimed with this study to provide constructive suggestions to upcoming researchers interested in the energy management issue in hybrid systems.

Key words: Renewable energy, neural networks, hydrogen energy, solar energy, wind energy

1. Introduction

The options of energy production are increasing as the research studies conducted on finding different alternative energy sources have been recently rapidly growing in number. However, here, the main question is why does humankind need to find alternatives to widely used mature conventional fossil fuel-based energy production? The basis to find an answer to this main question lies in environmental and economic concerns. The most significant concern is related to the adverse environmental effects of the conventional means of energy production. Processing fossil fuels, such as oil, coal, and natural gas, to produce different kinds of energy provides a variety of harmful gas emissions, like CO and CO_2 (which are also known as greenhouse gas emissions briefly). These emissions may accordingly cause irrevocable results like global warming, which is significantly important for the continuity of humankind [1]. Moreover, the cost of fossil fuel utilization, especially oil, has the potential to significantly affect the economies of several countries, as the reserves of these sources are finite, depleting, and under the control of a few countries [2]. Thus, this issue provides the fact that many countries are energy

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dependent on the countries owning the reserves of the mentioned conventional sources of energy. According to these brief explanations, we can find a simple answer to our question: humankind needs alternative sources of energy production so as to save the environment and future, obtain energy independence, and prevent the effects of the economic shock of the fossil fuel cost variation.

There are several alternative ways of energy production that have found different kinds of application areas. Renewable sources like wind and solar energy have become prominent in this regard among the different alternatives due to the huge energy potential of wind and solar power, suitable structure to meet local demands independently, and the policies that governments have declared that promote the widespread penetration of these sources in terms of the economy [3]. Moreover, the expected future decrease in the cost of wind turbines (WT) and photovoltaic (PV) panels to turn, respectively, the wind and solar energy into electric energy will rapidly increase the growth of this new energy production market. However, the main disadvantage of these technologies is the direct relation of their electric power production with the meteorological conditions like wind speed, solar radiation, and temperature. These conditions may change from season to season, and even from one moment to another, providing the need to balance the load demand variation and variable renewable power production [4]. This issue can be overcome by employing some form of backup unit that can provide deficit power when the renewable sources are not sufficient to meet the load demands and accept and store excess power production when the renewable power production is greater than the load power [5]. This integration of renewable sources with backup units provides a hybrid system to ensure the supply of the load in all of the possible conditions.

This study proposes a backup unit based on hydrogen energy utilization, composed of a combination of an electrolyzer and a fuel cell (FC) system. The word 'regenerative' is used for these hydrogen systems due to the fact that the produced hydrogen via an electrolyzer system during excess power conditions (the charging process) can then be reused by the FC system during insufficient power production periods (the discharging process). Interest in the use of such a regenerative hydrogen system has recently increased in the literature and several authors have presented papers related to this issue from different points of view [4–9]. Moreover, as FC systems have slow operating dynamics caused by the natural response characteristics of the FC systems together with bulky necessary auxiliary units, a relatively small-sized battery bank is also inserted in the hybrid structure to compensate for the mentioned slow dynamics of the FC. Thus a wind, solar, and hydrogen hybrid system together with an electrochemical battery utilization is proposed in this study.

The supply of the load demand from more than one source in such hybrid structures provides the need of efficient power sharing between the available power sources, considering their natural dynamic characteristics for power production. WT and PV systems in this study are nondispatchable sources, where their power production is uncontrollable due to their direct relation with the meteorological conditions. Thus, the power production of dispatchable systems such as a FC, electrolyzer, and battery should be managed with a supervisory energy flow management strategy. This paper proposes an artificial neural network controller (ANNC) to be utilized in this regard due to the proved prosperity of the artificial neural network (ANN) approach for the control of complex systems like the proposed hybrid structure in this study. The ANNC performance in the proposed hybrid system operation is examined and evaluated with different case studies, including summer, winter, autumn, and spring conditions.

This paper is organized as follows. Section 2 describes the infrastructure of the simulation studies, including the hybrid system component models and energy flow management strategy details. Section 3 presents the obtained simulation results, and the overall study is concluded in Section 4.

2. Infrastructure for simulation studies

2.1. Modeling of the hybrid system components

The simulation models of the hybrid system components shown in the power flow diagram (Figure 1), including a WT, a PV system, a regenerative hydrogen energy unit composed of a proton exchange membrane FC system combined with an electrolyzer unit, and a separate battery system, are employed in a MATLAB/Simulink environment based on the explanations given below. It is to be noted that as the main objective is not the modeling details of the hybrid system components, only the fundamental equations are presented below and the readers are referred to the related literature studies for further details.

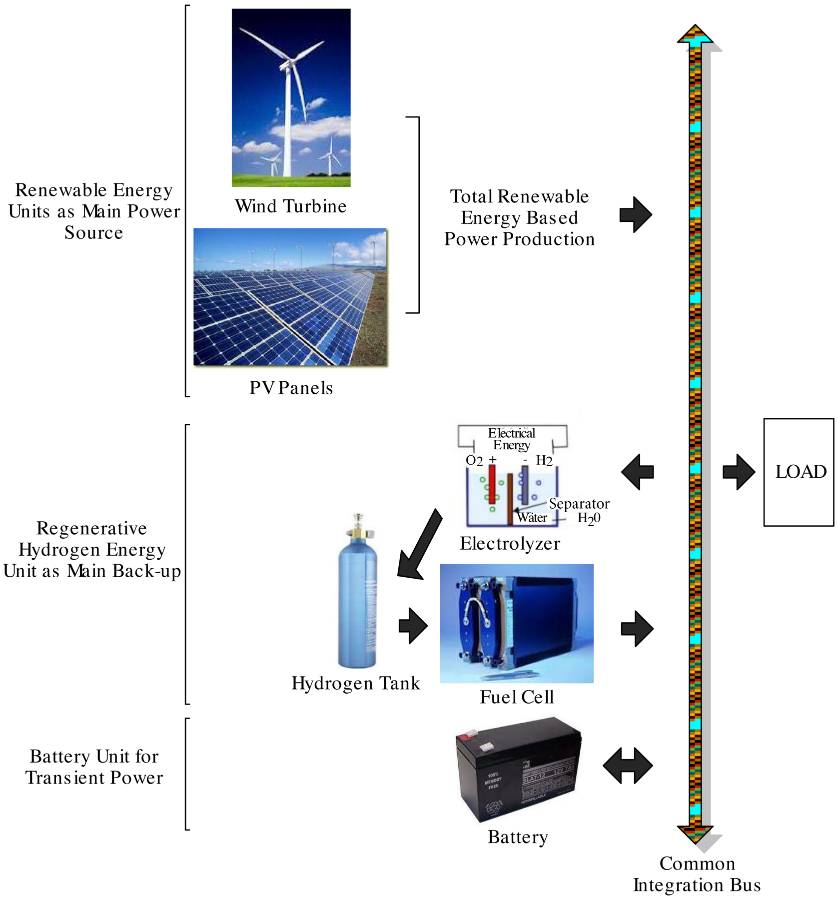


Figure 1. Power flow diagram of the hybrid system.

The WT system dynamics are considered utilizing the electrical output characteristics of a 50 kW WT [10]. Moreover, a PV model is developed based on the I-V characteristics given by:

$$I_{PV} = I_L - I_0[\exp(\frac{V_{PV} + I_{PV}R_S}{\alpha}) - 1], \tag{1}$$

where I_{PV} is the PV output current (A), I_L is the light current (A), I_0 is the saturation current (A), V_{PV} is the PV output voltage (V), R_s is the PV equivalent series resistance (Ω), and α is the thermal constant of the PV system. The details of the mentioned PV model together with the consideration of the thermal effects on the PV electrical performance can be found in [6].

As the main backup of the proposed hybrid structure, the output voltage of the FC can briefly be expressed as:

$$V_{FC} = E_{Nernst} - V_{act} - V_{conc} - V_{ohmic}, \tag{2}$$

where V_{FC} stands for the FC output voltage, E_{Nernst} is the Nernst instantaneous voltage (V), V_{act} is the activation overvoltage, V_{conc} is the concentration overvoltage, and V_{ohmic} is the ohmic overvoltage. For subdetails of the mentioned FC model, the readers are referred to [11]. Furthermore, it is to be noted that the simple electrolyzer model given in [12] is utilized in the FC-electrolyzer combination. Within the mentioned hydrogen system combination, the possible excess production of the PV and WT systems are utilized by the electrolyzer system to produce hydrogen that will be necessary to operate the FC system during high power demand periods. This hydrogen production and the utilization periods can be examined by the proposed models, together with the important I-V dynamics of the FC system.

The last hybrid system component, the battery unit, is modeled considering the cases of charge and discharge, separately. For the discharge, the output voltage of the battery can be calculated as [13]:

$$V_{bat} = E_b - I_{bat} R_{dch}. \left[1 - \exp\left(-\frac{t}{R_{dch}.C_{ov}}\right)\right], \tag{3}$$

where V_{bat} is the battery voltage (V), E_b is the battery open circuit voltage (V), I_{bat} is the battery current (A), R_{dch} is the discharge resistance, t is a sampling time related to the battery dynamics (min), and C_{ov} is the battery polarization capacity (F). Moreover, in charge conditions, the battery voltage is considered to vary with respect to Eq. (4) [13]:

$$V_{bat} = E_b + I_{bat} R_{ch}. \left[1 - \exp\left(-\frac{t}{R_{ch}.C_{ov}}\right)\right]. \tag{4}$$

Here, as an important parameter of the battery unit that will be mentioned again in the following parts of the study, the state of charge (SOC) of the battery system is dynamically calculated by the following equation in each step of the simulation [4]:

$$\%SOC = \%SOC_0 - \left(\frac{1}{C_n}\int I_{bat} dt\right) \times 100, \tag{5}$$

where $\%SOC$ stands for the instantaneous SOC of the battery (%), $\%SOC_0$ is the initial SOC of the battery (%), and C_n is the battery capacity (Ah). These briefly presented models of the system components are then combined and an overall hybrid system model is obtained for conducting simulation-based test studies.

2.2. Energy flow management

The load demand and renewable-based power production varies subject to the operating and environmental conditions as mentioned before. Thus, an energy management strategy that dynamically regulates the energy flow in such a hybrid system is quite necessary to integrate the efficient supply of the load variations in all cases. In this regard, a remarkable number of studies in the literature are dedicated to the efficient energy management of hybrid power systems, including several alternative techniques such as intelligent approaches (ANN, fuzzy logic), optimal control approaches [14], model-based predictive controllers [15], and nonlinear flatness-based control methods [16]. In this study, the ANN approach is chosen due to the effective performance of the ANN method for the control of complex systems [17]. The ANN method is based on the modeling of the human information processing capability that develops itself from learning the example behaviors in different conditions in order to provide a more effective response in case of facing a similar condition. This learning process of the ANN is called 'training'. With the aid of the learned behaviors after the 'training' procedure, the ANN can also provide sufficient responses to new conditions that have not been faced before [18,19]. These facilities of the ANN lead to effective solutions for complex problems, and thus provide an effective way of controlling complex systems, including dynamic variations of the system parameters like the proposed hybrid structure in this study.

In this paper, a feed-forward back propagation type of ANNC architecture is utilized for the hybrid system control. Two hidden layers are employed in the ANNC training procedure. The commercial tool of MATLAB for the ANN approach is utilized for the mentioned training action. Possible foreseen values of the ANNC inputs and outputs are given as the initial training data and the ANNC provides a regression for the input and the values that have not been initially defined using the given training set. The trained ANNC employed in the system provides the maintaining of the battery SOC, together with the power share of hybrid system components during the supply of load. The SOC level is considered to be sustained at the level of 70%, as utilized in some literature studies [11,20]. The power deviations from the load demand that define the extra power requirement and excess power production periods are evaluated by:

$$P = P_{RES} - P_{LOAD}, \tag{6}$$

where P is the power excess or requirement, P_{RES} is the total power supply by the renewable energy sources (WT and PV), and P_{LOAD} is the load demand. Thus, the ANNC provides 2 different types of control actions: excess power control and extra power requirement control, according to the instantaneous values of the inputs and outputs seen in Figure 2.

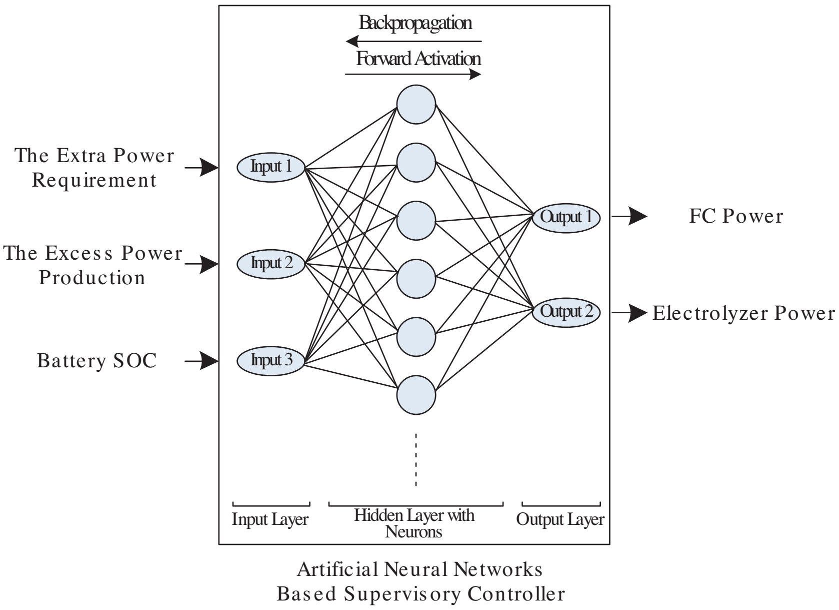


Figure 2. The block diagram of the ANNC based energy management strategy.

The first operating condition is the power share among the sources during excess power conditions. In this condition, the total power production of the nondispatchable PV and WT systems is above the net load demand. Thus, this excess power should be sent to the available energy storage systems (electrolyzer and battery units in this study) for future use during the extra power requirement periods. As more than one energy storage system is available in the proposed hybrid structure, the mentioned excess power should be shared among these systems. For this power share, the ANNC observes the value of the battery SOC in each step. During the moments that the battery system has a SOC value of around or above 70%, all of the excess power is sent to the electrolyzer system for the hydrogen production that can further be utilized by the FC unit. Moreover, during the periods when the SOC of the battery is lower than desired, the ANNC shares the excess power between the electrolyzer and the battery, taking into consideration how low the SOC value is. As an example, if there is an excess power of 10 kW and the SOC is 70%, then the entire excess power of 10 kW is sent to the electrolyzer. However, if the SOC is 65% during the same excess power value, a power value of 5 kW can be sent to the electrolyzer. Moreover, during a value of 60% battery SOC at the same excess power condition, the electrolyzer power can be decreased to 2.5 kW to more rapidly sustain the battery SOC around the desired value. This numeric example may be used to show the mentality of the ANNC during excess power conditions.

The second operating condition of the hybrid system provides the necessity of the power share during extra power requirement periods. Contrary to the above mentioned excess power condition, the total power production of the renewable sources is below the load demand level in this situation, which provides the need for an extra power supply from other sources in the hybrid system (FC and battery in this study). This extra power requirement is shared between the FC and the battery by the ANNC. If the SOC level of the battery is around 70%, the extra power requirement is supplied by the FC unit, utilizing the before produced hydrogen during the excess power conditions. As the battery SOC is aimed to be sustained, the FC system transmits more power than the extra power requirement of the load during the case where the battery SOC is lower than 70%. Surely, the lower the SOC value is, the greater the FC power becomes in the mentioned period. On the other hand, the FC power is decreased and the battery is discharged to supply the load requirements during the condition where the battery SOC is greater than 70%. Thus, the hydrogen consumption can be reduced and the depletion of the available hydrogen can be prevented. It is to be noted that the FC power output is zero while there is excess energy and, accordingly, a value of power to be sent to the electrolyzer and vice versa. Thus, there is a period where the ANNC simultaneously gives output values apart from zero for the FC and electrolyzer reference power. To conclude, the efficient power share between the dispatchable sources in the hybrid system can be ensured by considering the dynamics of the load and nondispatchable sources by the proposed methodology.

3. Obtained results of simulation

During the simulation-based test studies, the behavior of the proposed system under different case studies including autumn, winter, spring, and summer conditions is examined and evaluated. In the simulation of the hybrid system, parts of a real-time measured minute-scale meteorological data are utilized. Moreover, the minute-scale real-time measured load profile demonstrated in Figure 3 is applied in the simulation studies.

The load demand and meteorological conditions are also employed for the hybrid system component sizing. The 50 kW WT is considered to be already available in the construction area. The other hybrid system components are sized considering this power rating and the capacity factors of the renewable energy sources, as well as the minimum and maximum values of load demand. The approach of sizing such a system considering the capacity factors of the renewable energy sources is given in [4]. Thus, the 69 kW PV, 60 kW FC, and 50 kW electrolyzer systems have been employed in the hybrid system structure. The battery unit size is also determined considering the rapid fluctuations of the load demand and meteorological data that cause the changing power production of the renewable sources. Regarding to this information, the model parameters for the PV system and FC-electrolyzer units utilized in the test process are, respectively, shown in Tables 1 and 2. It is to be noted

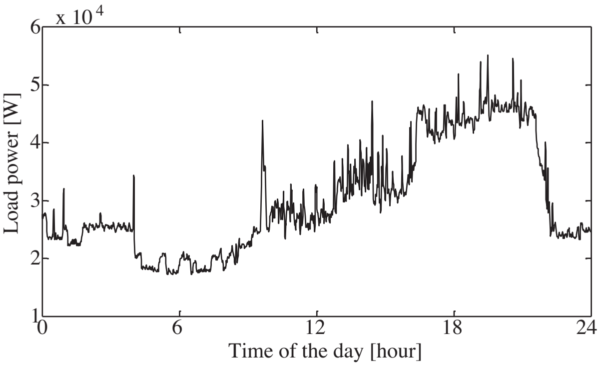


Figure 3. The load demand variation.

Table 1. PV model parameters.

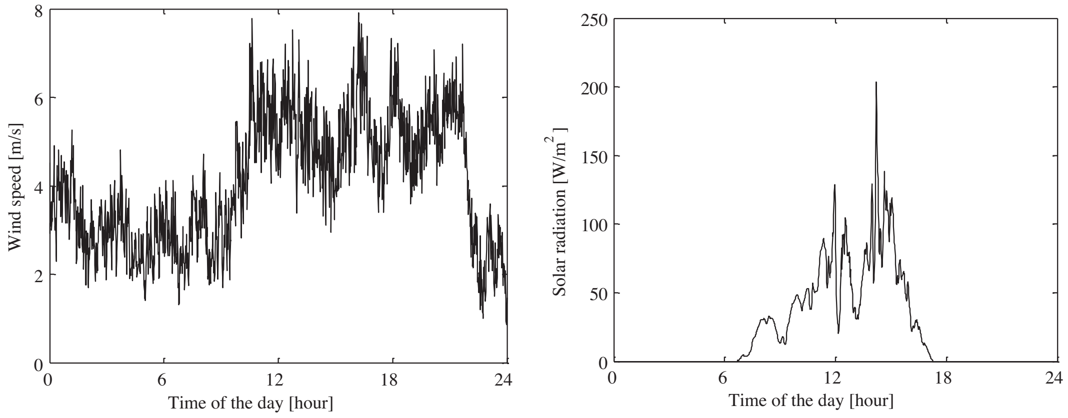
A	1.5 (m^2)
C_{PV}	5×10^4 (J/cm^2)
e_{gap}	1.17 (eV)
$I_{L,ref}$ ($I_{sc,ref}$)	2.664 (A)
k_{cmppt}	0.9245
$k_{in,PV}$	0.9
k_{loss}	30 ($W/(cm^2)$)
N_s	153
N_p	411
R_s	1.324 (Ω)
q	$1.60217733 \times 10^{-19}$ (C)
$T_{C,ref}$	25 (°C)
$U_{OC,ref}$	87.72 (V)
$U_{mp,ref}$	70.731 (V)
$I_{mp,ref}$	2.448 (A)
Φ_{ref}	1000 (W/m^2)
α_{ref}	5.472

Table 2. FC and electrolyzer model parameters.

A	150 (cm^2/cell)
B	0.016 (V)
C	2.5 (F)
F	96486.7 (C/kmol)
J_{maks}	1.5 (A/cm^2)
N_s	176
N_p	6
R_c	2×10^{-4} ()
$T_0, T_{rt}, T_{ic}, T_{it}$	28, 20, 0.7, 4000
U	0.8
$\zeta_1, \zeta_2, \zeta_3, \zeta_4$	-0.9514, 0.00312, 7.4×10^{-5}, -1.87×10^{-4}
n_c	8

that the overall efficiency of such a hybrid system is around 45%–50%, as stated by Abdullah et al. [21] for a similar study considering a PV/Hydro/FC-based hybrid structure.

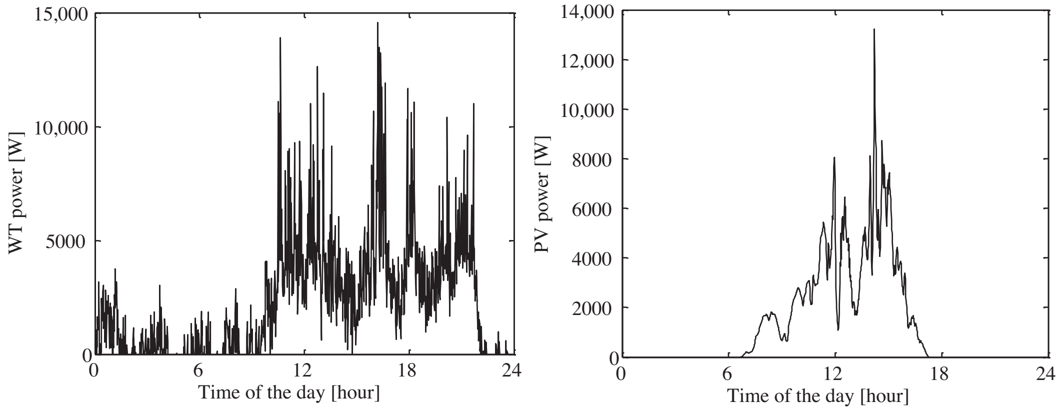
In order to demonstrate and evaluate the performance of the developed methodology, the hybrid system simulation results under different meteorological conditions based on the case studies are given in Figures 4–11.



(a) Wind speed

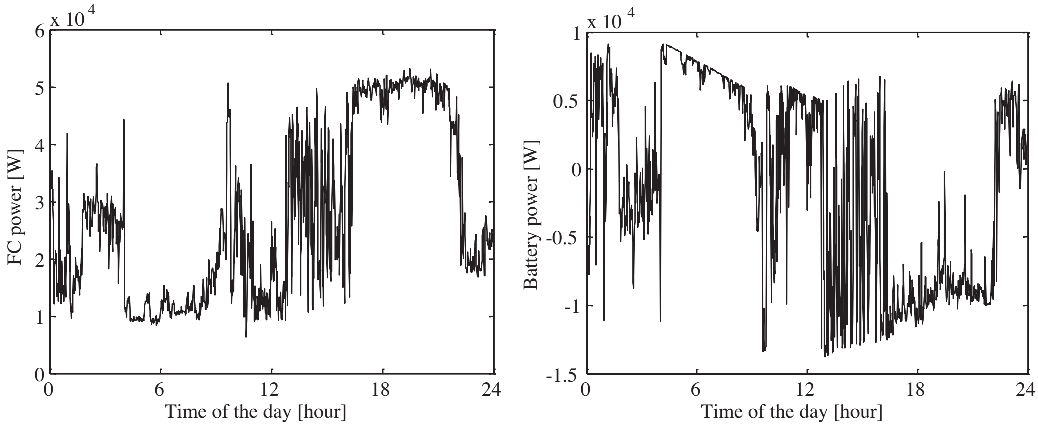
(b) Solar radiation

Figure 4. Recorded weather conditions on 28 October 2009 for the autumn condition test (case study 1).



(a) WT output power

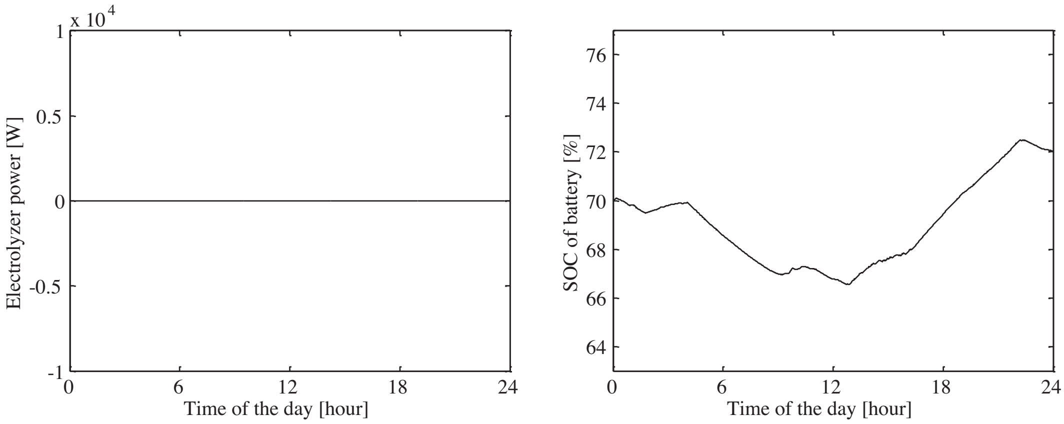
(b) PV system output power



(c) PEMFC system output power

(d) Battery bank output power

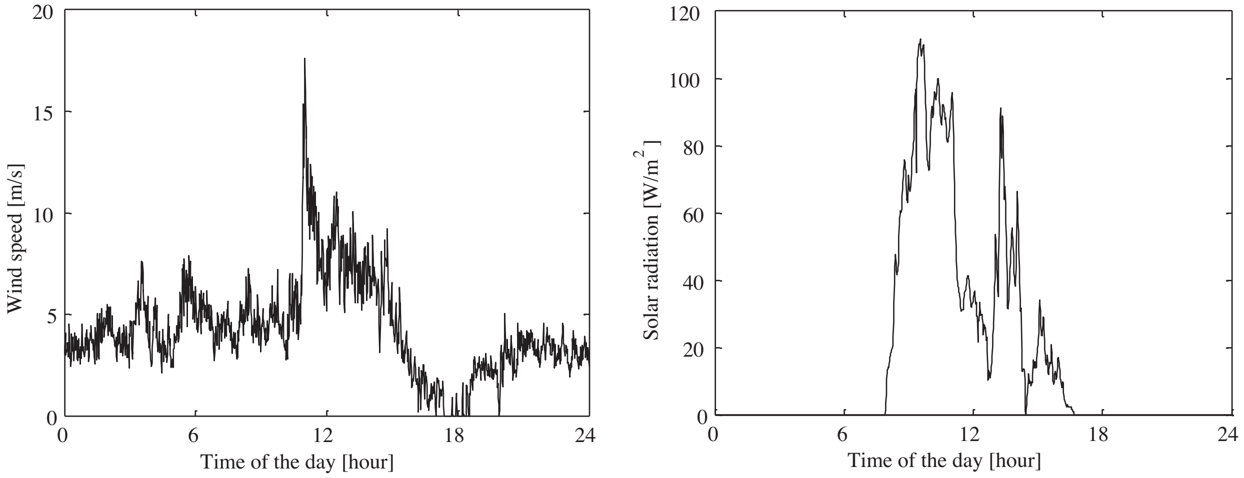
Figure 5. Results of the autumn condition test (case study 1).



(e) Electrolyzer system power

(f) SOC of the battery bank

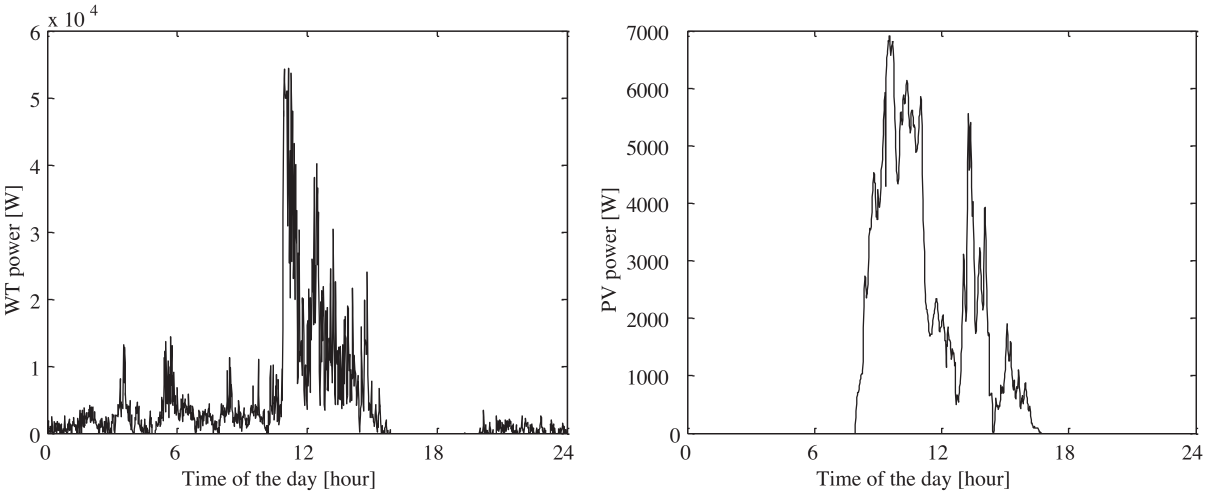
Figure 5. Continued.



(a) Wind speed

(b) Solar radiation

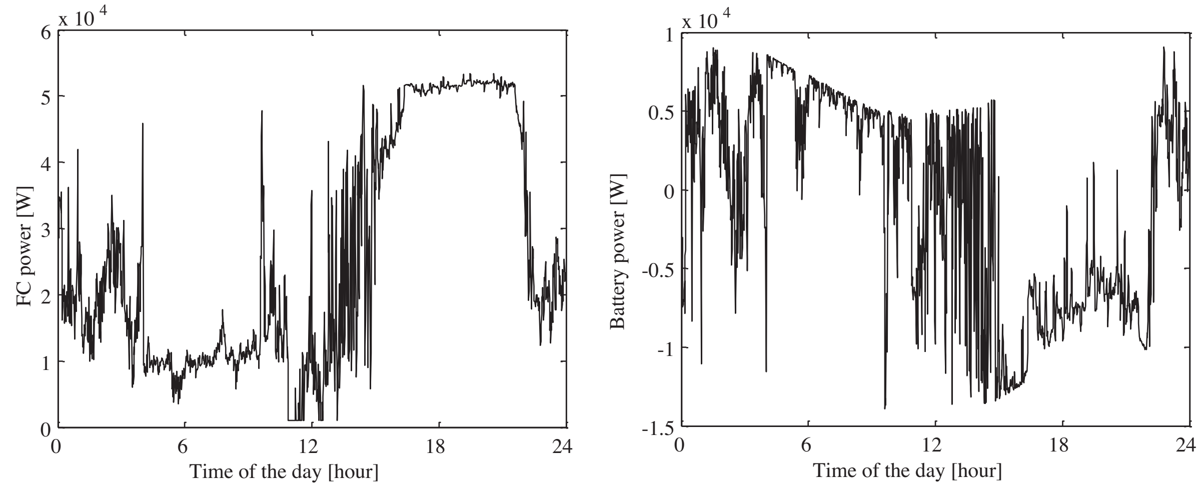
Figure 6. Recorded weather conditions on 28 December 2009 for the winter condition test (case study 2).



(a) WT output power

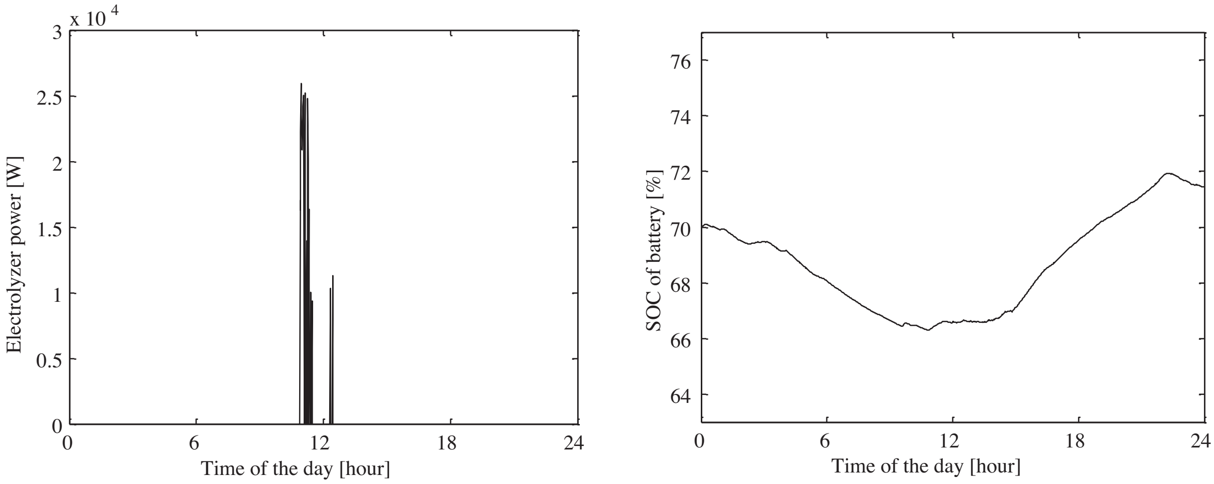
(b) PV system output power

Figure 7. Results of the winter condition test (case study 2).



(c) PEMFC system output power

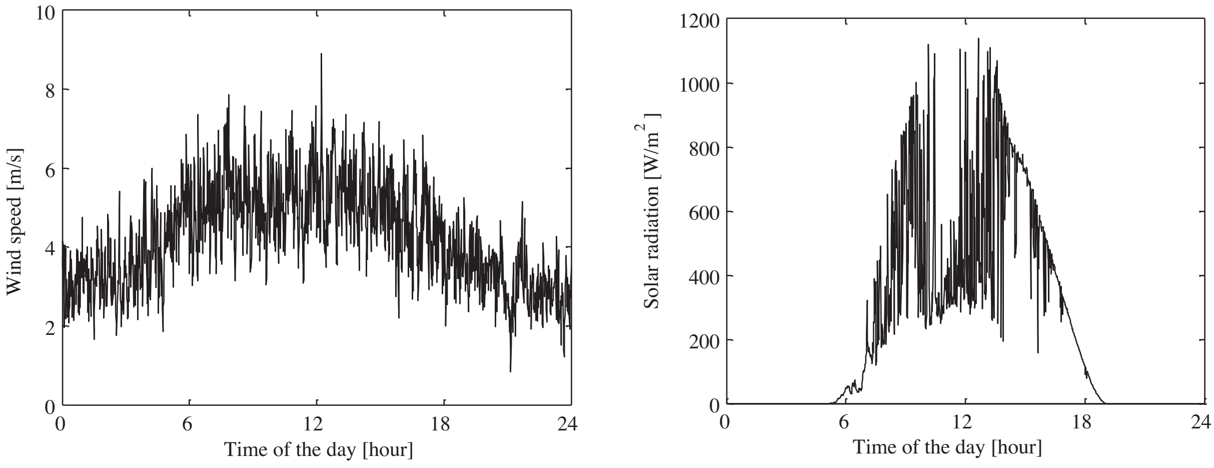
(d) Battery bank output power



(e) Electrolyzer system power

(f) SOC of the battery bank

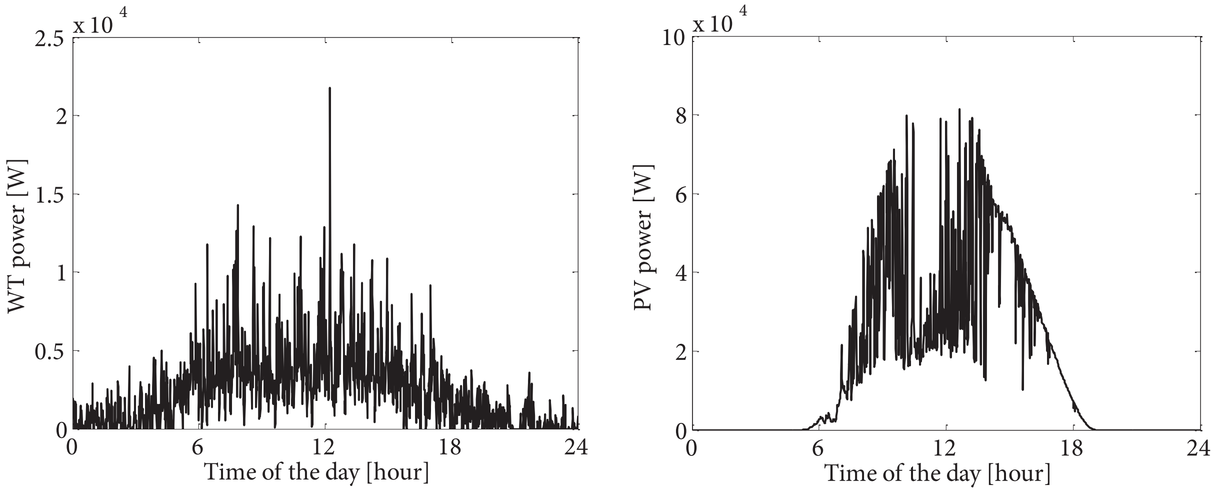
Figure 7. Continued.



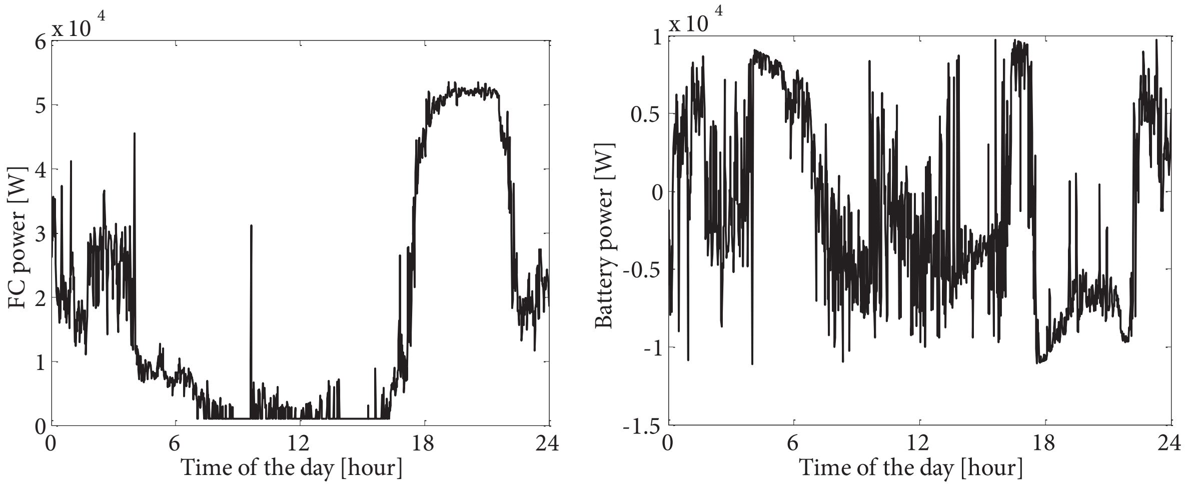
(a) Wind speed

(b) Solar radiation

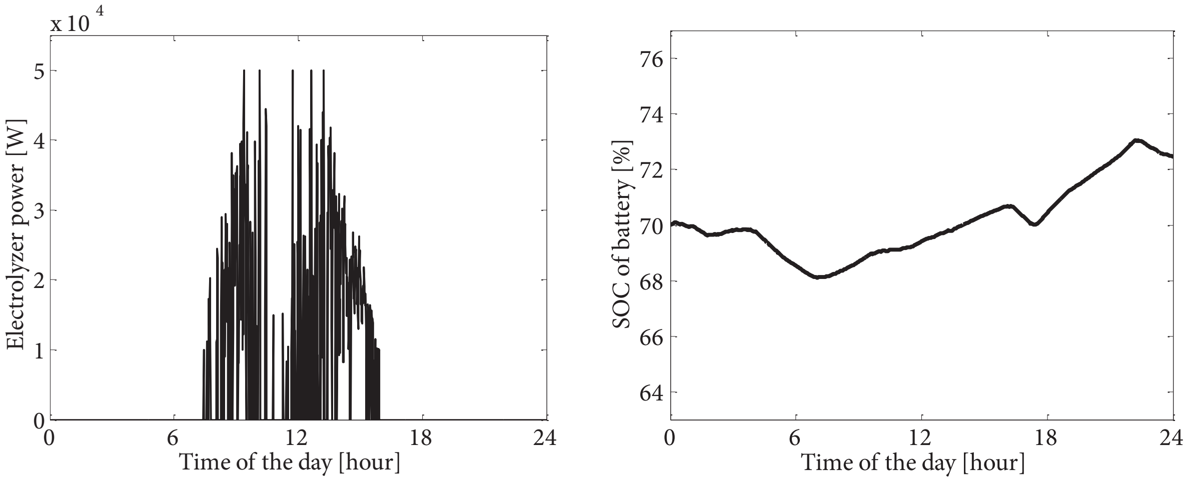
Figure 8. Recorded weather conditions on 28 April 2010 for the spring condition test (case study 3).



(a) WT output power (b) PV system output power

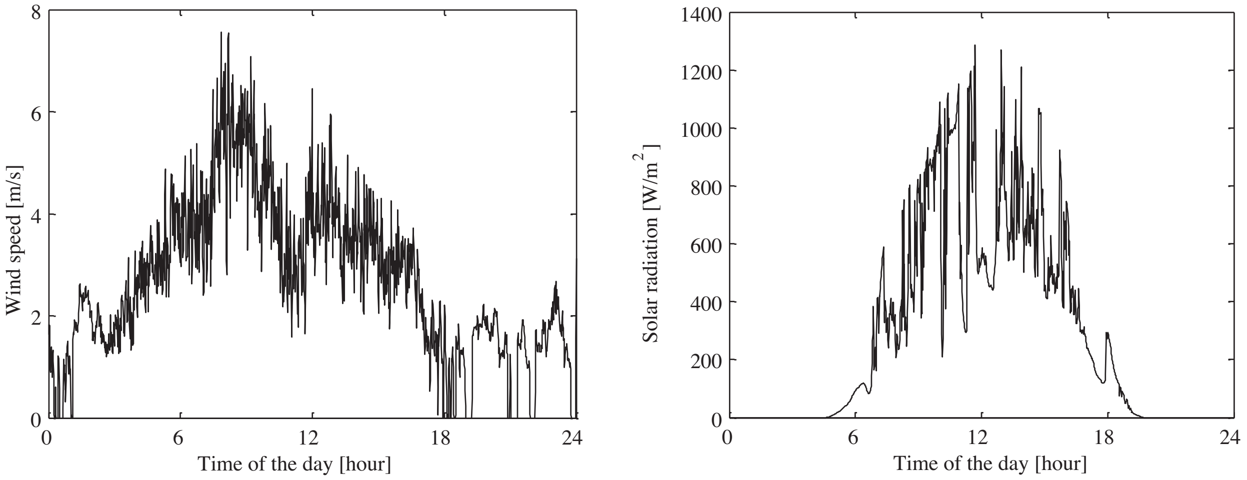


(c) PEMFC system output power (d) Battery bank output power



(e) Electrolyzer system power (f) SOC of the battery bank

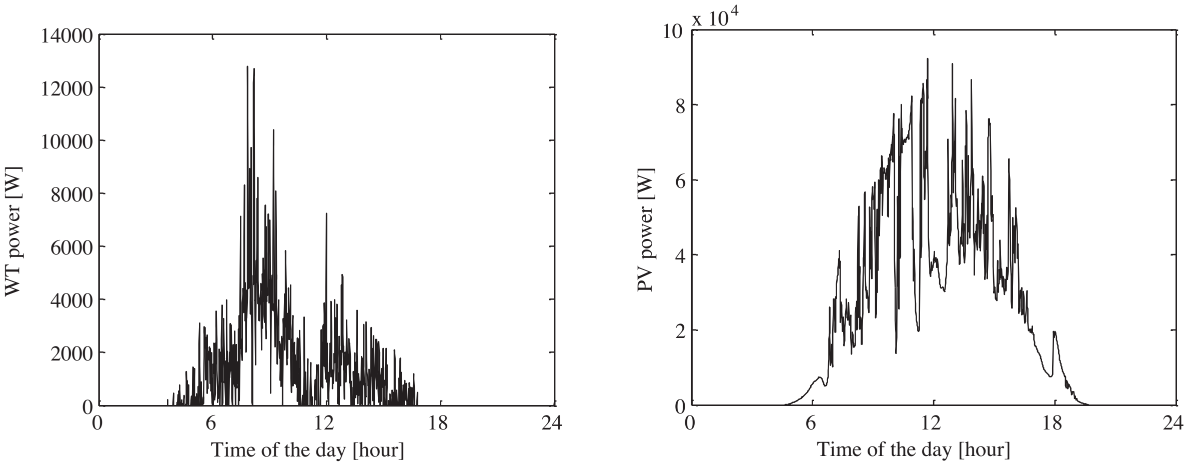
Figure 9. Results of the spring condition test (case study 3).



(a) Wind speed

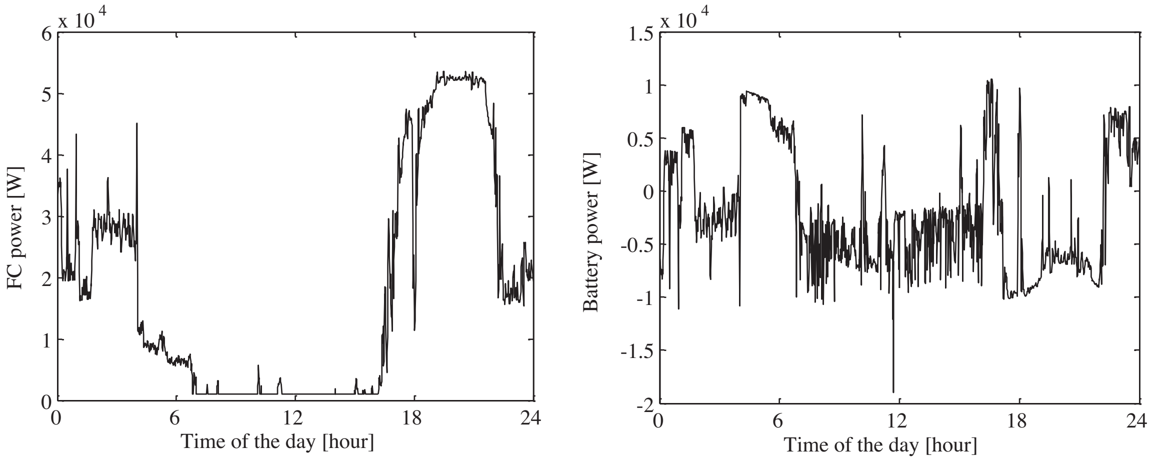
(b) Solar radiation

Figure 10. Recorded weather conditions on 26 June 2010 for the summer condition test (case study 4).



(a) WT output power

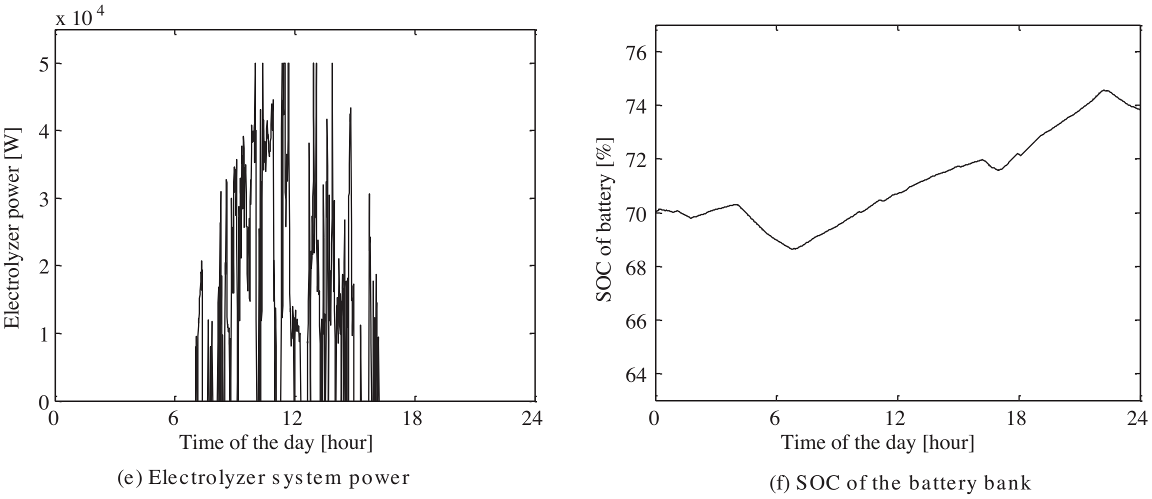
(b) PV system output power



(c) PEMFC system output power

(d) Battery bank output power

Figure 11. Results of the summer condition test (case study 4).



(e) Electrolyzer system power

(f) SOC of the battery bank

Figure 11. Continued.

The autumn conditions are evaluated in case study 1. The meteorological data recorded on 28 October 2009 are presented in Figure 4. As clearly seen, the wind speed varies between 0.85 m/s and 7.96 m/s during different hours of the day, while the solar radiation reaches 207 W/m^2 at peak conditions within the mentioned period. Due to these wind speed and solar radiation data, the WT and PV power productions occur as seen in Figures 5a and 5b. Moreover, the FC system output power determined by the proposed ANNC due to the load demand and the output power of the WT and PV systems is shown in Figure 5c. The FC system generates output power in the insufficient load supply periods due to the low values of the WT and PV power and the battery output power varies as seen in Figure 5d due to the system's power requirements. Moreover, the electrolyzer power is zero within the evaluated period due to the fact that the total PV and WT power does not exceed the load demand at any instant as shown in Figure 5e. Furthermore, Figure 5f shows the SOC variation of the battery bank with respect to the load changes. From Figure 5f, it is clear that the SOC is sustained near the desired value. Thus, the battery bank always has enough charge to successfully supply the load requirements and accept the upcoming excess energy production.

A different case study (case study 2) is realized considering the meteorological data recorded on 28 December 2009, and shown in Figure 6. This day is specifically chosen, as it includes the windiest moment in the winter data of 2009. In this period, the solar radiation is at low levels, reaching a peak of 134 W/m^2. The related PV and WT power variations can be seen in Figure 7a and 7b. As seen, the WT power reaches its maximum power value of 55 kW within this period, while the PV-based power production varies between 0 and 6970 W. Moreover, the FC system provides an output power variation as shown in Figure 7c, while the battery and electrolyzer powers occur as seen in Figure 7d and 7e, respectively. As seen, due to the existence of high level wind speed periods, the electrolyzer power and the related hydrogen production are available when compared to the autumn case. Furthermore, the SOC sustaining capability of the ANNC is shown in Figure 7f, which presents the SOC variation of the battery bank during different hours of the day.

Case study 3 includes the spring condition-based evaluation of the hybrid system performance. During this period, the utilized meteorological data recorded on 28 April 2010 are presented in Figure 8. As clearly seen, the solar radiation is significantly higher compared to the autumn and winter conditions during the mentioned day, while lower values of wind speed occur. The relevant WT and PV power productions are depicted in Figures 9a and 9b, while the FC power output accordingly varies as shown in Figure 9c. Due to the given power profiles presented in Figures 9a and 9c, the battery and electrolyzer power variations are given in Figures 9d and 9e. As clearly seen, the battery bank picks up the transient periods during different hours of the day, preventing the FC from facing the sharpest transients, and accordingly promotes its operating lifetime. This produced hydrogen from the power sent to the electrolyzer unit is available for the future use by the FC system for the load demand supply. Moreover, it can again be seen that the ANNC can prosperously maintain the battery SOC around the desired level at the end of the day, as seen from Figure 9f.

As the last case study, the system performance is investigated during summer conditions in case study 4. The meteorological data recorded on 26 June 2010, which includes the sunniest day within this period, are presented in Figure 10. As presented, the solar radiation reaches the maximum point among all of the days considered in case studies. Moreover, due to the WT and PV power productions shown in Figures 11a and 11b, the FC, battery, and electrolyzer power variations determined by the proposed ANNC are presented in Figures 11c and 11e, respectively. As seen, the battery bank again picks up the transients in the extra energy requirement, while the ANNC shares the available excess energy between the electrolyzer and battery, taking into consideration the instantaneous SOC value of the battery bank. In this regard, it is also to be noted that the SOC of the battery varies close to that of the predefined level, similar to the above given case studies, as shown in Figure 11f, which shows the prosperity of the proposed ANNC-based energy management strategy.

4. Concluding remarks

An ANNC-based energy management approach is considered in the current study to efficiently and effectively operate a wind, solar, and hydrogen energy-based hybrid renewable stand-alone structure. The insufficient power production periods of the renewable sources to meet the load demand and excess power production periods after satisfying all of the load requirements are separately considered in the energy flow regulation process of the ANNC. Different seasonal conditions through a year period are evaluated, which includes the most windy and sunny moments, providing significant excess production and low-wind and radiation moments that present the condition of insufficient production. The load following the ANNC-based approach performs effectively as the simulation results are examined. The given quantitative results prove the applicability of the proposed methodology. A large variation range of renewable energy source-based power production can be suppressed in several load demand conditions together with the regulation of important hybrid system parameters, such as the battery SOC. The proposed approach has a fast response capability compared to optimization-based methods and even the fuzzy logic approach widely used for similar purposes in the literature. The ability of ANN systems to spontaneously learn from examples and to provide adequate and quick responses to new data that are not previously stored in memory has resulted in wider acceptance of this technology in many fields. The widely used fuzzy logic approach does not need a training procedure; however, the rule-based fuzzy structure makes it take longer to respond compared to the ANN approach. Further studies can be conducted focusing on optimizing the specific ANNC parameters, such as weights and biases, employing an optimization algorithm to further enhance the controller performance, to provide the necessary basis for the real-time application of the proposed methodology.

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