Innovative Energy Storage for Off-Grid RES-Based Power Systems: Integration of Flywheels with Hydrogen Utilization in Fuel Cells

G. N. Prodromidis[1] and F. A. Coutelieris[2]

Abstract: This work investigates the feasibility of a renewable energy sources (RES)-based stand-alone power system for electricity supply, to several simulated buildings, where energy is stored in a flywheel energy storage system (FESS). The system is assumed to be located on Naxos Island, Greece, due to the island's high wind and solar potential and was designed to cover both the load of a typical house and a country house, where the excess electricity could be sold to the grid. An innovative storage device type, consisting of flywheels and electrochemical batteries, was selected as the energy buffer. The energy produced by hydrogen used in the proton electrolyte membrane (PEM) fuel cell (FC) charges the flywheel. This apparatus is compared to diesel generators commonly used in stationary applications. Optimization of the system, in terms of energy efficiency and economic feasibility, is also considered. The two systems were simulated using sensitivity, optimization, and simulation modeling software, and custom calculations of both energy and finance were carried out. It was found that a one-way grid connected project using state-of-the-art and totally green technologies, including hydrogen-fed PEM-FC and flywheels, can totally cover the electrical demands of a typical house and country house, obtaining cost per consumed energy as low as 1.374 and 0.097 $/KWh, respectively. These results actually indicate that hydrogen technology could be a reliable energy alternative in the near future. **DOI: 10.1061/(ASCE)EY.1943-7897.0000167.**

Author keywords: Simulation; Hybrid storage system; Flywheel; Hydrogen technologies; Renewables.

Introduction

Renewable energy sources (RES) are characterized by their unpredictable behavior, since their availability is generally driven by local meteorological conditions. Therefore, intermediate energy storage (buffering) is essential for continuous energy supply, especially for off-grid or one-way grid connected systems (Glasnovic and Margeta 2010). Energy storage devices offer to hybrid systems the stability of the supplied DC load characteristics (Niknam et al. 2013; Wang et al. 2008; Bolund et al. 2007). Although nonenvironmental-friendly options, such as diesel generators, are often available (Elmitwally and Rashed 2009), the most common currently commercially available choice is the batteries, even of state-of-the-art technologies such as lead-acid, lithium, nickel-based, and flow batteries (Nair and Garimella 2010). The most advanced technologies of energy storage systems are hydrogen-based energy storage (Stamenic et al. 2012; Posso et al. 2009) and flywheels (Niiyama et al. 2008). These are more advanced than batteries of any type because are not plug-and-play systems. This means that to finalize a project, which incorporates such systems, several safety issues have to be taken into consideration by expert teams on these establishments. Both are at an early commercial stage and are thus characterized by high initial costs for installation in large-scale power systems (Stamenic et al. 2012). This happens because in large-scale power plants the increased desirable load is essential to be supported by more expensive equipment and such an investment might not be as profitable as in a smaller-scale system (Ziogou et al. 2013). In Greece, the majority of the RES-relative projects are based on a one-way grid connection (i.e., the scope is to produce energy through RES and to sell it to the National Power Corp., who is the owner and administrator of the national grid). Usually, they are large-scale (higher than 50 kW) wind parks or solar farms (Doukas et al. 2012). For the majority of cases, these are established by European or US investors/manufacturers because of the extremely high costs needed for such an establishment (Kaldellis et al. 2012). For this reason, a study on small-scale projects that can stand without a grid connection can reinforce small investors to hybrid RES projects in order to be relieved of the national grid, which continuously raises the price per kW for the small-scale and medium-scale consumers.

In the present study, an advanced hybrid energy storage system is proposed and simulated. It is based on flywheels in combination with the mature technology of electrochemical batteries. Flywheel-based energy storage systems are modular devices containing a flywheel stabilized by nearly frictionless magnetic bearings, integrated with a generator motor and housed in a sealed vacuum enclosure (Fig. 1). This advanced combination of two different technologies for the development of a new battery-type storage stack is crucial for two reasons: the successful long-time storage of electric energy and at the same the coverage of an excessive increase of the desirable load whenever it is considered as essential, because of the operational characteristics of the two different combined technologies such as the high discharge rate of flywheels. One of the main advantages of flywheels is their lifetime because they can be charged and discharged at high rates for many cycles without major efficiency losses. The efficiency of flywheels is theoretically 92–96%, decreasing only 2–3% in an established system

[1]Ph.D. Candidate, Dept. of Environmental and Natural Resources Management, Univ. of Patras, Seferi 2, 301 00 Agrinio, Greece. E-mail: gprodrom@cc.uoi.gr

[2]Professor, Dept. of Environmental and Natural Resources Management, Univ. of Patras, Seferi 2, 301 00 Agrinio, Greece (corresponding author). E-mail: fcoutelieris@upatras.gr

Note. This manuscript was submitted on March 11, 2013; approved on October 2, 2013; published online on October 4, 2013. Discussion period open until July 19, 2014; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Energy Engineering***, © ASCE, ISSN 0733-9402/04014006(10)/$25.00.

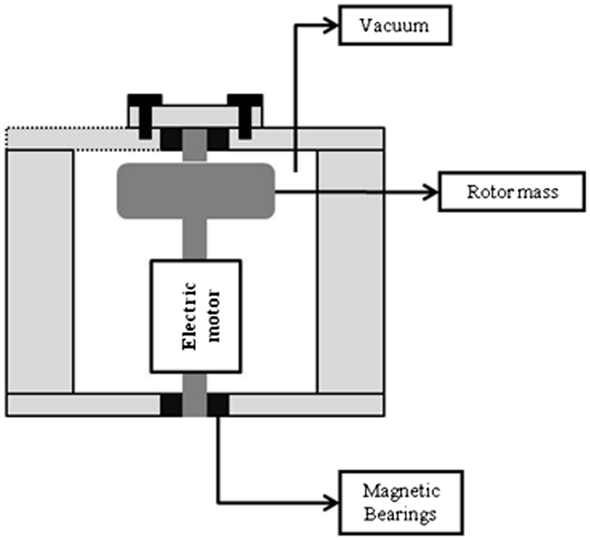

Fig. 1. Schematic diagram of typical flywheel energy storage system

(Liu and Jiang 2007; Ruddell 2002). Moreover, the capacity of a FESS to offer a huge variety of frequencies when connected to an AC-bus underlines its adaptable character and allows DC-coupled or AC-coupled to meet the demand of the established hybrid system (Wang et al. 2008; Bolund et al. 2007). Flywheels are considered as totally green technology because their operation is not supported by chemicals and their raw materials are completely recyclable. However, in most applications this advanced technology is accompanied by diesel generators (Wang et al. 2008; Leclercq et al. 2003; Davies et al. 1988), which are not considered an environmental friendly solution. The innovation in this study is the use of flywheels in combination with hydrogen technology in an autonomous system for continuous operation, as a backup energy system. Currently, flywheels and hydrogen technologies are not commonly used for energy storage because of their estimated high cost, which is directly connected to storage time (200–500$ per kW for 5–30 s and 1,000–3,000 per kW for 1 h); however, flywheels in this range are not commercially available at this time (Ruddell 2002; Leclercq et al. 2003; Davies et al. 1988; US Dept. of Energy 2003).

In this study, special effort has been made for advanced technologies (such as flywheels) to be integrated in everyday systems, thus promoting their further commercialization worldwide. For this simulation, specific loads of a typical house and typical country house (Prodromidis and Coutelieris 2011) were taken into account, while Naxos Island, Greece, was assumed to be the installation location, selected due to its high RES-potential (Prodromidis and Coutelieris 2011). In these hybrid RES-based systems, the excess electricity necessary to charge the flywheel is produced either by a diesel generator or a hydrogen-fed proton electrolyte membrane (PEM) fuel cell (FC). Moreover, in the country house scenario, the excess electricity is sold to the Greek Public Power Corp. through a one-way grid connection at 0.60 \$/kWh, since the desirable load is lower than that of a typical house allowing for a significant excess of produced power, which increases the economic benefit of the project. This extremely high selling tariff arises from the contract being signed between the Greek authorities and the owner of a project up to 10 kW, in accordance with Greek law. This price affects the amount of money spent during the annual operation of a hybrid system. These gains, from the selling, must be eliminated from the annual investment and O&M costs.

The project presented here is analogous to the power plant established at Utsira Island, Norway (Nakken et al. 2006). The system integrated there uses wind power to produce hydrogen, which is utilized in a PEM FC. Batteries along with a flywheel supported by a synchronous motor are used as backup module for the coverage of ten consumers served by the microgrid. Conceptually, the main differences between the Utsira project and the system presented here are focused on the design and the use of the flywheels. In the Utsira project, flywheels are treated independently of batteries to stabilize the local grid rather than to store the excess of energy. It is also important to underline the absence of photovoltaic (PV) panels in the design and integration for the system established at Utsira Island.

The initial motivation is to design and study a battery bank with the stable operation of electrochemical batteries in combination with the high lifetime and the totally environmental friendly character of a flywheel. This combination is considered a new battery-type storage stack because all its parts operate as a portable compact device. In terms of techno-economics, the basic scope of this project is to investigate the feasibility of hydrogen usage in an already established system and to find out the operational differences between the specific loads for a typical house and a country house that must be covered by the same power system. Additional information about the estimation of these loads can be found in related literature (Prodromidis and Coutelieris 2011, 2012). Finally, the core point to be shown by this work is whether a RES-based totally environmental friendly system can be feasible without being supported by a grid connection.

Theory

Technological Aspects

Technological achievements that take advantage of wind and solar energy are generally known: PV panels transform solar radiation into DC load and wind turbines (WT) convert kinetic wind energy to electrical power. The total power produced by a typical PV array is given as (Kolhe et al. 2003; Duffie and Beckman 1980)

$$P_{\text{solar}} = P_{\text{STC}} f_{\text{der}.PV} \left(\frac{\bar{G}_T}{\bar{G}_{\text{STC}}} \right) [1 + \alpha_P (T_C - T_{C,\text{STC}})] \quad (1)$$

where P_{STC} is the output power of the panels in standard test conditions, $f_{\text{der}.PV}$ is the derating factor, $\bar{G}_T$ is the solar radiation incident, $\bar{G}_{\text{STC}}$ is the radiation in standard test conditions ($1{,}000\ \text{W/m}^2$), and α_P is the temperature coefficient of the PV's power. The last brackets in the equation represent the performance of the PV cells, influenced by the temperature, T_C, to which the photovoltaic array is exposed in real-time conditions.

The total power that can be utilized from the blowing wind passing through a specific surface A can be calculated as (Manwell et al. 2002; Lilienthal et al. 2004)

$$P_{\text{wind}} = n 0.5 A^2 \rho_{\text{air}} u^3 \quad (2)$$

where n is the efficiency factor; A is the swept area of the turbine's rotor; ρ_{air} is the air density, assumed constant; and u is the wind velocity. It must be noted, however, that only approximately 30–40% of the total wind power can be transformed to electrical energy at the horizontal axis turbines because of the mechanical losses of the construction (Manwell et al. 2002).

A flywheel is usually charged by spinning its rotor to maximum speed using the electrical power offered by a diesel generator and the grid. In this study, this electrical power is offered by the excess electricity, over the system demands, which is offered by the RES technologies used and discharge occurs by slowing the spinning mass. In accordance, the stored energy in a flywheel can be written as (Farret and Simoes 2006)

$$E = \frac{1}{2} I \omega^2 \tag{3}$$

where ω and I are the angular velocity of the flywheel and the rotor inertia, respectively.

The most efficient way to increase the stored energy is to speed up the flywheel, whose limit is generally set by the tensile strength due to inertial loads and the materials used. This limitation can be partially overcome by the use of composite materials with low density and high tensile strength, which develop inertial loads and store kinetic energy more efficiently. These special composite materials are rare and expensive (Bolund et al. 2007; Ruddell 2002; Kolhe et al. 2003) and thus outside the scope of this study.

Hydrogen is usually produced by electrolysis and is considered a totally *green* fuel as long as the electrical input comes from truly renewable sources as in the present simulated project. In this study, a PEM electrolyzer is supplied excess RES-produced electricity to produce hydrogen from plain water (Clarke et al. 2010). This hydrogen is piped through a compressor into special tanks that withstand high pressures. The hydrogen is then used in the fuel cell system that directly converts the chemical energy of the feeding fuel into electricity without Carnot limitations (Millet et al. 2011). Due to the high conversion efficiencies and the negligible environmental impact, fuel cell technology is considered a promising technology for the generation of electrical power in the near future (Shabani and Andrews 2011). Among several types of available fuel cells, PEM FCs, which are used in the simulated projects of the present work, present high power densities, quick start-up times and load characteristics, while their normal operational temperature is quite low (Hamelin et al. 2001). Moreover, due to the low space limitations usually encountered, no compressor is used here to pressurize hydrogen because the electrical needs of the system would be increased and this would not constitute a promising scenario from every aspect both financially and energetically.

Economic Aspects

The economic analysis of a hybrid stand-alone system, where flywheels are used to store energy in combination with electrochemical batteries, is a very important step for the commercial use of flywheel energy storage systems (FESSs). Moreover, the financial analysis of technologies using hydrogen and their direct comparison with diesel generators for a stand-alone system is essential. Note that the capital cost of a RES-based stand-alone system is quite high, being a critical parameter for the design of such a system. In the present study, the economic analysis is finalized by comparing the net Present cost (NPC) of the systems (including the cost of CO_2 emissions for a system with a generator, in accordance with the Kyoto protocol), the levelized cost of energy, and the annual operating costs. The above cost metrics have to be analytically studied in off-grid RES-based projects because each comprehends different parameters being crucial throughout a completed financial study, revealing the economic feasibility. The different parameters involved in this study are presented in the equations that follow. The NPC represents the total capital spent by the apparent investor at the end of the project's lifetime and is given as (Brealy and Myers 1991)

$$C_{\text{NPC}} = \frac{C_{\text{an.tot}}}{\text{CRF}(i, R_{\text{proj.}})} \tag{4}$$

where $C_{\text{an.tot}}$ is the total annualized costs of the system and $\text{CRF}(i, R_{\text{proj.}})$ is the capital recovery factor, which is obtained by the expression (Brealy and Myers 1991)

$$\text{CRF}(i, R_{\text{proj.}}) = \frac{i(1+i)^{R_{\text{proj.}}}}{(1+i)^{R_{\text{proj.}}} - 1} \tag{5}$$

where $R_{\text{proj.}}$ is the lifetime of the project in years, determined as 25 years in the present study, and i is the real interest rate, given as (Brealy and Myers 1991)

$$i = \frac{i' - \text{AIR}}{1 + \text{AIR}} \tag{6}$$

where AIR is the annual inflation rate and i' is the nominal interest rate. Note that the total annualized cost of a system is the sum of total replacement, operating and maintenance costs as well as the salvage value of each component. The replacement costs differ for each component.

The levelized cost of energy is calculated by

$$\text{COE} = \frac{C_{\text{an.tot}}}{L_{\text{primAC}} + L_{\text{grid,sales}}} \tag{7}$$

where L_{primAC} is the primary AC load of the system and $L_{\text{grid,sales}}$ is the energy (kWh) that is sold back to grid.

Moreover, the total NPC of a system with a diesel generator is given by

$$C_{\text{TNPC}} = C_{\text{NPC}} + C_{\text{emissions}} \tag{8}$$

where $C_{\text{emissions}}$ is the total cost of the CO_2 emissions in the project's lifetime, given as (Prodromidis and Coutelieris 2011)

$$C_{\text{emissions}} = \text{Emissions} C_{\text{perton}} \tag{9}$$

where Emissions are the pollutant species from the diesel generator (in tons) and C_{perton} is the cost of emissions per ton.

Simulations

The aforementioned integrated mathematical model requires the successful selection of different variables to obtain feasible results. The crucial parameters for the financial aspects of the present project are the lifetime of the specific power plant $R_{\text{proj.}} = 25$ years, the nominal interest rate, $i' = 4\%$, the annual inflation rate, $\text{A.I.R} = 1.6\%$, which is the average price according to European Statistical Economical Data (European Union 2012), and the cost of emitted CO_2 per ton, $C_{\text{perton}} = 46.5\$$. The latter is given by the Kyoto protocol. After studying the local meteorological data to identify the most appropriate RES as elsewhere presented (Prodromidis and Coutelieris 2011), the 12V DC system was designed to satisfy the requirement of efficiency maximization. During the system design stage, a hybrid photovoltaic-wind system was selected to cover the desirable load. The next step was the development of a new storage system, equivalent to a battery-type storage unit but including flywheels (Prodromidis and Coutelieris 2012). The *HOMER* software (HOMER Energy Team 2013) incorporated the flywheels in the form of load, which must be covered in every time step of simulation, without giving the option to use them as energy storage devices for the excess electricity in a system. This hybrid storage system is a combination of a flywheel, a DC-DC converter, and an electrochemical battery [Hoppecke 3,000 Ah (Hoppecke Power from Innovation, Germany)]. The specific type of electrochemical battery presents a round-trip efficiency of approximately 80% and was ultimately chosen because it offers great

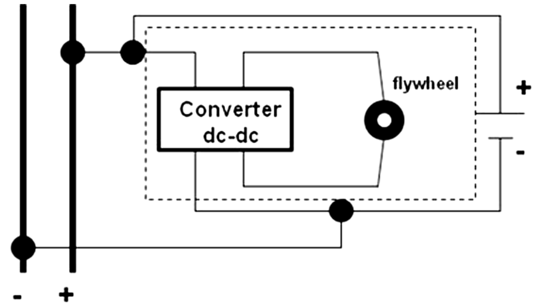

Fig. 2. Innovative storage system

capacity at an affordable price and can be combined effectively with flywheels (Prodromidis and Coutelieris 2012). A 10-kW high-voltage flywheel was used in this scenario. The hybrid energy storage system's main characteristics are the round-trip efficiency (75.2%) and the maximum charge rate (3.926 A/Ah), which is higher than the most powerful commercial battery (Prodromidis and Coutelieris 2012; Perrin et al. 2006). The flywheel is permanently connected to a DC-DC converter for voltage regulation

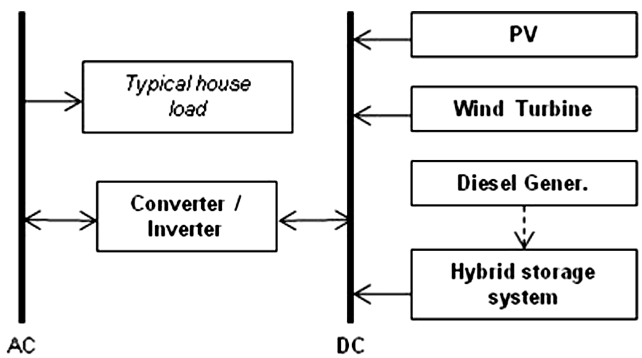

Fig. 3. Components of hybrid system with diesel generator

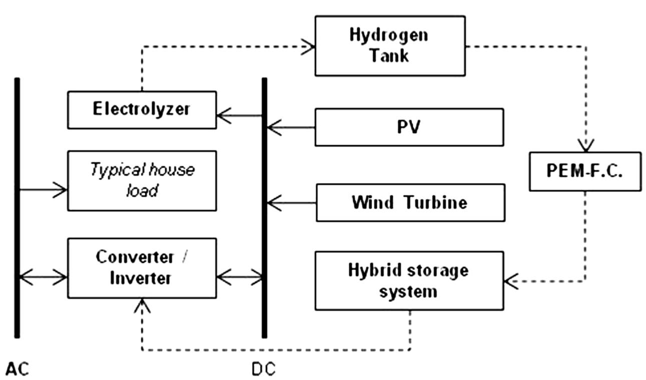

Fig. 4. Components of hybrid system with hydrogen technology

purposes between the devices (being necessary due to the DC current and parallel connection chosen), as shown in Fig. 2. To compare with Nakken et al. (2006), the aforementioned hybrid backup system is the main difference to that of Utsira; in the Norwegian power plant flywheels are not connected with the batteries to operate as one compact hybrid storage system. What they actually have done is to use the flywheel/asynchronous machine system independently as a grid stabilizer rather than as an energy storage system. Furthermore, solar energy is not used in Utsira power plant; thus, a direct comparison between these projects underlines the difference of the selected approaches.

Integration of the completed simulated systems was finalized through the electromechanical layouts as presented in Figs. 3 and 4. The figures present hybrid RES-based systems capable of covering the load of a typical house and a typical country house using solar and wind energy sources. However, they present some differences concerning the energy storage and grid connection, as shown in Table 1. Scenario a2 uses a one-way grid connection only for selling the excess electricity and not for covering the load as a back-up energy source. The hybrid battery bank is charged by a diesel internal combustion engine (Fig. 3), which could be replaced by a fully equipped system that uses hydrogen to charge the hybrid storage system (Fig. 4).

To construct the most environmentally friendly system, an internal combustion engine (ICE) was directly compared to hydrogen technologies for charging the hybrid battery bank (Direct Industry 2013). This consideration allows better management of the otherwise wasted excess electricity. It is important to note that the direct supply of electricity from the fuel cell has not been avoided here due to the significantly increased initial costs of a high-power PEM-FC (Barbir 2005) because the operational and maintenance costs of such a project based on hydrogen can fluctuate on a low level. In the present paper, this will be analytically examined through the simulation of different scenarios.

Besides the use of different technologies for the coverage of the hybrid storage system, the main difference between the ICE and the hydrogen systems as presented herein is that the hybrid storage system of the second case (flywheel with Hoppecke battery, Fig. 4) is not directly connected to a DC-bus, but to an inverter that provides the load to the typical house. This is crucial to allow direct comparison of the ICE and hydrogen system, because the electrolyzer load should be covered exclusively by the RES technologies. Thus, the load from the hybrid battery bank can be used only for the needs of the typical house and not for the electrolyzer.

All of the systems considered were assumed to utilize solar and wind energy simultaneously while the desirable load for the charge of the hybrid storage system is covered either by a hydrogen-fed fuel cell or a diesel generator, for the sake of comparison. Actually, the FESS technology incorporated here consists of a rotor suspended by bearings inside a vacuum chamber to reduce friction, connected to an electric motor that has the capability to operate as a generator whenever it is appropriate (Bolund et al. 2007). Specifications of the simulated devices are presented in Table 2. The devices used here, with the exception of the hydrogen-related equipment, are as in previously presented works for Naxos Island

Table 1. Presentation of Different Scenarios

Scenarios	Load (kWh/year)	Description
a1	7,775 (typical house)	PV, wind, electrolyzer, hydrogen tank, PEM FC, hybrid storage system, one-way grid connection
a2	2,980 (typical country house)	PV, wind, electrolyzer, hydrogen tank, PEM FC, hybrid storage system, one-way grid connection
b1	7,775 (typical house)	PV, wind, diesel generator, hybrid storage system
b2	2,980 (typical country house)	PV, wind, diesel generator, hybrid storage system

Table 2. Specifications of Devices Used

Devices	Capacity	Capital costs	Lifetime	Reference
Diesel generator	1 kW	200 $	15,000 h	http://www.directindustry.com/prod/cadoppi/gasoline-generator-sets-66301-585676.html
Electrolyzer (except membranes)	3 kW	3,200 $/kW	20 years	Barbir (2005)
Membranes	—	4,800 $/kW	10 years	Barbir (2005)
Hybrid storage system				
Flywheel	2 × 10 kW	6,500 $/unit	30 years	http://epp.eurostat.ec.europa.eu/portal/page/portal/publications/recently_published
Hoppecke battery	2 × 3,000 Ah		10 years	
Hydrogen tank	40 kg	1,150 $/kg	25 years	Barbir (2005)
PEM-Fuel cell (except membranes)	5 kW	4,000 $/kW	Project lifetime	Wilkinson et al. (2010)
Photovoltaic plus invertors	1 kW	3,000 $/kW	30 years	Kolhe et al. (2003)
Wind turbine	1 × 5 kW	32,500 $/unit	15 years	Duffie and Beckman (1980)

Table 3. Efficiency per Device

Device	Efficiency (%)	Reference
Converter/inverter	≥94	Generally known (typical)
Diesel generators	≈ 30	http://www.directindustry.com/prod/cadoppi/gasoline-generator-sets-66301-585676.html
Electrochemical battery	80	Nair and Garimella (2010)
Electrolyzer	65–75	Barbir (2005)
Flywheel	92–96	Ruddell (2002)
Hybrid storage system	75.2	Prodromidis and Coutelieris (2012)
PEM-FC	40	Wilkinson et al. (2010)
PV	13	Kolhe et al. (2003)
Wind turbine	30 (of the blowing wind energy)	Duffie and Beckman (1980)

(Prodromidis and Coutelieris 2011, 2012), and their efficiencies are presented in Table 3.

Regarding the economic parameters, attention was paid to the lifetime of each component, which does not affect the energy calculations. Moreover, the electrolyzer and fuel cell do not have the same initial and replacement costs at the end of their life, because the parts replaced are the membranes and not the entire apparatus (about 60% of their initial cost [30]). The lifetime of the main body of the electrolyzer is defined as 20 years (Table 2) while the lifetime of membranes has been estimated as 10 years. Also, the costs of the whole hybrid storage unit (Table 2) came from the standard cost of batteries in combination with the average price between 200 and 500 $/kW for the flywheels. For this reason, and because CO_2 emissions are also included, the economic study was finalized by custom calculations without using *HOMER* software. This software was used to specify the systems' energy calculations while the costs were calculated separately for each component and then appropriately summed to obtain the final budget. Finally, the lifetime of each battery, converter, and flywheel was decided to be 10, 15, and 30 years, respectively (Prodromidis and Coutelieris 2012).

Methodology

The selected technical characteristics of the apparatuses used here are presented, as well as the methodology followed for the energetic and financial optimization. The efficiency of inverters/converters is typical, obtained through technical data sheets published by their producers (California Energy Commission 2013). The mass of the diesel consumed in the diesel generator can be found throughout the combination of density of the diesel fuel and the consumption of a typical diesel generator (lt/kWh) (Cummins Power Generation 2008) and by using the higher heating value (HHV) for diesel (44.8 MJ/kg ≈ 12.5 kWh/kg) (NIST 2011). Thus, the produced energy can be easily calculated. The value used for the DC electrolyzer in the present study is based on the technical characteristics of HOGEN PEM electrolyzer, which produces 1.0 Nm^3/h of hydrogen and consumes 6.6 kWh/Nm^3 (73.95 kWh/kg) (Barbir 2005). Typical industrial electrolyzers have electricity consumption in the range between 4.5 and 6.0 kWh/Nm^3 (Barbir 2005), which means that efficiency varies from 65% up to 75% (Barbir 2005). Accordingly, a value of 70% (Table 3) has been selected for the current project, being representative for this hydrogen technology.

PEM fuel cell efficiency varies between 34% and 40% (Wilkinson et al. 2010). The operating lifetime for the membranes is 12,000 h before being replaced, while the rest of the device parts (cables, gauges, metallic parts, etc.) are of endless life, i.e., their lifetime has been set equal to the duration of the whole project (Wilkinson et al. 2010). Finally, the efficiency of PV and wind technologies, which are used during simulations, exists in *HOMER* technical libraries (http://homerenergy.com/Pre_DL.html). This software tool uses several types of PV panels and several wind turbines with specific predefined characteristics (http://homerenergy.com/Pre_DL.html). The values used in the present study are presented in Table 3. The values used are all within the allowable ranges with a maximum variation of ±5%, which is lower than the total error produced by the simulations carried out by HOMER; therefore, their accuracy does not significantly affect the final results.

Validation

To validate the process presented here, an already established RES-based system was simulated and optimized in terms of both energy and economics, namely HARI project, located at Leicestershire, UK (Little et al. 2007). A detailed description of the simulation parameters and techniques used as well as relative discussions about the results can be found elsewhere (Prodromidis and Coutelieris 2010). In general, excellent agreement between predictions by simulations with experimental observations has been observed, while the power of optimization was also indicated.

Results and Discussion

The proposed system (Fig. 4) was first validated against the simulation of a power plant based on PV panels, wind turbine and hydrogen technologies, which has already studied and installed in Morocco (Panahandeh et al. 2011), which is the only available system using solar and wind energy sources along with a hydrogen and battery storage system. This validation was performed only in terms of energy due to the limited economic data being available. The results of the Morocco installation have been reproduced here throughout the HOMER platform with the use of local meteorological data (World Weather Online 2013). For the given load and the combination of equipment in the DC-coupled configuration of the above system (Panahandeh et al. 2011) (which is compatible with the configuration proposed here), the energy production was found to be 22,418 kWh per year and the excess electricity 11,172 kWh per year. The above values, for the energy production and the excess electricity, are not shown in the original cited work (Panahandeh et al. 2011), but this does not constitute a major problem since the objective of the validation is to reconstruct an already established system and to replace the battery-based storage system with the innovative hybrid storage system, as in Fig. 2, in order to evaluate the power of the proposed configuration. It was found that the amount of energy for the uninterrupted operation of the system is 3,060 kWh per year, which could be used to charge the storage system. The equivalent amount of hydrogen, which could be produced by this energy excess, is 215 kg. As can be easily calculated from the typical efficiencies for each device (Table 3), this amount of hydrogen is produced by 10,928 kWh of excess energy, while 11,267 kWh are available. Consequently, the scenario is feasible while the innovative configuration presented here allows for an easier manipulation of the excess electricity and for lower energy losses. It must be noted that the amount of energy has to be supplied from/to the energy storage bank (batteries plus hydrogen) for the Moroccan power plant is 3,060 kWh per year while its losses equal 7,596 kWh per year, which corresponds to 67.9% of the available energy excess, since the total input of the storage energy devices is 3,576 kWh per year (Panahandeh et al. 2011). As far as this percentage for the proposed system here is only 2.18% (244 kWh per year, Fig. 4), thus underling the significant eliminations of energy waste due to the use of the hybrid storage system in conjunction with the innovative design used.

After validation and the discussed clear benefits of the innovative system applied in an already existed power plant, the one-way connection of the hybrid storage system to a DC-bus was considered for the present project, which will take place in Naxos Island using different devices to satisfy the desirable loads (typical house and country house). Since the environmentally friendly character of the system is the major criterion to be fulfilled, a two-way grid connection must be avoided due to the use of polluting technologies throughout the energy mixture of the country. The minimum amount of energy that is appropriate to be stored to the hybrid storage system for the continuous operation of the system was covered by hydrogen technology (electrolysis, hydrogen storage unit, PEM FC) or a diesel generator depending on the scenario considered, without the use of RES components. Each scenario was divided into sections that were simulated separately, while their energy parts were combined to produce the final results. To further understand the energy results, four different scenarios have been examined: a1 and a2 with the hydrogen technology, and b1 and b2 with the diesel generator as shown in Figs. 3 and 4. After optimizing the systems, in terms of energy, Fig. 5 shows that both scenarios a1 and b1 fulfill the requirements to cover the desirable AC primary load for a typical house (7,775 kWh/year). Fig. 6 respectively shows that systems a2 and b2 cover the load of a typical country house (2,980 kWh/year) by using the same established technologies as the typical house's load; therefore, the amount of excess electricity produced is higher because the desirable load is lower. Note that these specific desirable simulated loads were designed after studying the electricity consumption of several appliances considered essential for operation of a typical house and typical country house (Prodromidis and Coutelieris 2011). The amount of energy produced by both systems is the same; however, scenarios a1 and a2 utilize the excess load from RES-based components more efficiently than scenarios b1 and b2 with the diesel generator. This occurs because both systems use the one-way connection of the hybrid storage system to a DC-bus; thus, in scenarios a1 and a2 hydrogen is produced by the excess electricity, but in scenarios b1 and b2 the excess electricity is wasted. As far as diesel generator is used in a system (scenario b1 and b2), sales to the grid are not considered because the energy produced there is not *green* due to diesel use. Scenarios a1 and a2 represented totally green energy

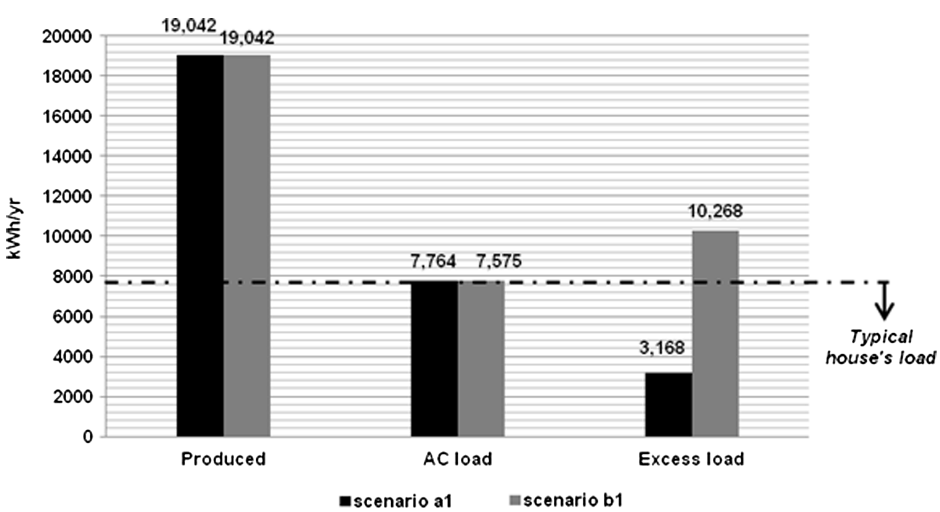

Fig. 5. Produced, AC-primary, and excess load for each system (load = typical house)

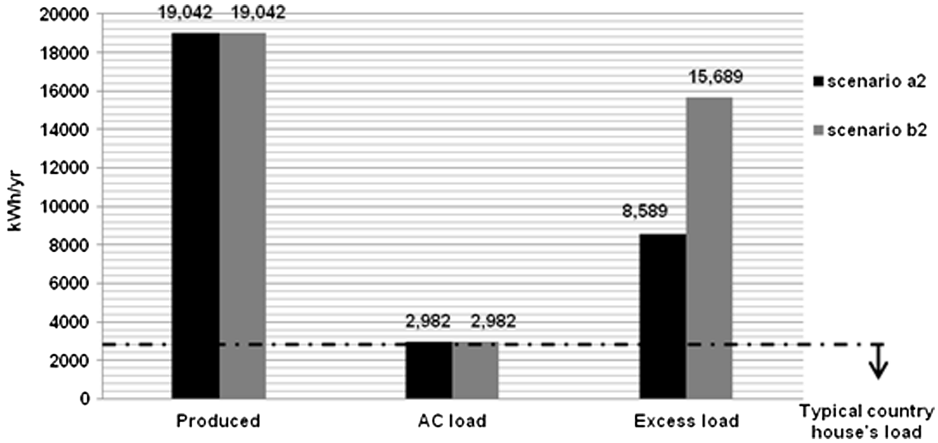

Fig. 6. Produced, AC-primary, and excess load for each system (load = typical country house)

production, which is only prerequisite for an energy producer to sell electricity, as each contract between the Greek Public Power Corp. and any individual producer, back to Greek grid. Fig. 6 also shows that scenarios a2 and b2 present the same results because the same peak load must be covered when the country house is being used.

The results from the *HOMER* simulation show that the annual electrical energy necessary to charge the hybrid storage system (2,890 kWh/yr) can be covered either by hydrogen technologies (a1) or by a diesel generator (b1), as depicted in Fig. 7. Only scenarios a1 and b1 are important since the other scenarios a2 and b2 use exactly the same technologies to cover a significantly lower load. It is interesting to show analytically in Fig. 7 the scenarios that use advanced technologies like hydrogen and also use a combination of devices, which marginally cover the desirable loads (AC primary load and hydrogen load). In the systems with the diesel generator, it was found that 2,856 kWh/year must be provided by the diesel use for more economical results. This small shortfall for scenario b1 to meet the storage system's demands (34 kWh/year) is a negligible amount (1.2%) being in the range of experimental error. Moreover, this amount of energy in the hydrogen system is much larger (12%) because the benefit of selling energy back to grid is higher than of transforming this to hydrogen in order to precisely cover the needs of the hybrid storage device. Besides, this percentage is smaller than the sudden increase of the peak desirable load (15%), defined for *HOMER* simulation purposes. Three steps are involved from hydrogen production to consumption; thus, power losses increase and the electricity required to charge the hybrid storage system has to be a level higher than in the diesel generator system. However, for the hydrogen-based system, the appropriate H_2 load that should be stored is found to be about 202 kg/year.

The simulation results determined the average produced electricity value per hour per month and this value represents a percentage of the total production, which can be used to predict the amount of excess electricity stored in the hybrid storage system. The energy produced can be transformed to hydrogen stored through the following approach: the energy needed to produce the total mass of hydrogen stored (kg) is the summation over 1 year of the energy produced at each month times the total energy that enters the hybrid storage system during the same month over the total energy produced. This amount must be finally multiplied by an efficiency factor defined by the rated consumption of a fuel cell over the rated power produced by this cell. For a typical PEM FC, the annual amount of hydrogen need for the specific load considered here is 202 kg H_2 [for a PEM FC: 0.035061 kg H_2/h correspond to 0.5 kWh (Yilanci et al. 2008)]. Although *HOMER* is widely accepted in the relative scientific community (Bernal-Agustin and Dufo-Lopez 2009), the finalization of the whole project with this tool has been roughly satisfied because of the internal limitations

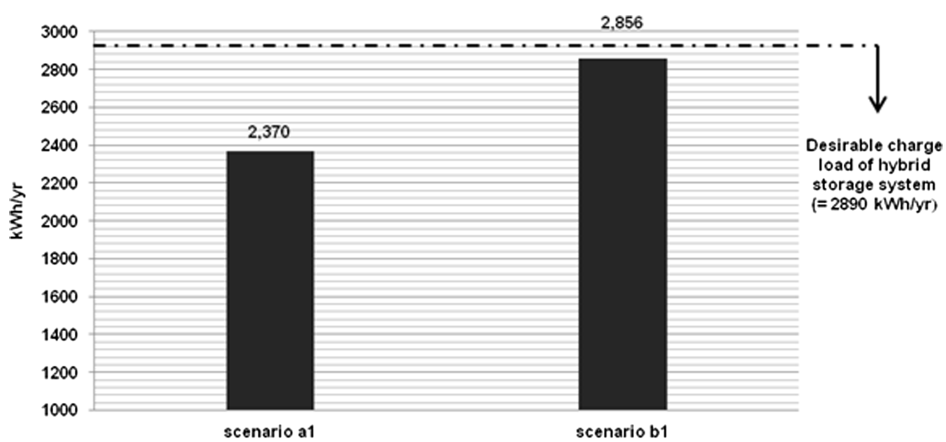

Fig. 7. Desirable annual electrical energy of hybrid storage system using a flywheel with a Hoppecke 3 kAh battery

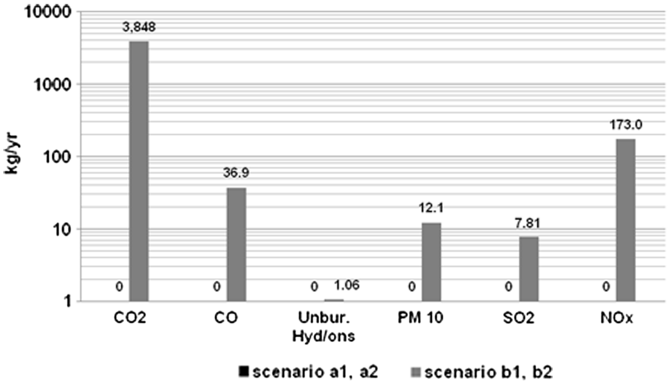

Fig. 8. Comparison of emissions per scenario; emissions for scenarios a1 and a2 are zero and emissions for scenarios b1 and b2 are identical

(especially in terms of economics) for the overall simulation of each power system. Therefore, exact results have to be carried out through external custom calculations.

Another factor considered when comparing the two systems is emission reduction. The results of comparing the different scenarios for emissions are presented in Fig. 8. Scenarios a1 and a2 present zero emissions; thus, hydrogen technologies seem to be the most preferable. Scenarios b1 and b2 emit large quantities of CO_2 into the environment due to diesel consumption.

The final step of this study is to compare the scenarios in terms of economy. Emission costs as specified by the Kyoto protocol were taken into account to determine how the costs of the diesel generator system (scenarios b1 and b2) increase through time. The preferred power system would be that with the lowest initial and NPC costs. Fig. 9 shows that the capital costs of the established hydrogen technologies (scenarios a1 and a2) are higher than those of the conventional diesel generator (scenarios b1 and b2). However, the same results are not observed in terms of NPC in any of this study's scenarios. Scenario a2, which incorporates hydrogen technology and covers the load of a typical country house, is capable of minimizing NPC by selling excess electricity to the grid, because the total load is smaller than in scenarios a1 and b1. These estimates depend upon the project's lifetime, which in the present study is considered constant (25 years). Fig. 9 shows that the initial cost of a system using hydrogen technologies is 65% higher than one using more conventional technologies. On the contrary, the NPC for scenario incorporating hydrogen technology is 72% lower than that of more conventional technologies. This increases as the

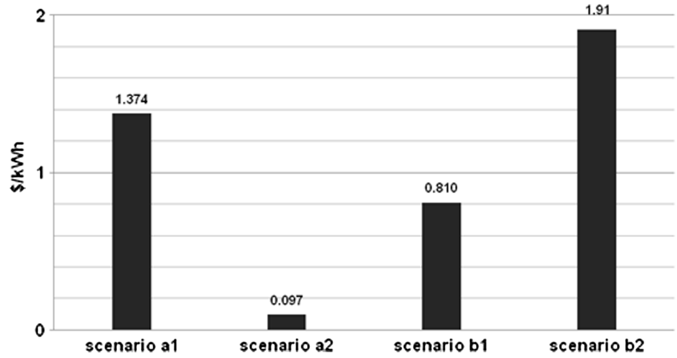

Fig. 10. Levelized cost of energy of each system

excess electricity not used by the typical country house in one year is sold to the grid.

The levelized cost of energy (Fig. 10) and annual operating costs (Fig. 11) represent the economic feasibility of each system. The behavior of Eq. (7) is depicted in Fig. 10. The results for hydrogen technologies presented in this figure are very optimistic, although the NPC values of system a1 are rather higher than those of system a2, which covers the typical country house's load and gives excess electricity back to the grid. Accordingly, system a2 presents an 88% lower energy cost than system b1, a result that sounds feasible. The same comparison also applies to scenarios a2 and b2 for the same load coverage, where the system with hydrogen technology (a2) appears to be more economic for the given energy production. This discrepancy of the energy costs between systems a2 and b2 increases from the previously mentioned 88% to 95%. The cost per kWh in a2 is 0.097 \$/kWh and is directly comparable that of the Public Power Corp. (0.10 \$/kWh). Therefore, the economic aspects of this design also encourage the use of advanced technologies rather than conventional ones.

Further economic results are presented in Fig. 11, where the annual operating costs are 8.2% lower in scenario a1 than in scenario b1 while system a2 provides a substantial annual return. The impressive result is that in scenario a2, the amount of −5,192 \$/year is the clear benefit of an investor after the coverage of the operating costs. Presently, diesel generator systems appear the most economically feasible, and only in some specific circumstances specifically, when the desirable load fluctuates in a low-level hydrogen technology is used in totally green power plants.

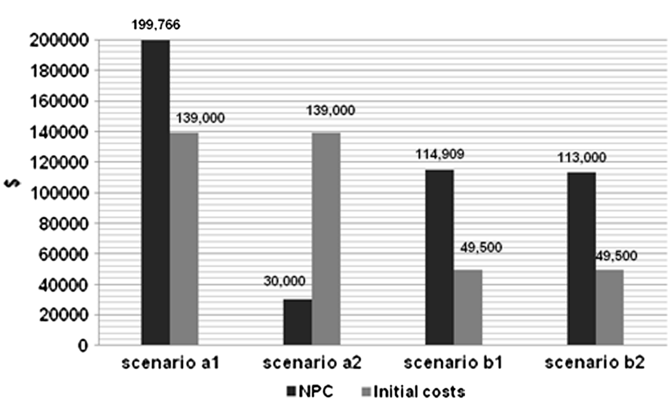

Fig. 9. Initial costs and NPC for scenarios

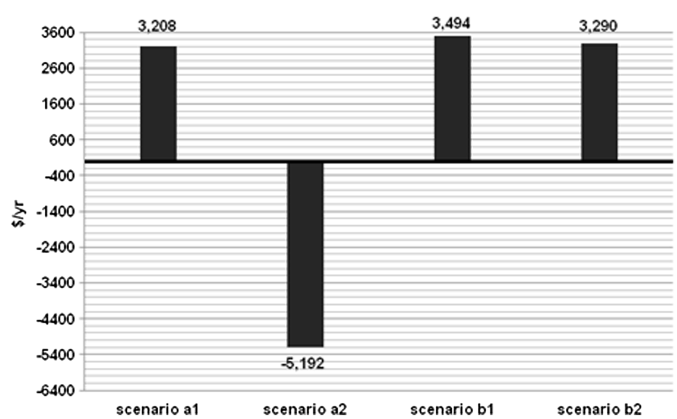

Fig. 11. Operating costs for each system

Conclusion

In this present study, four different RES-based scenarios were simulated for an off-grid power plant, assumed to be located on Naxos Island, Greece. The innovation of this project is the use of nonconventional technologies (namely, flywheels and hydrogen) for energy storage/buffering in conjunction with RES systems for electricity production. Although the combined use of hydrogen with flywheels has already been presented elsewhere (Prodromidis and Coutelieris 2012), the ecofriendly character and the stable operation throughout a typical year for such a system was under question. Furthermore, the proposed solutions were compared with the alternative of supporting the hybrid system with a diesel generator. Simulations were carried out using a modified calculation tool incorporating *HOMER* software and custom calculations. The use of flywheels in combination with batteries and hydrogen technologies is found to be feasible, as the simulations show that all the hybrid systems can satisfy the desirable loads for both a typical house and typical country house. The system comprising flywheels and hydrogen was founded competitive against well-established technologies like batteries, while it can be considered as unique solution through the years for some specific cases such as scenario a2. This is further strengthened by the totally green character of the system, which has zero CO_2 emissions. Finally, this study indicates that flywheel systems and hydrogen technologies can be both considered as alternative back-up energy options, at least for low-budget investments.

Notation

The following symbols are used in this paper:

A = surface area (m^2);
AIR = annual inflation rate;
C = costs ($);
COE = levelized cost of energy ($/kWh);
CRF = capital recovery factor;
E = energy (J);
Emissions = amount of emissions (kg);
F = photovoltaic factor;
$\bar{G}$ = solar radiation (W/m^2);
I = inertia of the flywheel's rotor ($kg\,m^2$);
i = real interest rate;
i' = nominal interest rate;
L = load (kWh);
P = power (W);
R = lifetime (years);
T = temperature (°C);
u = velocity (m/s);
X = distance (m);
α = temperature coefficient (%/°C);
ρ = density (kg/m^3); and
ω = angular flywheel's speed (rad/s).

Subscripts

air = atmospheric air;
an.tot = total annualized;
C = photovoltaic cell;
der.PV = photovoltaic derating factor;
emissions = pollutant emissions;
grid,sales = energy (kWh) sold back to grid;
NPC = net present cost;
P = power;
perton = per ton;
primAC = covered primary AC load;
proj. = simulated project;
solar = sun as source;
STC = standard test conditions;
T = temperature;
TNPC = total net present cost; and
wind = blowing wind as source.

References

Barbir, F. (2005). "PEM electrolysis for production of hydrogen from renewable energy sources." *Solar Energy*, 78(5), 661–669.

Bernal-Agustin, J. L., and Dufo-Lopez, R. (2009). "Simulation and optimization of stand-alone hybrid renewable energy systems." *Renew. Sustain. Energy Rev.*, 13(8), 2111–2118.

Bolund, B., Bernhoff, H., and Leijon, M. (2007). "Flywheel energy and power storage systems." *Renew. Sustain. Energy Rev.*, 11(2), 235–258.

Brealy, A. R., and Myers, C. S. (1991). *Principles of corporate finance*, 4th Ed., McGraw-Hill, New York.

California Energy Commission, and California Public Utilities Commission. (2013). "List of eligible inverters." ⟨http://www.gosolarcalifornia.org/equipment/inverters.php⟩ (Oct. 14, 2013).

Clarke, R. E., Giddey, S., and Badwal, S. P. S. (2010). "Stand-alone PEM water electrolysis system for fail safe operation with a renewable energy source." *Int. J. Hydrogen Energy*, 35(3), 928–935.

Cummins Power Generation. (2008). "Generator set data sheet, Model DGDB." ⟨http://www.cumminspower.com/www/common/templatehtml/technicaldocument/SpecSheets/Diesel/na/d-3425.pdf⟩ (Jan. 1, 2008).

Davies, T. S., Jefferson, C. M., and Mayer, R. M. (1988). "Use of flywheel storage for wind diesel systems." *J. Wind Eng. Ind. Aerod.*, 27(1–3), 157–165.

Direct Industry. (2013). "Products > Energy: Production and distribution > Gasoline generator > Cadoppi." ⟨http://www.directindustry.com/prod/cadoppi/gasoline-generator-sets-66301-585676.html⟩ (Oct. 14, 2013).

Doukas, H., Papadopoulou, A., Savvakis, N., Tsoutsos, T., and Psarras, J. (2012). "Assessing energy sustainability of rural communities using principal component analysis." *Renew. Sustain. Energy Rev.*, 16(4), 1949–1957.

Duffie, J. A., and Beckman, W. A. (1980). *Solar engineering of thermal processes*, Wiley, New York.

Elmitwally, A., and Rashed, M. (2009). "High-performance isolated PV-diesel system." *J. Energy Eng.*, 10.1061/(ASCE)0733-9402(2009)135:2(44), 44–52.

European Union. (2012). "European Commission > Eurostat > Publications > Recently published." ⟨http://epp.eurostat.ec.europa.eu/portal/page/portal/publications/recently_published⟩.

Farret, F. A., and Simoes, M. G. (2006). *Integration of alternative sources of energy*, Wiley, New York.

Glasnovic, Z., and Margeta, J. (2010). "Sustainable electric power system: Is it possible? Case study: Croatia." *J. Energy Eng.*, 10.1061/(ASCE)EY.1943-7897.0000027, 103–113.

Hamelin, J., Agbossou, K., Laperrieve, A., Laurencelle, F., and Bose, T. (2001). "Dynamic behavior of PEM fuel cell stack for stationary applications." *Int. J. Hydrogen Energy*, 26(6), 625–629.

HOMER Energy Team. (2013). "HOMER (The hybrid optimization model for electric renewables)." ⟨http://homerenergy.com/Pre_DL.html⟩ (Oct. 14, 2013).

Kaldellis, J. K., Kapsali, M., and Katsanou, E. (2012). "Renewable energy applications in greece—What is the public attitude?" *Energy Policy*, 42, 37–48.

Kolhe, M., Agbossou, K., Hamelin, J., and Bose, T. K. (2003). "Analytical model for predicting the performance of photovoltaic array coupled with a wind turbine in a stand-alone renewable energy system based on hydrogen." *Renew. Energy*, 28(5), 727–742.

Leclercq, L., Robyns, B., and Grave, J. M. (2003). "Control based on fuzzy logic of a flywheel energy storage system associated with the wind and diesel generators." *Math. Comput. Simulat.*, 63(3–5), 271–280.

Lilienthal, P. D., Lambert, T. W., and Gilman, P. (2004). "Computer modeling of renewable power systems." *Encyclopedia of energy*, Vol. 1, C. J. Cleveland, ed., Elsevier, Amsterdam, Netherlands, 633–647.

Little, M., Muray, T., and David, I. (2007). "Electrical integration of renewable energy into stand-alone power supplies incorporating hydrogen storage." *Int. J. Hydrogen Energy*, 32(10–11), 1582–1588.

Liu, H., and Jiang, J. (2007). "Flywheel energy storage-An upswing technology for energy sustainability." *Energy Build.*, 39(5), 599–604.

Manwell, F. J., McGouan, G. J., and Rogers, L. A. (2002). *Wind energy explained theory design and application*, Wiley, New York.

Millet, P., Ngameni, R., Grigoriev, S. A., and Fateev, V. N. (2011). "Scientific and engineering issues related to PEM technology: Water electrolysers, fuel cells and unitized regenerative systems." *Int. J. Hydrogen Energy*, 36(6), 4156–4163.

Nair, N. K. C., and Garimella, N. (2010). "Battery energy storage systems: Assessment for small-scale renewable energy integration." *Energy Build.*, 42(11), 2124–2130.

Nakken, T., Frantzen, E., Hagen, E. F., and Strom, H. (2006). "Utsira—demonstrating the renewable hydrogen society." *WHEC*, Vol. 16, Norwegian Energy Company, Utsira, Norway.

National Institute of Standards and Technology (NIST). (2011). "NIST Chemistry WebBook." U.S. Secretary of Commerce, ⟨http://webbook.nist.gov/chemistry/⟩.

Niiyama, K., Yagai, T., Tsuda, M., and Hamajima, T. (2008). "Optimization of hybrid power system composed of SMES and flywheel MG for large pulsed load." *Physica C.*, 468(15-20), 2111–2114.

Niknam, T., Golestaneh, F., and Shafiei, M. (2013). "Probabilistic energy management of a renewable microgrid with hydrogen storage using self-adaptive charge search algorithm." *Energy*, 49, 252–267.

Panahandeh, B., Bard, J., Outzourhit, A., and Zejli, D. (2011). "Simulation of PV—wind-hybrid systems combined with hydrogen storage for rural electrification." *Int. J. Hydrogen Energy*, 36(6), 4185–4197.

Perrin, M., et al. (2006). "Temperature behaviour: Comparison for nine storage technologies Results from the INVESTIRE Network." *J. Power Sour.*, 154(2), 545–549.

Posso, F., Contreras, A., and Veziroglu, A. (2009). "The use of hydrogen in the rural sector in Venezuela: Technical and financial study of the storage phase." *Renew. Energy*, 34(5), 1234–1240.

Prodromidis, G. N., and Coutelieris, F. A. (2010). "Simulation and optimization of a stand-alone power plant based on renewable energy sources." *Int. J. Hydrogen Energy*, 35(19), 10599–10603.

Prodromidis, G. N., and Coutelieris, F. A. (2011). "A comparative feasibility study of stand-alone and grid connected RES-based systems in several Greek Islands." *Renew. Energy*, 36(7), 1957–1963.

Prodromidis, G. N., and Coutelieris, F. A. (2012). "Simulation of economical and technical feasibility of battery and flywheel hybrid energy storage systems in autonomous projects." *Renew. Energy*, 39(1), 149–153.

Ruddell, A. (2002). "Storage technology report: WP-ST6 flywheel. Investigation on storage technologies for intermittent renewable energies: Evaluation and recommended R&D strategy." *Project funded by the European Community under the 5th Framework Programme*.

Shabani, B., and Andrews, J. (2011). "An experimental investigation of a PEM fuel cell to supply both heat and power in a solar-hydrogen RAPS system." *Int. J. Hydrogen Energy*, 36(9), 5442–5452.

Stamenic, L., Rajkovic, M., and Klisic, D. (2012). "Performance optimization of the BIPV powered electrolyser and fuel cells installation." *Energy Build.*, 51, 39–47.

U.S. Dept. of Energy, Energy Efficiency, and Renewable Energy, by the Pacific Northwest National Laboratory. (2003) "Flywheel energy storage—an alternative to batteries for uninterruptible power supply systems." U.S. Dept. of Energy's Federal Energy Management Program (FEMP), Washington, DC.

Wang, L., Lee, D. J., Lee, W. J., and Chen, Z. (2008). "Analysis of a novel autonomous marine hybrid power generation/energy storage system with a high-voltage direct current link." *J. Power Sour.*, 185(2), 1284–1292.

Wilkinson, D. P., Zhang, J., Hui, R., Fergus, J., and Li, X. (2010). "Proton exchange membrane fuel cells: Materials properties and performance." CRC, Boca Raton, FL.

World Weather Online. (2013). "Historical or past local weather API." ⟨http://www.worldweatheronline.com/premium-weather.aspx?menu=historical⟩ (Oct. 14, 2013).

Yilanci, A., Dincer, I., and Ozturk, H. K. (2008). "Performance analysis of a PEM fuel cell unit in a solar–hydrogen system." *Int. J. Hydrogen Energy*, 33(24), 7538–7552.

Ziogou, C., Ipsakis, D., Seferlis, P., Bezergianni, S., Papadopoulou, S., and Voutetakis, S. (2013). "Optimal production of renewable hydrogen based on an efficient energy management strategy." *Energy*, 55, 58–67.