Load and weather profile, and time simulation impacts for the PEPITE PV/H2 project

C. Darras, Christophe Thibault, Marc Muselli, Philippe Null Poggi, S. Melscoet, Jc Hoguet, Eric Pinton, F. Gailly, Christophe Turpin

Load and weather profile, and time simulation impacts for the PEPITE PV/H_2 project

C. Darras, C. Thibault, M. Muselli*, P. Poggi
University of Corsica, UMR CNRS SPE 6134
Route des Sanguinaires, F-20000 Ajaccio
darras@univ-corse.fr, cthibault@univ-corse.fr, marc.muselli@univ-corse.fr, philippe.poggi@univ-corse.fr

S. Melscoet, J.C.Hoguet
HELION Hydrogen Power
Domaine du Petit Arbois – Bâtiment Jules Verne, BP 71
13545 Aix en Provence, France
sandrine.melscoet@helion-fuelcells.com, jean-christophe.hoguet@helion-fuelcells.com

E. Pinton
Commissariat à l'Energie Atomique (CEA/LITEN)
17 rue des Martyrs, 38 054 Grenoble Cedex 9, France
eric.pinton@cea.fr

F. Gailly [1,2], C. Turpin [1,2]
[1]Université de Toulouse; INP, UPS; LAPLACE (Laboratoire Plasma et Conversion d'Energie);
ENSEEIHT, 2 rue Charles Camichel, BP 7122, F-31071 Toulouse cedex 7, France.
[2]CNRS; LAPLACE; F-31071 Toulouse, France.
gailly@laplace.univ-tlse.fr, turpin@laplace.univ-tlse.fr

Abstract

This paper concerns the impacts of the meteorological data, the choice of the load profile, and the time simulation (1 to 11 years) on the energy flows and on the $H_2/O_2/H_2O$ storage sizing in a PV/FC/EL hybrid system (PEPITE project). The simulations were computed with the ORIENTE software. 4 load profiles have been investigated (3 diurnal and 1 nocturnal) with an identical daily consumption (26 kWh).

According to load profiles, the gap observed between the most favorable and the most disadvantageous years induces H_2 storage variations rates between 45.5 % and 55.3 %. Furthermore, if we compare the most penalizing meteorological year with the sizing when we simulate several successive years, we also obtain variation rates ranges from 24.4 to 37.9 % for the 3 diurnal profiles. The nocturnal profile presents specific results because it is unsustainable. The main conclusion of this work is the great importance to consider several consecutive years of tilted irradiation data, 7 in our case, to size the $H_2/O_2/H_2O$ storages.

Keywords: Renewable energy, Photovoltaic, Hybrid system, Fuel cell, Electrolyzer, Hydrogen

* Corresponding author: Marc MUSELLI, tel: +33 4 95 52 41 30, fax: +33 4 95 52 41 42

email: marc.muselli@univ-corse.fr

1. Introduction

Several projects in the field of renewable energy sources are on progress since the last three decades. To overcome the intermittency problem of renewable energy sources, hydrogen seems to be an appropriate technology. A lot of development efforts to achieve technological breakthroughs, are required to bring these technologies to commercial maturity. Like electricity, hydrogen must be produced and transported but has additional advantage: it can be easily stored.

Many countries try to decrease their primary energy consumptions by integrating renewable energy sources to their energy policies. There are more than ten hydrogen fuelling stations in the world that use photovoltaic systems [1-3]. Photovoltaic-hydrogen/fuel cell hybrid energy systems may supply the energy demands for many cases. These systems can be divided into grid connected systems, and stand-alone systems. Grid connected systems [4, 5] are used to eliminate problems with intermittent electrolyzer operations by combining the photovoltaic with an input from the grid. If the photovoltaic installation is in a remote area, stand-alone systems can be used to supply the load. The capacity of the storage device can be used as a backup system. Several projects were carried out around the world which such hybrid systems and are fully adapted in particular in the case of islands [6-8]. Few of them are described below:

The **FIRST-project** was a photovoltaic-hydrogen stand-alone power system for telecommunication application in Spain [9]. The general principle of this project is based on the short-term storage (with batteries) of solar energy as additional system. The **HARI** (Hydrogen and Renewable Integration, UK) investigated methods to store the energy generated by intermitted renewable sources through hydrogen [10, 11]. Then the objectives of **SAPHYS** (Stand Alone Hydrogen Project) project were to assess the efficiency of hydrogen used as a storage mean for solar electric energy, and to design and test a stand-alone system.
One of the most impressive projects is the **PHOEBUS** project (electrical energy used to supply a part of the Central Library in Forschungszentrum Jülich, Germany) which was carried out from 1993 to 2003 [12-14]. This project was devoted to stationary and stand-alone applications. This kind of project can be used as a basis for comparison regarding the richness of results and conclusions collected during these ten years. The technical feasibility of a self-sufficient energy-supply system based on solar energy, battery, and hydrogen storage was demonstrated. The PHOEBUS project proved that an electrical energy generated by a purely renewable source without connection to the public grid was possible. The **Schatz Solar Hydrogen Project** was a stand-alone PV energy system at the Humboldt State University (HSU), which used hydrogen as the energy storage means and a PEM fuel cell as the regeneration technology, between 1989 and 1996 [15-19]. Recently, Ipsakis et al. [20] have reported some results from a complete renewable system at Neo Olvio of Xanthi in Greece. This application uses a stand-alone power system based on photovoltaic array and wind generators that stores excess energy from renewable energy sources in the form of hydrogen via water electrolysis for future use with Fuel Cell (PEMFC). The **MYRTE** Project (Mission hYdrogen Renewable for the inTegration to the Electrical network) has as main goal the decrease of daily load peaks in the case of an insular electric network (Corsica Island, France) by using a PV/FC/EL renewable energy system.

Recently Hwang and al. [21] investigated on a dynamic model of PV/FC power system with Simplorer simulation environment and utilized to predict its operational behaviours through numerical simulation. The system hybridizes photovoltaics and fuel cells to support the power requirement of a typical family in the daily life. The results showed that the present hybrid system has successfully tracked the daily power consumption of a typical family. The effectiveness of the management of a stand-alone hybrid system that maximizes the use of renewable energy sources is verified. Dufo-Lopez et al. [22, 23] worked on a PV-hybrid system and focused researches on design and control strategies using generic algorithms. In these articles [22, 23], five different load profiles had been considered and results on principal variables analyzed for a hybrid system of electrical generation. The three objectives of this paper were to minimize the total cost throughout the useful life of the installation, pollutant emissions (CO_2), and unmet load. Uzunoglu and al. [24] described dynamic simulation for a PV/FC/UC hybrid power generation system. Each sub-system has been simulated by SIMULINK^{TM} and stand-alone residential micro-grid has been designed and modelled. A detailed simulation model has been developed which allows designing and analyzing any PV/FC/UC hybrid system with various power levels and parameters. In a last paper, Shahnia et al. [25] simulated different cases of micro-grid load demands and results have been reported (how the power quality can be improved in a microgrid that is supplying a nonlinear and unbalanced load).

The project presented in this paper, called **PEPITE** (Study and experimentation of intermittent energy management using electrochemical technologies), is a project endorsed by the French PAN-H research program (action plan on hydrogen and fuel cell) supported by ANR (French Research National Agency). This project concerns, among various other tasks, a demonstration of a weather station electricity supply with help of a PV/FC/EL hybrid system. It started in January 2008 for a 4-years duration. The purpose of this article is an assessment of the impacts of the meteorological data profiles on the energy flows and on the H_2 storage (O_2 and H_2O equally). We have computed these comparisons with three adjustable parameters: hourly tilted irradiation profiles (11 measured years), hourly load profiles (4 repartitions) and time simulation (from 2 to 11 consecutive years).

The demonstration system **(**Fig. 1**)** will be composed by a PV array (14.85 kWp), a PEM fuel cell (10 kW) and PEM electrolyzer (2 Nm^3/h nominal output) with their auxiliaries, batteries, storage tanks for H_2, O_2 and H_2O, and associated converters. The size of the gas storage will not be fixed; nevertheless tanks will be filled from the beginning of the simulation.

The H_2 line (fuel cell, electrolyzer and gas tank) will be supplied by the HELION Hydrogen Power Company and by the CEA (Commissariat à l'Energie Atomique, France). The hypotheses concerning the FC are the following [30]:

- the number of cells for the PEMFC stack (series association) is 85 and the active area of a single fuel cell is 400 cm²,
- H_2 and O_2 stoichiometric ratios are equal to 1.01,
- the Faraday efficiency is fixed at 0.99,
- a minimal consumption of fuel cell's auxiliaries is considered to be equal to 50 W. Moreover, the additional consumption of FC's auxiliaries, dependent on the supplied power, is taken equal to 20 %,
- the FC has a "below" power threshold (5 % of the nominal FC power installed) for which its operation is stopped in order to limit FC damages .

The hypotheses concerning the electrolyzer are the following [30]:

- the number of electrolyzer cells (series association) is 17 and the active area of a single electrolyzer cell is 300 cm²,
- H_2O stoichiometric ratio is equal to 1.05,
- a minimal consumption of electrolyzer's auxiliaries is considered to be equal to 1840 W. Moreover, the additional consumption of electrolyzer's auxiliaries, dependent on the absorbed power by the electrolyzer, is taken equal to 17.6 %,
- the electrolyzer has a power threshold under which its operation is stopped (25 % of the nominal power).

At last, the hypotheses concerning the tank are the following [30]:

- the hydrogen and oxygen losses in the storage are 2.5 mol/h (corresponding to monthly losses equal to 0.01 % of the maximal quantity which can be contained in the tank). This value corresponds to an objective for this project.
- The electrolyser and tank pressure are fixed to the same values (30 bars).

In this hybrid system, batteries are transparent energetically at normal operating condition. They remain nevertheless indispensable for the instantaneous exchanges of power. They are also used in normal regime to maintain the potential of the electrical DC BUS, to assure the start-up/stop in correct conditions and thereby to smooth the electrical power [9, 31] from the fuel cell and the electrolyzer systems. They have to be charged before the system starts.

In the majority of cases and contrarily to the PEPITE project, hybrid systems use batteries in their configurations for critical periods or for energy storage. The lead-acid battery is commonly associated with stationary solar systems. This kind of battery fits well with the system and its efficiency is at least 80 % [32]. A fully description of the batteries management will be reported in a future paper. In the present paper, batteries are not used as means of storage (in opposition with other projects where batteries are considered like a short-term energy storage [10, 11, 13, 14]), but they must be sized to smooth the electrical power. Thus, for the proposed project, hydrogen is used as means of short and long-term storage too.

Fig. 1

The global hourly solar radiation (30° tilted) and ambient temperature data were measured (universal time) by

Meteo-France from the French weather station of Campo del'Oro in Ajaccio. These data are available from the 1st January 1998 to the 31 December 2008 (Fig. 2) in UT (Universal Time). The approach of this work is to focus on simulations results (not optimization sizing) of the energy flows and on the hydrogen storage.

Fig. 2

We have considered 3 diurnal and one nocturnal UT hourly load profiles (Fig. 3). Each of them has an identical daily consumption of 26 kWh but a different hourly repartition. The first one (from 08:00 am to 12:00 am called P1) and the 2nd one (from 12:00 am to 04:00 pm called P2) are two symmetric profiles. The 3rd one (from 10:00 am to 2:00 pm called P3) is around noon and the last one (from 22:00 pm to 2:00 am called P4) is the nocturnal profile. All profiles operate 4 hours for an unchanged consumption of 6.5 kW.

Fig. 3

The simulations were made with help of ORIENTE (Optimization of Renewable Intermittent Energies with Hydrogen for Autonomous Electrification) model which was developed for this project [26-29].

The implemented flow control is the following: the PV array supplies in priority the load via the DC/AC converter. In the case of an excess of PV power (above the power threshold of the electrolyzer) and a non-full hydrogen storage, this extra power will be transferred to the electrolyzer via its DC/DC converter. If the electrolyzer cannot absorb it (under the power threshold or full storage) then the “transparent” batteries could absorb it to a certain limit depending of their sizing. And if the batteries are full, then the PV array is totally shut down. In intermediary cases, we can be brought to adjust the production PV by degrading the power (the operation is not any more the MPPT mode). Thus, we have a part of the PV energy which is not used by the system. This energy is lost for the moment, but it could be valorised (heat and/or cold production for building needs). When the PV array is not able to satisfy the load power, the fuel cell supplies the complementary amount of power. If the power required for the fuel cell is under its power threshold or if the gas storage is empty, the “transparent” batteries could supply it to a certain limit depending of their sizing. And if the batteries are fully discharged, then the system is shut down. This last case should not happen because we size exactly the system to avoid this scenario. Nevertheless, it is necessary for the electric safety of the system. In a previous work, G. Notton and al. [33] focused their study on an optimized sizing method of an autonomous photovoltaic system located in Corsica. Influences of the temporal repartition of the load and of the simulation time step were determined in this case.

2. Results

This first series of results corresponds to different simulations from 1998 to 2008, with various load profiles.

From the 11 annual hourly tilted irradiation profiles, we see that the annual PV energy ranges from 25.21 MWh to 26.79 MWh, has a mean value of 26.37 MWh and a standard deviation of 0.47 MWh (Tab. 1). We note that the year 2004 corresponds to the year with the lowest sunshine period, -4.4 % compared to the mean value calculated from the 11-years. These variations also lead to differences for the electrolyzed energy [MWh], the FC production [MWh], the load cover rate [%] from PV and FC, the operating time [h] and the storage capacity [Nm^3] **(**Tab.2 and Tab. 3**).** In these tables, the parameters “H_2 quantity”, “O_2 quantity” and “H_2O quantity” represent respectively the hydrogen, oxygen and water quantity necessary to obtain LLP = 0 during the simulation time (i.e. the load autonomy). If the gas quantity in the tank only just decreases, the system is said unsustainable (the P4 profile is an example), on the other hand if the gas quantity oscillates between the minimal and maximal size, the system is said sustainable (P1, P2 and P3 profiles are exemples).

Tab. 1

Tab. 2

Tab. 3

The meteorological data impact (11 annual profiles) on the energy flows depending on load profiles are represented in Fig. 4. According to the simulated irradiation years, high energy balance variations are observed for the annual electrolyzed energy (ranges from 3.38 to 4.76 MWh for P1, ranges from 3.53 to 5.3 MWh for P2, ranges from 2.02 to 3.19 MWh for P3 and ranges from 13.42 to 14.72 MWh for P4). The same results are obtained for the FC production (for P1: between 2.08 and 2.82 MWh, for P2: between 2.12 and 3.3 MWh, for P3: between 1.28 and 2 MWh and for P4: between 13.05 and 13.09 MWh). The variation rates are considerable according to the chosen load profile (up to 36.7 % for the electrolyzer and 36 % for the FC) concluding that the chosen meteorological year represents a discriminated parameter for a PV/H_2 system sizing.

Fig. 4

The impacts of the meteorological data profiles on the hydrogen, oxygen and water storages depending on load profiles are represented in Fig. 5. For a maximum clarity, the load profile P4 does not appear on the figure. Indeed, P4 being unsustainable, the sizes of tank are enormous with regard to those necessary for the other profiles. The hydrogen, oxygen and water storages vary respectively from 269 to 494 Nm^3, 135 to 247 Nm^3, and 26 to 42 L for P1. Also, for P2, the variations are 253 to 566 Nm^3, 126 to 283 Nm^3, and 26 to 44 L respectively. Then, for P3, the variations are 182 to 361 Nm^3, 91 to 181 Nm^3, and 17 to 30 L respectively. Finally, for P4, the variations are 3761 to 4039 Nm^3, 1880 to 2020 Nm^3, and 2 to 4 L respectively. We obtain dispersion rates going from 2.1 to 22.6 %, from 2.1 to 22.7 %, and from 12.7 to 16.5 % respectively for the hydrogen, oxygen and water tanks, according to the load profiles.

Fig. 5

As we can observe in the Fig. 6, the meteorological data has a variable impact on the operating time [h] depending on load profiles. For this parameter, the mean annual electrolyzer operating time corresponds to 781 h (standard deviation: 66.7 h), 787 h (standard deviation: 81.8 h), 596 h (standard deviation: 75.1 h) and 2409 h (standard deviation: 56.2 h) respectively for P1, P2, P3, and P4. For this parameter, according to the simulated year, dispersion rates ranges from 2.3 % (P4) to 12.6 % (P3).

For the FC, the mean operating time corresponds to 526 h (standard deviation: 32.9 h), 545 h (standard deviation: 48.6 h), 354 h (standard deviation: 37.2 h) and 1461 h (standard deviation: 1.8 h). Here, dispersion rates exhibit amplitude between 0.1 % (P4) and 10.5 % (P3).

For a 50000 hours and 2500 hours lifetime for the electrolyzer and the FC stacks respectively [31], the operating time becomes a significant parameter, especially for the FC. The load profiles, according to meteorological data, can be successively repeated between: 4 and 5 years for P1, 4 and 5 years for P2, 6 and 8 years for P3, and 2 years for P4 before having to change the fuel cell stack.

Fig. 6

Concerning the PV cover rates (the FC cover rates can be deducted), we observe that it varies between 75.1 % (P2, 2008) to 90.4 % (P3, 2006) according to the load profiles (Fig. 7), except for P4 (nocturnal profile with FC only supplying the load). As expected, P3 presents the best PV cover rate taking into account the profile equally distributed around 12am (UT). We obtain dispersion rates going from 1.8 to 3.0 %, for the PV cover rates, according to the load profiles (P1, P2 and P3).

Fig. 7

The Fig. 8 represents the available PV energy that the system is not able to receive (MPPT degradation or PV array shut down) according to the meteorological years and the load profiles. For the 3 diurnal profiles, these annual energies are close and oscillate respectively between 8.7-11.8 MWh (P1), 8.8-11.6 MWh (P2), and 10.2-13.1 MWh (P3). For P4, this energy is clearly lower and varies from 3.4 to 3.8 MWh. A ratio of 3 for the lost energy is observed between the diurnal (P1 to P3) and nocturnal (P4) profiles. The both reasons of this difference are the following:

- The diurnal profiles are sustainable and during the summer period, the gas quantities in the tank reach their maximum values. At this moment, the PV array feeds only the load and the supplement of power is lost.
- As described previously, the load is fed in priority. Only the surplus of PV power transits to the electrolyzer characterized by a not insignificant operation threshold, and thereby the PV power is lost when the threshold is not reached. For the profile P4, as the load is consuming at night, the problem of threshold happens less often because the totality of the PV power goes directly to the electrolyzer.

Fig. 8

Fig. 9 presents the evolution of the H_2 storage computed from several consecutive years, from 2 to 11 successive years and for various load profiles. The profile P4 being unsustainable, the storage increases in a linear way with huge values. That explains why in the following figure, the values of the storage are presented with a 1/50 multiplicative coefficient to improve the figure clarity.

Fig. 9

We note that for 3 renewable profiles, the tank size increases in agreement with 3 different periods:

- strongly when 2 to 4 successive simulated years are used as input of the PV/H_2 system (P1: from 498 to 784 Nm^3, P2: from 489 to 712 Nm^3, P3: from 288 to 570 Nm^3),
- then weakly from 4 to 7 (P1: from 784 to 795 Nm^3, P2: from 712 to 749 Nm^3, P3: from 570 to 574 Nm^3)
- And finally following an asymptotic behavior after 7 consecutive simulated years as input of the ORIENTE model.

For P4, the size of tanks increases in a linear way from 7630 to 42268 Nm^3. In our case and for the load profiles (P1, P2 and P3), 7 consecutive meteorological years are necessary and sufficient to know the size of tanks necessary for the system autonomy (Loss of Load Probability LLP = 0).

3. Discussion

If we compare each year of the PV production and of electrolyzed energy consumption, we can notice that the increase of the one does not necessarily bring the increase of the other one. Moreover if this increase is significant in summer period, PV production is often lost (system stop and/or MPPT degradation) because the H_2 storage oscillates close to its maximum value. And vice-versa during the winter the storages being almost empty, the electrolyzer consumes more energy.

Considering these simulated results, we show that an increase of the PV production will not decrease necessarily the FC energy production. We also deduce that the capacity of gas tanks will not necessarily decrease. A future study considering a small time-step of simulation must be done to evaluate these phenomena.

Concerning the operating time, an asymmetry is observed. For example, the electrolyzer can consume the same amount of energy in a week as well as in the day. The device can operate nonstop during several hours, fuelled by lower impact powers.

Load profiles P1 and P2 are very similar considering several simulated variables. The most gap between these both profiles is 3.4 % for the operating time of the fuel cell. This result is not surprising because the average solar energy from 8h to 12h and from 12h to16h is very close. If we compare similarly the profiles P3 and P4, we observe important differences. There are respectively variations of 82.9 and 88.0 % concerning the electrolyzer and the FC energies. With regard to the size of H_2 tank, we have a variation of 93.1 %. Thereby, for the electrolyzer and the fuel cell operating time, we have respectively a variation of 75.3 and 75.8 %. Indeed, P4 privileges the use of the H_2 chain (energy necessarily transits through the electrolyzer and the fuel cell) and P3 privileges the diurnal load supply by the renewable source.

The P4 profile that is characterized by an identical daily consumption compared to the other profiles is clearly different. This profile presents an unsustainable behavior: the gas quantity in the tank during the simulation always decreases even if the gas amounts are important. In the case of simulations made with consecutive years, the quantities are over-sized. This kind of profile must be banned for this demonstration tool.

Choosing a load profile which follows the sun trajectory (P1, P2 and P3), allows to have reasonable tank sizes, but with the disadvantage to obtain a lost energy more important. Using batteries in order to avoid these losses could be an adapted solution.

According to diurnal load profiles (P1 to P3), the H_2 storage gaps observed between the poorer meteorological year (classically used to design a PV system) and their values obtained after 11 consecutive years of input data represent respectively 37.9 % (P1), 24.4 % (P2) and 37.1 % (P3).

In view of the results, we are able to notice that the use of the most unfavorable year to size the PV/FC/EL system is not the effective solution. The choice of the load profile is critical because it determines if the system is sustainable or not.

According to load profiles, the optimal configuration of the PV/H_2 system leading to LLP = 0 on a 11-years successive simulated period are (P_{pv} = 14.85 kWp):

<u>P1</u>: H_2=795 Nm^3 O_2=398 Nm^3 H_2O=603 L.

<u>P2</u>: H_2=749 Nm^3 O_2=375 Nm^3 H_2O=602 L.

<u>P3</u>: H_2=574 Nm^3 O_2=287 Nm^3 H_2O=388 L.

<u>P4</u>: H_2=42268 Nm^3 O_2=21135 Nm^3 H_2O=4 L.

If we consider 11 years of simulation, we have respectively an efficiency for the H_2 chain (Energy supplied by the fuel cell divided by the electrolyzed energy) of 42.2, 43.0 and 44.0 % for 3 different load profiles (P1, P2 and P3). The profile P4 is not evaluated in terms of efficiency due to the fact that the gas quantity in H_2 tank is not the same at the end and the beginning of the simulation. These efficiencies are still low with regard to the solar battery sector (from 70 to 80 %), but the technology not having reached its maturity, we expect considerable improvements in future years.

4. Conclusion

According to load profiles, the gap observed between the most favorable and the most disadvantageous years induces a H_2 storage variation between 45.5 % and 55.3 %. But the main conclusion of this work is the importance to consider several successive years of meteorological data for sizing H_2/O_2/H_2O storages of a hybrid PV-H_2 system. In our case, 7 years are necessary to obtain the optimum size. Moreover, a variation, from 24.4 to 37.9 %, is observed between the most unfavorable meteorological year and the seven consecutive years. The choice of the load profile is also fundamental, because for an identical daily consumption, the hourly repartition of the load can generate a considerable increase of the gas storage required for the system autonomy. In fact, a variation rate of 28 % of the size of the hydrogen tank between P1 and P3 is obtained where as both profiles are rather close.

For this case of application, the consumption of FC and electrolyzer's auxiliaries represents an important energetic part. In future works, a fully description of the batteries management coupled with an optimized auxiliaries energy balance will be reported to obtain a hybrid PV/H_2 systems with long and short-term storages.

5. Acknowledgments

This work is partially funded by the French Research Agency (ANR – PAN-H program) within the frame work of the PEPITE project (reference ANR-07-PANH-012). First-author Christophe Darras was financially supported by the Collectivité Territoriale de Corse (CTC). We thank Metéo-France for the supply of the meteorological data on the Campo del' Oro station.

6. References

[1] Zini G, Tartarini P. Hybrid systems for solar hydrogen: A selection of case-studies. Applied Thermal Engineering 29(2009) 2585-2595

[2] Yilanci A, Dincer I, Ozturk H.K, A review on solar-hydrogen/fuel cell hybrid energy systems for stationary applications. Progress in Energy and Combustion Science 35 (2009) 231-244

[3] Fuel Cells 2000. Available from http://www.fuelcells.org/info/charts/h2fuelingstations.pdf (2007)

[4] Paramashivan Kaundinya D, Balachandra P, Ravindranath N.H. Grid-connected versus stand-alone energy systems for decentralized power – A review of literature. Renewable and Sustainable Energy Reviews 13 (2009) 2041-2050.

[5] Eltawil M. A, Zhao Z. Grid-connected photovoltaic power systems: Technical and potential problems – A review. Renewable and Sustainable Energy Reviews 14 (2010) 112-129.

[6] Krajacic G, Martins R, Busuttil A, Duic N, Da Graça Carvalho M. Hydrogen as en energy vector in the island's energy supply. International Journal of Hydrogen Energy 32 (2008) 1091-1103.

[7] Kaldellis J.K, Zafirakis D, Kondili E. Optimum sizing of photovoltaic-energy storage ystems for autonomous small islands. Electrical Power and Energy Systems 32 (2010) 24-36.

[8] Ulleberg O, Nakken T, Eté A. The wind/hydrogen demonstration system at Utsira in Norway : Evaluation of system performance using opertational data and updated hydrogen energy system modeling tools. International of Hydrogen Energy 35 (2010) 1841-1852.

[9] Shuncan T. International Energy Agency Hydrogen implementing agreement task 11: integrated systems final report of subtask A: case studies of integrated hydrogen energy systems. Chapter 4. IEA/H2/T11/FR1-2000, 2000, A.M.

[10] Gammon R, Roy A, Barton J, Little M. Hydrogen and Renewable integration (HARI). International energy agency hydrogen implementing agreement, case study, 2006.

[11] Hoffheinz G, Kelly N, Ete A. Evaluation of hydrogen demonstration systems & United Kingdom hydrogen infrastructures (Years 2-3 of Task 18 of the IEA Hydrogen Implementing Agreement) Contact number: F/04/00287/00/Rep, URN number: 07/770, Contractor: Sgurr Energy Ltd., 2007

[12] Agbossou K, Lal Kohle M, Hamelin J, Bernier E, Bose TK. Electrolytic hydrogen based renewable energy system with oxygen recovery and re-utilization. Renewable Energy 2004; 29:1305-18

[13] Meurer C, Barthels H, Brocke WA, Emonts B, Groehn HG. Phoebus – an autonomous supply system with renewable energy: six years of operational experience and advanced concepts. Solar Energy 1999; 67 (1-3): 131-8

[14] Barthels H, Brocke WA, Bonhoff K, Groehn HG, Heuts G, Lennartz M, et al. Phoebus-Jülich: an autonomous energy supply system comprising photovoltaics, electrolytic hydrogen , fuel cell. International Journal of Hydrogen Energy 1997; 23 (4) 295-301

[15] Lehman PA, Chamberlin CE, Pauletto G, Rocheleau MA. Operating experience with a photovoltaic-hydrogen energy system. International Journal of Hydrogen Energy 1997; 22 (5) 465-70

[16] Chamberlin CE, Lehman PA, Reid RM, Herron TG. Preliminary results of the Schatz Fuel Cell research project, hydrogen '94: the 10th world hydrogen energy conference, Cocoa Beach, Florida: June 20-24, 1994

[17] Shucan T. Case studies of integrated hydrogen systems, international energy agency hydrogen implementing agreement final report for subtask A of task 11 – integrated systems, 1999

[18] Lehman PA, Chamberlin CE, Zoellick JI, Engel RA. A photovoltaic/fuel cell power system for a remote telecommunication station. In : 28th IEEE photovoltaic specialists conference. Anchorage, Alaska: September 15-20, 2000

[19] Voss K, Goetzberger A, Bopp G, Haberle A, Heinzel A, Lehmberg H. The selfsufficient solar house in Freiburg – results of three years of operation. Solar Energy 1996; 58 (1-3) 17-23

[20] Ipsakis D, Voutetakis S, Seferlis P, Stergiopoulos F, Elmasides C. Power management strategies for a stand-alone power system using renewable energy sources and hydrogen storage. International Journal of Hydrogen Energy 2009; 34 7081-95

[21] Hwang J.J, Lai L.K, Wu W, Chang W.R. Dynamic modeling of a photovoltaic hydrogen fuel cell hybrid system. International Journal of Hydrogen Energy 34 (2009) 9531-9542

[22] Dufo-Lopez R, Bernal-Augustin J.L. Design and control strategies of PV-Diesel systems using genetic algorithm. Solar Energy 79 (2005) 33-46

[23] Dufo-Lopez R, Bernal-Augustin J.L. Multi-objective desing of PV-wind-hydrogen-battery systems. Renewable Energy 33 (2008) 2559-2572

[24] Uzunoglu M, Onar O.C, Alam M.S. Modeling, control and simulation of a PV/FC/UC based hybrid power generation system for stand-alone applications. Renewable Energy 34 (2009) 509-520

[25] Shahnia F, Majumder R, Ghosh A, Ledwich G, Zare F. Operation and control of a hybrid micro grid containing unbalanced and nonlinear loads. Electric Power System Research (in press)

[26] Darras C, Poggi P, Muselli M. New approach for hybrid PV/H_2 system sizing. DOI : 10.4229/23rdEUPVSEC2008-5BV.2.12 (2008) 3402 - 3405

[27] Sailler S, Darras C, Thibault C, Muselli M, Poggi P. ORIENTE: A new numerical sizing software for PV-H_2 hybrid system. DOI : 10.4229/24thEUPVSEC2009-5BV.2.40 (2009) 4158 – 4161

[28] Darras C, Sailler S, Thibault C, Muselli M, Poggi P. PV/H_2 hybrid system sizing: The PEPITE project, DOI : 10.4229/24thEUPVSEC2009-5BV.3.11(2009) 4318 – 4320

[29] Darras C, Sailler S, Thibault C, Muselli M, Poggi P, Hoguet J.C, Melscoet S, Pinton E, Grehant S, Gailly F, Turpin C, Astier S, Fontès G. Sizing of photovoltaic system coupled with hydrogen/oxygen storage based on the ORIENTE model. International Journal of Hydrogen Energy (in press)

[30] HELION Hydrogen Power Company, Technical documentation 2010, Aix-en-Provence, France

[31] Zini G, Marazzi R, Pedrazzi S, Tartarini P. A solar hydrogen hybrid system with activated carbon storage. International Journal of Hydrogen Energy (in press)

[32] Lagorse J, Paire P, Miraoui A. Sizing optimization of a stand-alone street lighting system powered by a hybrid system using Fuel Cell, PV and battery, Renewable Energy 34 (2009) 683-691

[33] Notton G, Muselli M, Poggi P, Louche A. Autonomous Photovoltaic Sytems: Influence of some Parameters on the Sizing: Simulation Time-Step, Input and Output Power Profile. Renewable Energy, vol.7, n°4, p.353-369 (1996)

Figures and tables captions:

Fig. 1: Representation of the studied PV/H_2 hybrid system:
"__": Possible electrical flows; "- -": Fluid flows.

Fig. 2: Yearly Meteorological data:
'Grey bar chart': Yearly available solar energy; ' – Δ – ': Ambient temperature means.

Fig. 3: Consumption of the various studied load profile.

Fig. 4: Meteorological data impact on the energy flows depending on load profiles:
'Dark grey bar': Electrolyzed energy (mean value); 'Light grey bar': FC production (mean value).
Black bars: Standard deviation.

Fig. 5: Meteorological data impact on the hydrogen, oxygen and water storage depending on load profiles:
'Dark grey bar': Hydrogen tank (mean value) [Nm^3] ; 'Light grey bar' : Oxygen tank (mean value) [Nm^3]; 'Intermediary grey bar' : Water tank (mean value) [L].
Black bars: Standard deviation.

Fig. 6: Meteorological data impact (per year) on the operating time depending on load profiles:
'Dark grey bar': Electrolyzer (mean value); 'Light grey bar': FC (mean value).
Black bars: Standard deviation.

Fig. 7: Meteorological data impact on the load cover rate depending on load profiles:
'Dark grey bar': by PV (mean value) [%]; 'Light grey bar': by the FC (mean value) [%].
Black bars: Standard deviation.

Fig. 8: Photovoltaic energy not valorized according to the meteorological years and load profiles:
' – ◊ – ': Load profile P1; ' – * – ': Load profile P2; ' – Δ – ': Load profile P3; ' – X – ': Load profile P4

Fig. 9: Size of hydrogen tank according to the load profiles:
' – ● – ': Load profile P1; ' – X – ': Load profile P2; ' – **Δ** – ': Load profile P3; ' – ◊ – ': Load profile P4 (for this profile, the values are multiplied by a coefficient 1/50)

Tab. 1: PV production according to the weather profile.

Tab. 2: Summary of results (part a).
For each profile, maximal and minimal values are bold marked on the cells left side.

Tab. 3: Summary of results (part b).
For each profile, maximal and minimal values are bold marked on the cells left side.

Nomenclature			
η_{DCAC}	DC/AC converter efficiency [%]	P_{EL_Aux}	Power consumption of electrolyzer's auxiliaries [W]
η_{DCDC_EL}	Electrolyzer converter efficiency [%]	P_{EL_DCDC}	Electrolyzer converter input power [W]
η_{DCDC_FC}	Fuel cell converter efficiency [%]	P_{FC}	Fuel cell output power [W]
η_{DCDC_PV}	PV converter efficiency [%]	P_{FC_Aux}	Power consumption of fuel cell's auxiliaries [W]
$F_{H_2}^{C}$	Hydrogen consumption rate [mol. h^{-1}]	P_{FC_DCDC}	Fuel cell converter output power [W]
$F_{H_2O}^{C}$	Water consumption rate [mol. h^{-1}]	P_{Load}	Load consumption [W]
$F_{O_2}^{C}$	Oxygen consumption rate [mol. h^{-1}]	P_{MPPT}	PV array output power [W]
$F_{H_2}^{P}$	Hydrogen production rate [mol. h^{-1}]	P_{MPPT_DCDC}	PV converter output power [W]
$F_{H_2O}^{P}$	Water production rate [mol. h^{-1}]	Q_{H_2}	State hydrogen storage [mol]
$F_{O_2}^{P}$	Oxygen production rate [mol. h^{-1}]	Q_{H_2O}	State water storage [mol]
P_{EL}	Electrolyzer input power [W]	Q_{O_2}	State oxygen storage [mol]