Techno-economical Analysis of Hybrid PV-WT-Hydrogen FC System for a Residential Building with Low Power Consumption

Badea G.[1], Felseghi R.-A.[1], Raboaca M.-S.[2], Ashchilean I.[1], Bolboaca A.[1], Mureshan D.[1], Moldovan E.[1], Shoimoshan T.-M.[1]

[1] Building Services Engineering Department, Technical University of Cluj-Napoca, Romania
[2] National Researches and Development Institute for Cryogenics and Isotopic Technologies - ICSI, Rm.Valcea, Romania

Abstract. This paper shows a techno-economical analysis on performance indicators of hybrid solar-wind-hydrogen power generation system which supply with electricity a low - energy building, located in Cluj-Napoca. The case study had the main objectives, as follows: cost estimation, evaluation of energy and environmental performance for a fuel cell integrated into a small-scale hybrid system power generation and estimation of electrolytic hydrogen production based on renewable energy resources available on the proposed site. The results presented in this paper illustrate a case study for location Cluj-Napoca. The wind and solar resource can play an important role in energy needs for periods with "peak load" or intermittent energy supply. However, hydrogen production is dependent directly proportional to the availability of renewable energy resources, but the hydrogen can be considered as a storage medium for these renewable resources. It can be said that this study is a small-scale model analysis, a starting point for a detailed analysis of Romania's potential electrolytic production of hydrogen from renewable resources and supply electricity using fuel cells integrated into hybrid energy systems.

Keywords**:** fuel cell, hydrogen, hybrid system, renewable energies, low energy building.

Analiza tehnico-economică a unui sistem energetic hibrid cu panouri fotovoltaice-turbină eoliană-pilă de combustibil pe bază de hidrogen aferent unei clădiri rezidenţiale cu consum redus de energie

Badea G.[1], Felseghi R.-A.[1], Răboacă M.-S.[2], Aşchilean I.[1], Bolboacă A.[1], Mureşan D.[1], Moldovan E.[1], Şoimoşan T.-M.[1]

[1]Facultatea de Instalaţii, Univeristatea Tehnică din Cluj-Napoca, România
[2]Institutul Naţional de Cercetare-Dezvoltare pentru Tehnologii Criogenice şi Izotopice, Rm.Vâlcea, Romania

Rezumat. Această lucrare prezintă analiza tehnico-economică a indicatorilor de performanţă realizaţi de un sistem hibrid (solar-eolian-hidrogen) de generare a energie, care furnizează electricitate pentru o clădire cu consum redus de energie amplasată în Cluj-Napoca. Studiul de caz a avut ca obiective principale: estimarea costurilor, evaluarea performanţelor energetice şi ecologice în cazul integrării în sistemul hibrid a unei pile de combustibil, dar şi estimarea producţiei de hidrogen obţinută cu participarea sursele regenerabile de energie disponibile în locaţia propusă. Vântul şi soarele joacă un rol important în ceea ce priveşte asigurarea necesarului de energie în perioadele cu "vârf de sarcină" sau în alimentarea intermitentă cu electricitate. În consecinţă, producţia de hidrogen depinde direct proporţional de disponibilitatea surselor regenerabile de energie, iar hidrogenul poate fi considerat ca fiind un mediu de stocare pentru aceste surse regenerabile. Se poate spune că acest studiu de caz reprezintă un model la scară mică, un punct de plecare pentru o analiză detaliată la nivel de România a potenţialului de producţie a hidrogenului provenit din surse regenerabile, care poate fi utilizat mai apoi de către pilele de combustibil integrate în sisteme energetice hibride.

Cuvinte-cheie**:** pila de combustibil, hidrogen, sistem energetic hibrid, energie regenerabilă, clădire cu consum redus de energie.

Технико-экономический анализ гибридной фотофольтаической-водородной системы топливной ячейки для жилого здания с низким потреблением энергии

Бадя Г., Фелселги А., Рабоака М.С., Аскилян И., Болбоака А., Мурешан Д., Молдован Е., Шоймошан Т.

Технический университет, Клуж-Напока, Румыния

Аннотация. В статье представлен технико-экономический анализ показателей эффективности гибридной системы (солнце- ветер – водород) производства электроэнергии, которая снабжает электроэнергией здание с низким потреблением энергии, расположенное в городе Клуж-Напока. Целями исследования были: оценка стоимости, оценка энергетических и экологических характеристик в случае интеграции в гибридную систему топливного элемента и оценки производства водорода с использованием возобновляемых источников энергии, доступных на предложенном месте. Ветер и солнечный ресурс могут играть важную роль в обеспечении потребностей в энергии в периоды с «пиковой нагрузки» или при прерывистой подачи энергии. Тем не менее, производство водорода зависит

прямо пропорционально от наличия возобновляемых источников энергии, но водород можно рассматривать в качестве средства накопления этих возобновляемых ресурсов. Можно сказать, что это исследование является малой натурной моделью, отправной точкой для детального анализа возможности производства в Румынии водорода из возобновляемых ресурсов и его использования в гибридных энергосистемах.
***Ключевые слова*: топливный** элемент, водород, гибридная система, возобновляемые источники энергии, здание.

I. INTRODUCTION

A defining characteristic of XXI century represents the dependency of the world economy on new energetic resources. The problem's context represents the burn out of fossil fuels in a not so far future, the high volatility of prices for traditional energetic resources, satisfaction of economical and social necessities, problem regarding the energetic dimension of economic increase to cover the energy necessary in the conditions of environment protection by reducing the polluting emissions **[1].** The possible solutions are: exploitation of energetic resources from the natural environment, theoretically unexhausting and non polluting, which regenerates by natural processes, energetic technologies based upon conversion systems of renewable energies, which should offer a maximum yield, high reliability and minimum pollution.

Due to the fact that the hybrid systems produce energy using renewable resources, it is imposed regarding the following aspects: intermittencies in producing energy because of weather conditions and storage the excess energy. From an economical and environmental point of view, hydrogen and fuel cells can represent the solution to cover the intermittencies in producing energy and the „peak load" consumption, also storage the excess with returning it to the system when needed. A first step to using hydrogen and fuel cells with the goal to sustain buildings is introducing them in hybrid systems as an environment buffer of energy storage and then usage.

The present article deals with a solution, with iHOGA software functions, in which the energy from renewable resources produced by photovoltaic panels and wind turbines is used to cover the energy demand of a residential consumer, and the excess energy will be used by electrolysis of water to separate and get the hydrogen, that will be used later by the fuel cell for electrical energy production. This excess energy can cover the necessary consumption during „peak load" or can be introduced in the national network of energy supply. The case study results were performed after the simulations using genetic algorithms on a hybrid system which has as main elements of producing energy, photovoltaic panels, wind turbines, and as main storage medium of excess energy it was considered hydrogen obtained by electrolysis, which will be returned as electricity in the system by the fuel cell.

Simulations on the hybrid system mentioned above have as results the following aspects: technical and environment (the energetic balance of system, the excess of energy obtained by the system, the CO_2 emissions) and financially - economical (the system's costs - initial value of investment; NPC of the system for 25 years lifetime and the share of expenses regarding equipments in the total cost of system)._Also, there were presented the results of calculations to estimate the amount of hydrogen production by the electrolyser which is incorporated in the hybrid system, based on solar and wind energies.

II. PROBLEM FORMULATION

In the elaboration and foundation of the case study, the following stages need to be covered: definition of general information regarding the placement and consumer, calculated | the energy demand that needs to be assured by the hybrid system; background and availability of renewable resources used for energy production; design of schematic diagram for the system and optimal choosing of equipments for the hybrid system set to be analysis; establishing the objectives and determining system performance parameters that need to be shown, in order to highlight the production of electricity with fuel cells and the electrolytic hydrogen production using renewable energies.

2.1 Consumer Profile

This study was done for a category of building with the living destination which has an economical energy consumption, type "passive house", placed in Cluj - Napoca, Romania. The average load requirement for the building considered, calculate in accordance with the existing norms and standards **[2],** have the following values: AC max load in the year - active, 173 W and AC average load - active, 79.77 W; the diagram of variation for the hourly energy outfit in December is shown in fig 1.

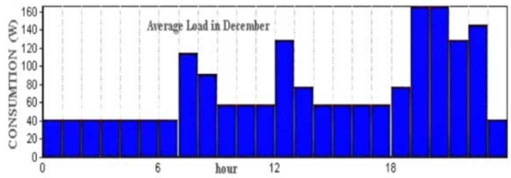


Figure 1. Variation graphic of the hourly energy outfit for 24 hours

2.2. Background and Availability of Renewable Resources

For Cluj - Napoca, climate dates of location are: latitude = 46.76°N, longitude = 23.60°E, elevation = 523 m, heating design temperature = -9.52°C, cooling design temperature = 24.26°C, earth temperature amplitude = 19,79°C according to Surface meteorology and Solar Energy: RETScreen Data **[3].**

For calculation of energy produced by the photovoltaic panels, the solar component which interests is solar irradiation. The values of daily solar irradiation for the proposed site analysis are presented graphically in **fig. 2**, with reference to the variation of the annual medium level of solar irradiation **[3].**

In Cluj-Napoca the horizontal, daily average irradiation is 3.3 kWh/m^2, total annual irradiation is 1204.65 kWh/m2, and on the photovoltaic panels surface the daily average irradiation is 4.0 kWh/m2 and total annual irradiation is 1461.41 kWh/m2. For the mentioned location the azimuth of photovoltaic panels is 0°, the soil's reflecting plane is 0.2, and the panels do not have a system that follows the sun.

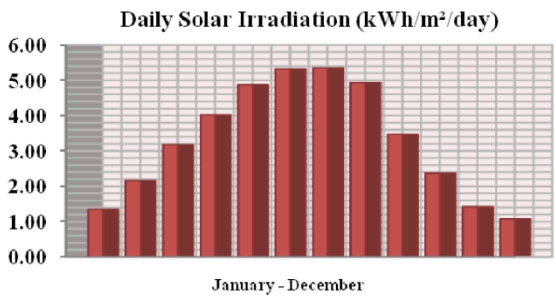


Figure 2. Variation graphic for average level of solar irradiation in Cluj-Napoca

Information regarding the wind speed in the area of system's placement are illustrated graphically and the values represent the monthly averages of wind speed, at a distance of 20m above the ground. The wind speed for Cluj-Napoca can be observed in **fig. 3 [3].**

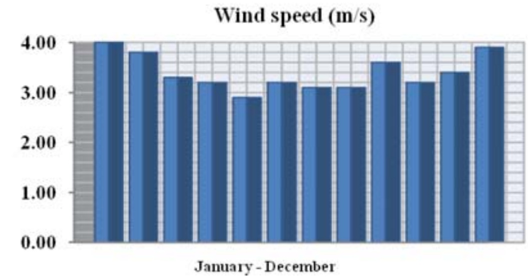


Figure 3. Variation graphic for average level of wind speed in Cluj-Napoca

2.3. Hybrid system configuration

The schematic diagram for hybrid system presented in **fig. 4:** photovoltaic panels, wind turbine, fuel cell, electrolyser and hydrogen tank, inverter. To note that, it was assumed hypothesis that the hybrid system is connected to the grid to provide start-up of equipments.

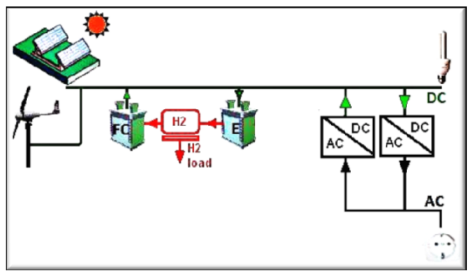


Figure 4. Schematic diagram for hybrid system

3. MATERIALS AND METHODS

Two aspects of the hybrid system performance are taking into account. On the one side, the choice of optimal equipment to become part of the hybrid system, equipments to provide energy efficient with the lowest cost and on the other side, electrolytic hydrogen production, calculated according to the literature **[4, 5].**

3.1 Optimal choosing of equipments

For configuration of the hybrid system and optimization of equipments have been performed simulations with HOGA Software, presently available program, having the basis the genetic algorithms for simulation and measuring the energy producing systems, which is a simulation and optimization program developed in C++ for Hybrid Renewable Systems for generation of electrical energy (DC and/or AC) and/or Hydrogen. Optimization is achieved by minimizing total system costs throughout the whole of its useful lifespan, when those costs are referred to or updated for the initial investment (Net Present Cost). Optimization is, therefore, financial (mono-objective). However, the program allows for multi-objective optimization, where additional variables may also be minimized: CO_2 emissions and unmet load **[6].**

3.2. Quantitative Calculation of Hydrogen Production

To estimate the hydrogen production of the electrolyser which is incorporated in stand-alone energy hybrid system, based on solar and wind energy, was adopted modeling the electrolyser as an ideal device, according to the first law of Faraday, as follows [4,5]:

$$\eta_F = \frac{V_{H_2\text{prod}}}{V_{H_2\text{calc}}}, \quad (1)$$

where:

$$V_{H_2\text{calc}} = n_c \frac{R \cdot I_{ely} \cdot T_a \cdot t_s}{F \cdot P_a \cdot z}, \quad (2)$$

η_F is the Faraday efficiency,
V_{H2prod} - volume of hydrogen produced,
V_{H2calc} - volume of hydrogen calculated,
n_c - the number of electrolyser cell stacks (6 for 1 kW),
R - the ideal gas constant (8314 J/mol K),
I_{ely} - the input current of the electrolyser in (A),
T_a - the ambient temperature in kelvin (K) (273+°C),
t_s - the period of time current supplied to electrolyser in (s) (3600),
F - the faraday constant (96.485 C/mol),
P_a - the ambient pressure, Pa (1 Pa = 1 J/m^3), z - the excess number of electron, for hydrogen is 2 **[4, 5].**

After calculations, Eq.2 becomes:

$$V_{H_2\text{calc}} = 0{,}4467 \cdot n_c \cdot I_{ely}, \quad (3)$$

based on Eq. 1 and Eq.3 result:

$$V_{H_2\text{calc}} = 0{,}4467 \cdot n_c \cdot I_{ely} \cdot \eta_F \,(\text{l/h}), \quad (4)$$

According to the literature, the faradaic efficiency of electrolysers is estimated to be more than 99%, and in the present study, the value is chosen arbitrarily to be of 96% **[7].**

4 RESULTS AND DISCUSSION

The simulation and calculation results are: energetic and environment type (energetic balance, hydrogen production, excess energy, CO_2 emissions), but also financial type.

4.1 System components

Taking into consideration above mentioned analysis and simulation, including the schematic diagram of hydrogen - fuel cell system, to ensure the necessary energy and the optimal function of systems, the following equipment components with the performance indicators are presented in table 1.

Table 1

Indicators of hybrid system

Components:		**1 year**
PV panels	100 Wp 4 serial * 6 paralel 65° slope	2630 (kWh)
Wind Turbine DC	925 W at 14 m/s	381 (kWh)
Fuel Cell	1 kW	385 (kWh)
Electrolyser	1 kW	2387 (kWh)
Inverter	PI 1200 900 VA	
Costs:		
Investment (euro)	43538	
Total System Cost (euro)	77267	
- in which: PV panels	4062	
Wind Turbine DC	5412	
Fuel Cell	29099	
Electrolyser	34287	
Inverter	1426	
Cost of energy (euro/kWh)	1,47	
CO_2 emissions (kg/year)	314	

The nominal power of equipments was illustrated graphically in **fig 5**. It illustrates the increased availability for solar energy, thus ensuring most energy by photovoltaic panels.

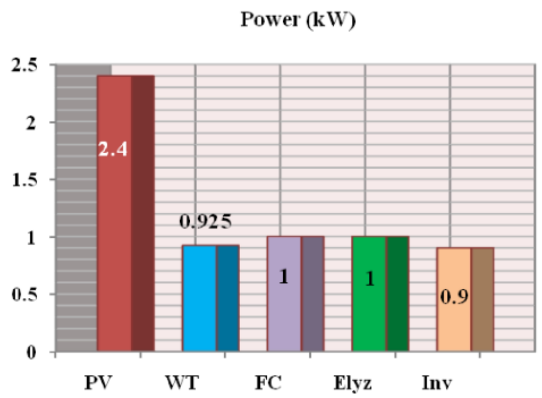


Figure 5 Nominal power of components

The energetic balance of hybrid system that was simulated during one year of operation highlights the overall load energy, also the energy produced in excess, the energy delivered by photovoltaic panels, wind turbines and by fuel cells, also the energy consumed by the electrolyser (fig 6). Favorable availability of solar energy is reflected also in the energy balance. Most of the energy delivered in one year, 2630 (kWh) is obtained by PV. The fuel cell generates electricity in the amount of 385 (kWh), with a running time of 3527 h/yr.

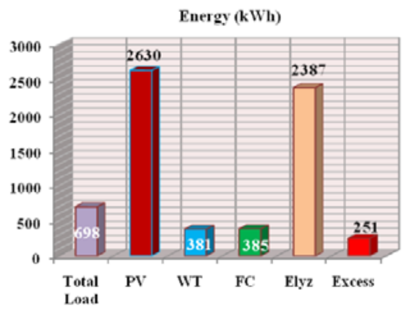


Figure 6. Energetic balance during one year of operation

Characteristics of efficiency curve of hydrogen technology are presented as follows:

The fuel cell that is a part from the analyzed hybrid system's configuration and has the hydrogen consumption on the nominal power of fuel cell and the real power delivered into the system **[8].**

The efficiency of the fuel cell is determined as the proportion between the delivered power into the system by the fuel cell and the production between the hydrogen consumption for the fuel cell and the calorific value of hydrogen **[6]** illustrated in **fig.7**.

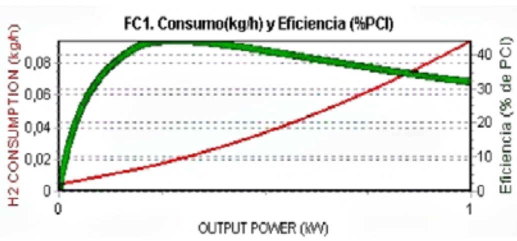


Figure 7. Fuel cell efficiency [6]

The electrolysis device represents the system that produces hydrogen, which is a part from the configuration of the hybrid system. The consumption of electrical energy of electrolysis device depends on the nominal flow and the real flow of the hydrogen produced by it **[8].** The efficiency of electrolysis device is determined as the proportion between the real flow of hydrogen produced multiplied by the calorific value of hydrogen and the consumption of electrical energy of electrolysis device, identical with the case of fuel cells **[6],** and has the curve illustrated in **fig 8**.

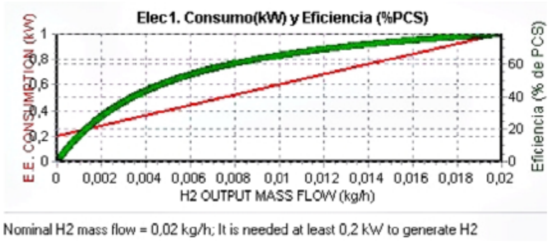


Figure 8. Electrolyser efficiency [6]

Calculation with formula (3) and (4) and the electrolyser, illustrated in Table 2, hours of operation of the electrolyser, obtained the results related to electrolytic hydrogen production and the energy consumes the elements involved.

Table 2.

Elements of hydrogen production

Electrolytic hydrogen production	
time operation of the electrolyser	3527 hours
energy consumed by the electrolyser	2387 kWh/year
the calculated amount of hydrogen	55.84 m3/year

The share of expenses for the main components elements in the total cost of the system are illustrated in the chart from fig-9. The photovoltaic panels (PV) represent 5.47 %, the wind turbine (WT) represents 7.29%, fuel cell (FC) is 39.17%, electrolysis device and H_2 tank are 46.16%, and other components represent 1.92%. Noticeable is the fact that the financial effort for storage the excess of energy, using the electrolyser and the fuel cell.

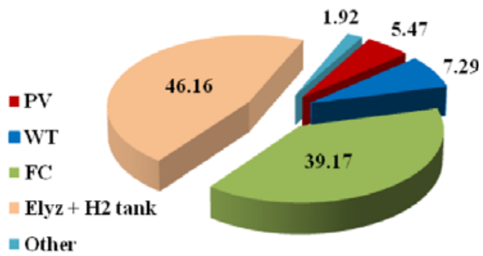


Fig 9. Chart regarding expenses with component equipments

5. CONCLUSION

Following the situation analysis, it can be concluded that fuel cell technology can play a key role in producing the electricity to power various hybrid systems consumptions of the optimal system configuration depending on the availability of renewable sources.

Integrating, the fuel cells technology in hybrid systems made the whole system more efficient by using hydrogen as energy storage medium to cover consumption peaks and periods of intermittent energy production, resulting in the reduction of excess energy produced by the system and the reduction of CO_2 emissions.

The simulations performed in order to determine an optimal configuration of hybrid systems with the fuel cells showed their important location in areas with high potential of renewable resources.

The universality of this approach makes it possible hydrogen as secondary energy carrier synthetic fuel, "energy vehicle" and storage medium for electricity produced from renewable resources.

Energy efficiency by primary energy savings, reduce network losses, reduced price and the cost of electricity to consumers, reduce environmental impacts, in particular, greenhouse gas emissions, all together contribute to the security of energy supply to consumers. Development of energy systems based on fuel cells is the focus of various demonstration projects that will allow validation of these technologies for energy production as alternatives to the classic one.

References

[1] Badea G., Felseghi R. A., et.al., *The role of hydrogen in the context of economic and technical actual way,* in the Conference Proceeding of "Ştiinţa Modernă şi Energia ediţia XXXI", Ed. Risoprint, Cluj-Napoca, 2012, pp. 40-49.

[2] Romanian Ministry of Transport, Construction and Tourism, *Methodology for calculating the energy performance of buildings Part II – Energy performance of buildings installations – Indicative Mc 001/2-2006,* Published Official Monitor, Part I no. 126bis of 21/02/2007.

[3] Climate data location NASA Surface meteorology and Solar Energy: *RETScreen Data,* Document generated on Mon Jun 9 03:41:38 EDT 2014 available on https://eosweb.larc.nasa.gov/sse/RETScreen/

[4] Djamila G., Abdellah K., et al, Study of *hydrogen production system by using PV solar energy and PEM electrolyser in Algeria,* Int J. Hydrogen Energy, **38,** 2013, 8480-8490.

[5] Sopian K., Ibrahim M. Z., et al., *Performance of a PV-wind hybrid system for hydrogen production,* J. Renewable Energy, **34,** 2009, 1973-1978.

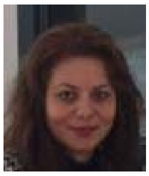
[6] Dufo - Lopez R., Bernal - Agustin J. L. *HOGA Software Version 2.2,* Electrical Engineering Department, University of Zaragoza, Spain, 2012.

[7] Gorgün H., *Dynamic modeling of a proton exchange membrane (PEM) electrolyser,* Int J. Hydrogen Energy, **31**(1), 2006, 29 – 38.

[8] Badea G., Felseghi R. A., et al., *Comparative study regarding the global influence of energy storage medium on autonomous hybrid systems for a building with economical energy consumption,* in the Book Computer Aplications in Environmental Sciences and Renewable Energy, WSEAS Press, Kuala Lumpur, Malaysia, **24,** 2014, 209-216.

About authors.

Emeritus Prof. Univ. Dr. Eng. Gheorghe Badea. Scientific research fields: energy and environment; membrane technologies for water treatment.
E-mail: gheorghe.badea@insta.utcluj.ro



Drd. Eng. Maria Simona Răboacă. Scientific Researcher. Research fields: energy and environment; hydrogen production, energy storage, fuel cell, hybrid electric vehicle.
E-mail: simona.raboaca@insta.utcluj.ro

Dr. Eng. Raluca-Andreea Felseghi. Scientific research fields: energy and environment; transport, distribution and use of hydrogen, fuel cells, buildings with low energy consumption.
E-mail:

Dr. Eng. Ioan Aşchilean. Scientific research fields: energy and environment; rehabilitation of water supply networks.
E-mail: aschileanioan@gmail.com

Raluca.FELSEGHI@insta.utcluj.ro

Dr. Eng. Andrei Bolboacă. Scientific research fields: energy and environment; trenchless technology for pipe rehabilitation.
E-mail: andrei.bolboaca@insta.utcluj.ro

Dr. Eng. Emil Moldovan. Scientific research fields: energy and environment; natural gas distribution networks.
E-mail: emil.moldovan@seacomplet.ro

Dr. Eng. Dan Mureşan. Scientific research fields: energy and environment; water treatment and purification systems.
E-mail: dan.muresan@insta.utcluj.ro

Dr. Eng. Teodora - Melania Şoimoşan. Scientific research fields: energy and environment; plants in district heating networks.
E-mail: teodora.soimosan@insta.utcluj.ro

Articolul a fost prezentat la Conferința ”Energetica Moldovei 2016”