MINISTRY OF EDUCATION
TECHNICAL UNIVERSITY
OF CLUJ-NAPOCA, ROMANIA

Civil Construction and Installations

PhD THESIS
– ABSTRACT –

CONTRIBUTIONS ON THE REALIZATION OF A PASSIVE HOUSE USING HYBRID ENERGY SYSTEMS

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General considerations

Fossil energy resources are finite, depletable and polluting, there has been a surge of interest among researchers and developers to find *solutions for the exploitation and large-scale use of alternative energy resources.* Energy is the driving force behind civilization and technical, scientific and economic development. With the identification of the current situation related to the limited availability of traditional energy resources, climate change and the negative influence of the energy sector on the environment, principles underlying sustainable development have been outlined and adopted. In this context, particular emphasis is placed on *increasing the share of renewable and alternative energy sources with low carbon emissions.* Climate change, threats to energy security, depletion of traditional energy resources and the health of the population are driving *energy strategies at national and international level*. Harnessing the energy potential of renewables in hybrid energy systems for electricity generation is a particularly important objective.

In the ***PhD thesis***, two concepts with demonstrated significance in the energy efficiency and decarbonization of the residential building sector in the context of sustainable development are addressed simultaneously, interdisciplinary and transdisciplinary: ***'hybrid energy system***' and ***'passive house'***.

This PhD thesis presents the ***studies carried out on solutions for the use and integration of renewable energy sources in the energy support of a virtual passive house.*** *At the same time, the energy, economic and environmental performances of hybrid energy systems are analyzed, integrating different storage solutions (rechargeable batteries, hydrogen), simulated under different assumptions and conditions of use, in order to highlight the performances of hybrid energy systems solutions in the energy support of passive houses.*

In this context, in the *PhD thesis*, the energy consumption of the passive house building (heating, hot water, air conditioning, lighting, appliances, auxiliaries) is mostly supported using various scenarios for hybrid energy systems with excess energy storage using hydrogen-based technologies or rechargeable batteries.

The originality of the thesis lies in the synergy between the concept of "passive house" and "hybrid energy system", in which hydrogen is used as an energy vector with a dual role, namely - medium and long-term storage medium of surplus energy from the conversion of renewable energies (sun and wind), respectively alternative solution for generating clean energy using fuel cell conversion equipment.

The scientific/technological impact of the topic is multiple, starting from the support offered to the practical activity by the unitary theoretical approach to the subject of the use of hybrid energy systems for passive house power supply, to the provision of appropriate tools for sizing these systems according to the user's requirements. Also, the scientific impact of the research is to establish the optimal clean energy alternatives/systems for supplying energy for operation and providing comfort conditions for passive house occupants. The *PhD thesis* presents the results obtained from theoretical research and simulations on the choice of energy conversion equipment, sizing, optimization and operation of hybrid energy systems, with the aim of developing a set of performance criteria to support the choice of the optimal configuration specific to the passive house consumer.

The socio-economic impact derives on the one hand from the possibility to increase the comfort level of users, and on the other hand from the possibility to save resources, reduce costs and comes both from the financial results generated by the use of hybrid energy systems and from those related to the building that corresponds to the passive house concept.

Climate impact. Because of the environmental impact benefits, renewable resource-based applications are seen as attractive solutions to 21st century energy problems, whether we are talking about the passive house or any other application. The current global trend is to promote primary energy resource structures with a focus on renewables, so this PhD topic can contribute to this goal through the positive impact that the use of hybrid renewable energy systems can generate. If we consider that the topic of the PhD thesis addresses clean and green technologies, then we can state that the environmental impact is a positive one, which can make an important contribution to improving the quality of life and health, as well as restoring the quality of the environment.

Chapter 1. The current state of knowledge worldwide

1.1. Current status and critical analysis of the use of hybrid energy systems

In order to minimize CO_2 emissions and reduce the price of energy, the optimization of the hybrid energy system has the greatest influence in achieving these goals. In the literature, different methods are used to size and optimize a hybrid energy system, taking into account all the component equipment in the energy system with energy consumption as input.

The bibliometric maps highlight the essential elements in the process of sizing and optimizing hybrid energy systems. The main components of the hybrid energy system are: photovoltaic panels, wind turbines, fuel cells, electrolyzer, hydrogen storage, rechargeable batteries.

This chapter presents the *bibliometric analysis* of hybrid energy systems using as input a database of selected scientific articles from the Web of Science that generates bibliometric maps using VOSviewer software. The following keywords were used in the selection process of scientific articles from the literature: hybrid energy system, renewable energy, wind turbine, photovoltaic panels, fuel cell, electrolyzer, hydrogen storage, rechargeable batteries. Different configurations for hybrid energy systems have been identified in the literature. Optimization, management and control strategies and algorithms were used according to the objectives of each case study. For the purpose of generating the bibliometric maps, the methodology presented in the paper [1] and the information in the VOSviewer software user manual [2] was used.

The sizing and optimization of hybrid energy systems depends on: the equipment used (photovoltaic panels, wind turbines, fuel cell, electrolyser, rechargeable batteries, hydrogen storage) and the research objective.

The indicators taken into account for the sizing and optimization of hybrid energy systems are: i) equipment costs; ii) technological evolution of equipment; iii) solutions to decrease energy consumption; iv) electrification of rural areas; v) reduction of energy prices; vi) minimization of greenhouse emissions;

Different management strategies are used to optimize hybrid energy systems. The performance of energy systems is closely related to the equipment technology used, the management strategy adopted, the energy storage solution, the type of renewable energy sources and whether the system is on-grid or off-grid.

Over the years, different configurations of hybrid energy systems have been designed, developed, tested and analyzed to support the consumer's energy profile by looking at efficiency, performance and system costs.

According to the analysis of trends in the literature, the most widely used hybrid energy systems are those that use solar and wind energy as the primary energy source and fuel cells that convert hydrogen energy into electricity as an alternative energy source. In this context, control algorithms and management strategies are used to optimized hybrid energy systems.

1.2. Current status of the "passive house" concept

The passive house concept limits heat loss to a maximum of 120 kWh/m^2* year (living area). The aim is to reduce heat loss through insulation, to save energy and thus to create an energy-efficient building. From an energy point of view, these buildings can be classified as follows:

Passive houses follow:

- Save energy by drastically limiting energy consumption;
- Achieving higher thermal comfort requirements;
- Use of innovative environmentally friendly and recyclable material solutions;
- Use of renewable energy sources.

The total heating/cooling requirement of a passive house may not exceed 15 kWh/m^2*year and the total energy requirement will be supplied from renewable sources. In the case of the Classic Passive House, this will be 60 kWh/m^2*year. A Passive House Plus building is much more efficient because it cannot consume more than 45 kWh/m^2*year of energy from renewable sources. The house must also be able to generate at least 60 kWh/m^2*year. In the case of the Premium Passive House, the energy requirement is limited to only 30 kWh/m^2*year, with at least 120 kWh/m^2*year of energy supplied from renewable sources.

1.3. Research directions

The topic addressed in this PhD thesis is in line with the theme addressed at international level on the measures required to reduce carbon dioxide emissions and increase the use of renewable energy sources, with the integration of innovative energy storage solutions using hydrogen technology, a direction that is also reflected in the research strategy of ICSI-Rm. Vâlcea.

This new direction responds to social needs and is in line with European Union directives with the impact of reducing energy consumption, greenhouse gas emissions and increasing the use of renewable energy sources in various applications. This PhD thesis addresses for the first time in the institute the topic of the use of hybrid energy systems for powering buildings.

A critical analysis of the state of play shows that there are concerns in the field of hybrid energy systems. Different primary energy sources and energy storage solutions have been identified. In this context, *a research direction of the PhD thesis* aims at configuring and optimizing hybrid energy systems capable of supporting a virtual passive house with energy. In order to identify the optimal hybrid energy system solution, multi-criteria analysis is used. The research itself starts from the establishment of seven types of hybrid energy systems, which supply energy to the virtual passive house, continuing with the simulation of the sizing of these systems, analyzing the results obtained in terms of energy, environmental and economic performance.

Configuration of the hybrid energy systems analyzed:

- Energen1 system - photovoltaic panels (PV), fuel cell (FC) and electrolyser (E) for on-site hydrogen production + hydrogen storage tank, the system is connected to the national grid;
- Energen2 system - wind turbine (TE), fuel cell (FC) and electrolyser (E) for on-site hydrogen production + hydrogen storage tank, the system is connected to the national grid;
- Energen3 system - photovoltaic panels (PV) and wind turbine (TE), fuel cell (FC) and electrolyser (E) for on-site hydrogen production + hydrogen storage tank, the system is connected to the national grid;

- Energen4 system - photovoltaic panels (PV), wind turbine (TE) and rechargeable batteries (B for electricity storage), the system is connected to the national electricity grid;
- Energen5 system - photovoltaic panels (PV), fuel cell (FC) powered by hydrogen taken from a hypothetical hydrogen transmission and distribution network, the system is connected to the national electricity grid;
- Energen6 system - wind turbine (TE), fuel cell (FC) powered by hydrogen taken from a hypothetical hydrogen transmission and distribution network, the system is connected to the national electricity distribution grid;
- Energen7 system - photovoltaic panels (PV) and wind turbine (TE), fuel cell (FC) powered by hydrogen taken from a hypothetical hydrogen transmission and distribution network, the system is connected to the national electricity grid.

Thesis objective. Decreasing the use of conventional energy resources, making stationary applications more energy efficient, ensuring energy security and reducing pollutant emissions are of great global concern. Reducing global fossil fuel reserves and the global warming effect by at least -2oC by 2030 has required action through national and international energy and environmental directives and strategies. In the field of stationary applications for ***more energy-efficient buildings, the integration of renewable energy technologies and the use of alternative technologies based on fuel cells and hydrogen as a storage solution, harnessing renewable sources (sun, wind, water) is required.***

In recent times, particular emphasis has been placed on energy efficiency measures, taking into account thermal insulation of the building envelope with appropriate materials and technologies, use of high efficiency heating/cooling equipment with automated/smart building energy management systems, programmed room temperature control systems and maximizing the use of natural lighting.

The main objective of the PhD thesis is to identify and define solutions for using the potential of unconventional resources capable of powering a virtual passive house.

The specific objectives are:

- Critical analysis of the current state of research in hybrid energy systems;
- Sizing the seven hybrid energy systems;
- Performance evaluation of energy indicators;
- Performance evaluation of environmental protection indicators;
- Performance evaluation of financial indicators;
- Multicriteria comparative analysis of hybrid energy systems;
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Chapter 2. Estimation of energy consumption for the virtual passive house building

2.1. Consumer description - passive house residential building virtual

2.1.1. Estimation of the energy consumption profile of the passive house residential building virtual house

Based on the estimated energy consumption profile of the consumer - a virtual passive house residential building - and on the basis of computational simulations, solutions for sizing and optimizing a hybrid energy system integrating renewable energy sources will be established, which will satisfy the consumption profile within the recoverable potential of the renewable sources.

Determining the energy consumption of the building under consideration requires the definition of initial data on the geo-climatic characteristics of the site and the assessment of the availability of renewable sources in the area under study.

Energy consumption was estimated for all types of building functions: heating/cooling, domestic hot water preparation, ventilation/air conditioning, lighting and the provision of electricity to run appliances and auxiliary electrical equipment for installations.

Estimated total energy consumption

In this chapter it is necessary to estimate the energy consumption to be provided by renewable energy generation systems in passive houses. To this end, this chapter has provided the necessary input data for the case studies in the following chapters with reference to the in-service simulations of the energy systems, namely: ***the total estimated energy consumption for the virtual passive house is 5070 kWh/year, of which the energy consumed for space heating is 1580 kWh/year and represents 31.16%, the energy for the preparation of hot water consumption is 1515 kWh/year being 29.88%, the energy consumed for the lighting installation and household consumption being 1566 kWh/year represents 30.88%, and the energy consumed for the consumption of auxiliary equipment is 400 kWh/year, i.e. 7.88% of the total energy consumption.***

Chapter 3. Virtual simulation tools

3.1. Virtual simulation tools for hybrid energy systems

This chapter is devoted to the description of virtual computational simulation tools for the optimization and simulation in operation of hybrid power generation systems based on unconventional, alternative energies.

The HOMER software was developed by the National Renewable Energy Laboratory (NREL) to optimize low power (micropower) energy systems . The software can evaluate a wide range of options related to stand-alone (off-grid) and grid-connected (on-grid) system components.

RETScreen International is a renewable energy generation system design software, developed from a collection of spreadsheet-based tools for renewable energy technology (RET) project assessment developed by Natural Resources Canada.

DER-CAM is a hybrid energy system optimization software developed by the Ernest Orlando Lawrence Berkeley National Laboratory (LBNL). In the first stage, hourly electricity consumption profiles and fuel prices are entered. The software generates reports with the results of the electricity and heat balance as well as other results such as costs and the amount of carbon dioxide emissions.

HYBRIDS is a commercially available renewable energy assessment app developed by Solaris Homes (Queenskand, Australia). It has a module to insert average daily consumption and estimated resource data for each month.

Hybrid 2, developed by the Renewable Energy Research Laboratory at the University of Massachusetts, is a software package for long-term performance and economic analysis of hybrid energy systems, including three types of electric generators, wind turbines, photovoltaic panels, and diesel generators.

FACES is a software tool dedicated to choosing the optimal primary energy source at the building design stage. It simulates the energy, environmental and economic performance of an energy system. The advantage of the software lies in the use of predefined algorithms and data that are integrated into FACES and that offer the possibility of simulation with insufficient data available at the design stage for calculating energy consumption.

The software iHOGA (improved Hybrid Optimization by Genetic Algorithms) was chosen for the case studies in this PhD thesis. In the following, a description of how the software is used and how it works is presented, as well as input data on the configuration, optimization criteria and technical, environmental and economic characteristics of unconventional energy conversion equipment.

3.2. Description of the iHOGA virtual simulation environment

In order to carry out the simulations, it was decided to use the commercial computational software *iHOGA PRO+*, for which a *license* was purchased *by the National Research and Development Institute for Cryogenic and Isotope Technologies Râmnicu Vâlcea, an* institution where I work as a research scientist.

In this sub-chapter the main components, structure, use and operation of the software are described, with the customization of the input data in order to realize the virtual conditions for the simulations in the sense of the PhD thesis topic, namely the simulation of hybrid energy systems that support the energy virtual passive house presented in Chapter 2, located in Râmnicu Vâlcea, with a developed area of 120 m^2 and an estimated final annual energy consumption of 5070 kWh.

Chapter 4. Case study simulations

This chapter is devoted to the presentation of the results of simulations under virtual operating conditions of configured hybrid energy systems, comprising the equipment for converting various forms of energy into electricity presented in the previous chapter. These energy systems**.**

4.1.1. Schematic diagram Energen1

The Energen1 energy system uses solar radiation as a primary source of energy[3], and as an alternative secondary resource for periods of weather intermittency and day/night alternations electricity is produced by a hydrogen fuel cell array. To ensure that the fuel cell operates as required by consumption, hydrogen is produced by electrolysis of water with an electrolyser fed with excess primary electricity,[4] and stored in a pressurized storage tank. The Energen1 system is shown schematically in Figure 4.1.

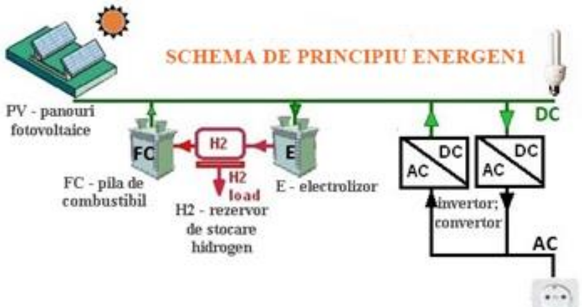


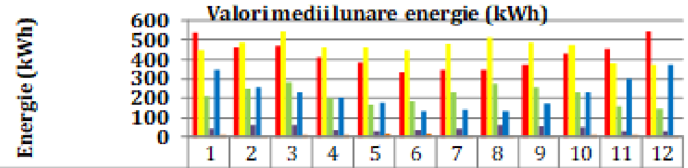
Figure 4.1. Schematic diagram of the Energen system1

Based on the input data presented in the previous chapters, a series of computational simulations were performed using *iHOGA* software. The component equipment that make up the optimal Energen1 system are: ***photovoltaic panels*** with a total installed nominal power of 6.16 kWp, ***fuel cell*** with a nominal power of 2 kW, electrolyser with a nominal power of 2 kW, 1800 VA inverter and hydrogen tank providing storage of maximum 10 kg of hydrogen.

4.1.2. Energy performance indicators

It is found that during one year of operation of the Energen1 system, PV panels produce 90.80% of the total energy generated by the system. Of the total electricity production using renewables for energy support of the passive house 52.95% is used, the remaining 47.05% is used in electrolysis of water and 40.60 kg H_2 /year is obtained.

The hydrogen produced is consumed by the fuel cell in the production of useful electricity for the consumer, which represents 9.20% of the total energy produced by the system. The monthly average values of the energy indicators, resulting from the simulations in operation of this type of system are illustrated numerically in Figure 4.2.



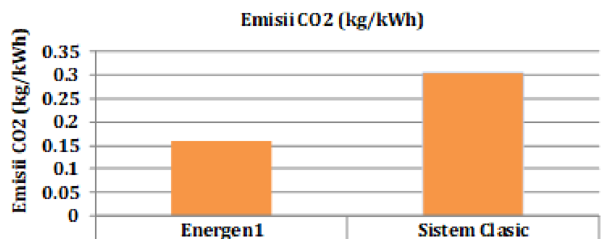
	1	2	3	4	5	6	7	8	9	10	11	12
Consum energie	537	460	465	410	382	332	345	345	369	426	454	546
PV	451	484	547	462	458	446	482	513	488	472	377	370
Electrolizor	209	249	280	198	165	186	230	273	259	229	162	146
Pila de combustibil	46.9	60.5	65.4	39.8	34.3	36.8	46.1	61.4	56	52	33.3	30.3
Energie neacoperită	347	259	232	205	180	134	138	136	175	229	299	372
Excces	10.5	4.6	9.6	12.9	19.1	16.8	6.7	8.2	6.4	12.5	10.5	6.4

Figure 4.2. Monthly average energy values of the Energen system1

The availability of solar radiation has a direct influence on hydrogen production,[5] i.e. on the electrolyser - the equipment that uses water and solar energy to generate hydrogen and oxygen, thus also influencing the running time of this equipment [6]. Hydrogen consumption is conditioned by the desired energy consumption produced by the fuel cell, imposed by the power load requirement.

The variable nature of the primary energy sources involved in electrolysis imposes intermittencies in hydrogen production that are directly related to the specific features of each month. In the course of a day, the fuel cell [7] will consume all the hydrogen produced by the electrolyser, operating intermittently depending on the amount of hydrogen available. Due to this, the fuel cell's function as a back-up to cover peaks in consumption and intermittency due to weather conditions is partially fulfilled.

4.1.3. Performance indicators for CO_2



	Energen1	Sistem Clasic
Emisii CO2	0.16	0.3055

Figure 4.3. Performance indicators for CO_2

The passive house supported by the studied Energen1 system incorporates carbon dioxide emissions of 0.16 $kgCO_2$ /kWh, which is 52.37% (fig. 4.3.) of the average value calculated for a standard building supported by conventional energy generation systems.

4.1.4. Financial performance indicators

In this hypothesis the hydrogen technology has the highest share in the cost diagram, the first place is occupied by the production and storage unit - the electrolyser together with the hydrogen tank, i.e. 48.20%, followed by the conversion unit - the fuel cell with 19.35%.

. The unit price of energy can be defined as the ratio of the total annual cost of the power generation system to the total annual amount of electricity produced by the system. In this case, a unit price of energy production from alternative resources of 0.63 €/kWh has been calculated.

4.2.1. Schematic diagram Energen2

The Energen2 hybrid energy system uses wind power as the primary renewable source of energy generation and electricity from a hydrogen fuel cell array as a secondary resource for periods of weather intermittency. In order to ensure that the fuel cells operate according to consumer requirements, the hydrogen produced by electrolysis of water with an electrolyser fed with excess primary electricity is stored in a pressurised storage tank. The Energen2 system is shown schematically in Figure 4.4.

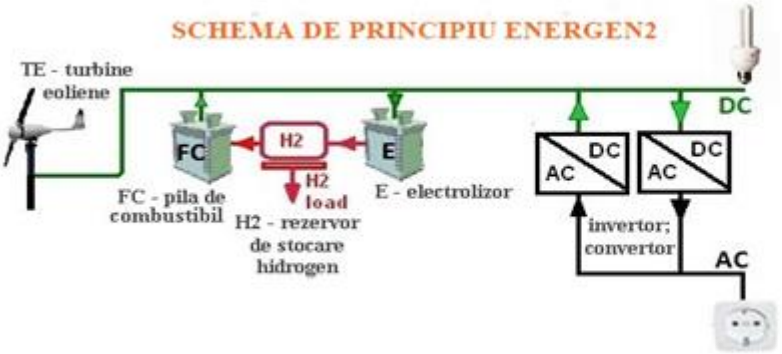


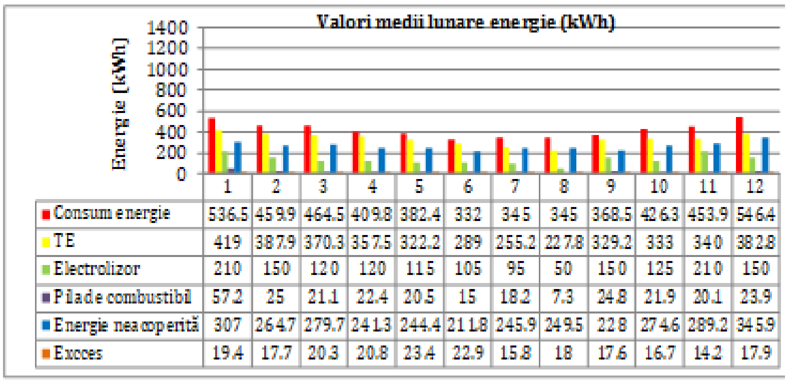
Figure 4.4. Schematic diagram of the Enegen2 type system

Based on the input data presented in the previous subchapters, simulations were performed with *iHOGA* software. The component equipment of the Energen2 system are: ***wind turbine*** with a total installed rated power of 3.26 kWp, ***fuel cell*** with a rated power of 2 kW, electrolyser with a rated power of 2 kW, 1800 VA inverter and hydrogen tank to store a maximum of 10 kg of hydrogen.

4.2.2. Energy performance indicators

The annual average values of the performance parameters are shown in Figure 4.5. It can be seen that during one year of operation of the Energen2 system, the wind turbines produce 93.54% of the total energy generated by the system.

Of the total renewable electricity production for the energy support of the virtual passive house 71.10% is used, the remaining 28.90% is used in the electrolysis of water and 18.80 kg H_2/year is obtained, which is consumed by the fuel cell in the production of electricity useful to the consumer, which represents 6.45% of the total energy produced by the system.



	1	2	3	4	5	6	7	8	9	10	11	12
Consum energie	536.5	459.9	464.5	409.8	382.4	332	345	345	368.5	426.3	453.9	546.4
TE	419	387.9	370.3	357.5	322.2	289	255.2	227.8	329.2	333	340	382.8
Electrolizor	210	150	120	120	115	105	95	50	150	125	210	150
Pila de combustibil	57.2	25	21.1	22.4	20.5	15	18.2	7.3	24.8	21.9	20.1	23.9
Energie neacoperită	307	264.7	279.7	241.3	244.4	211.8	245.9	249.5	228	274.6	289.2	345.9
Exces	19.4	17.7	20.3	20.8	23.4	22.9	15.8	18	17.6	16.7	14.2	17.9

Figure 4.5. Monthly average energy values of the Energen2 system

The intermittent nature of the wind speed has a direct influence on hydrogen production, i.e. on the electrolyser - the equipment that uses water and wind energy to generate hydrogen [8] and oxygen, and therefore also influences the running time of this type of equipment. Hydrogen consumption is conditioned by the energy consumption to be covered by the fuel cell, depending on the requirements of the consumer.

The variable nature of the primary energy sources involved in electrolysis imposes intermittencies in hydrogen production that are directly related to the specific features of each month. In the course of a day, the fuel cell will consume all the hydrogen produced by the electrolyser, operating intermittently according to the amount of hydrogen available. Because of this, the fuel cell's function is to reserve energy to cover peaks in consumption and intermittency due to weather conditions and is partially fulfilled.

4.2.3. Performance indicators for CO_2

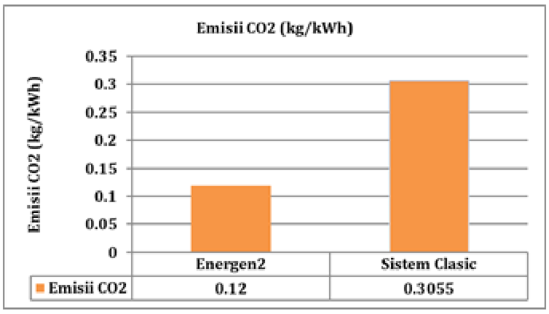


Figure 4.6. Performance indicators for CO_2

The passive house supported by the Energen2 system studied generates carbon dioxide emissions embedded in the system in the amount of 0.12 $kgCO_2$ /kWh, which is 39.28% of the average value calculated for a standard building supported by conventional energy generation systems.

4.2.4. Financial performance indicators

In this hypothesis it is observed that the hydrogen technology has the highest share in the cost diagram, the first place is occupied by the production and storage unit - the electrolyser together with the hydrogen tank, i.e. 45.65%, followed by the conversion unit - the fuel cell with 15.47%.

The unit price of energy can be defined as the ratio of the total annual cost of the power generation system to the total annual amount of electricity produced by the system. In this case, a unit price of energy production from alternative resources of 0.70 €/kWh has been calculated.

4.3.1. Energen3 principle scheme

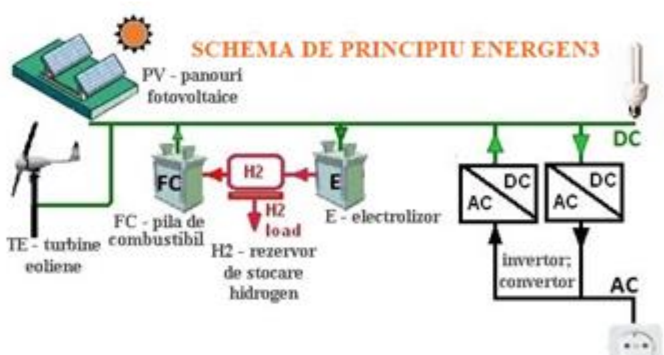


Figure 4.7. Schematic diagram of the Energen system3

The Energen3 hybrid energy system uses both types of primary energy generation sources, solar radiation and wind speed, and as an alternative secondary resource uses electricity produced by a fuel cell array powered by hydrogen produced locally by an electrolyser and stored in a pressurised container. The Energen3 hybrid system is shown schematically in Figure 4.7.

4.3.2. Energy performance indicators

It is found that during one year of operation of the Energen3 system, 57.32% of the total renewable electricity production for energy support of the passive house is used, the remaining 42.68% is used in the electrolysis of water and 68.40 kg H_2 /year is obtained, which is consumed by the fuel cell in the production of electricity useful to the consumer, which represents 9.73% of the total energy produced by the system.

The availability of solar radiation and wind speed have a direct influence on hydrogen production, [9] respectively on the electrolyser - the equipment that uses water and solar energy and/or wind energy to generate hydrogen and oxygen, thus also influencing the running time of this equipment [10]. Hydrogen consumption is conditioned by two considerations: on the one hand by the energy consumption to be covered by the fuel cell [11].

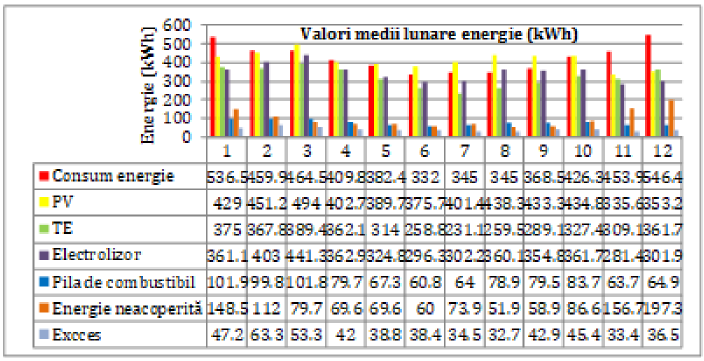


Figure 4.8 Monthly average energy values of the Energen system3

4.3.3. Performance indicators for CO_2

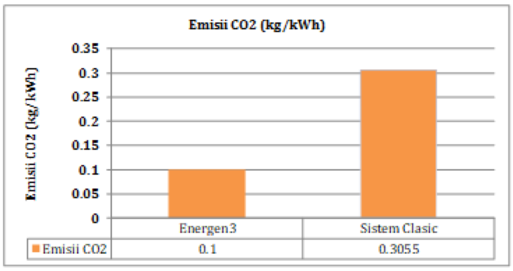


Figure 4.9. CO_2

The passive house supported by the Energen3 system studied generates carbon dioxide emissions embedded in the system in the amount of 0.10 $kgCO_2$ /kWh, which is 32.73% of the average value calculated for a standard building supported by conventional energy generation systems.

4.3.4. Financial performance indicators

It can be seen that the hydrogen technology has the largest share in the cost diagram, the first place is occupied by the production and storage unit - the electrolyser together with the hydrogen tank, i.e. 42.41%, followed by the conversion unit - the fuel cell with 23.03%.

4.4.1. Energen principle scheme4

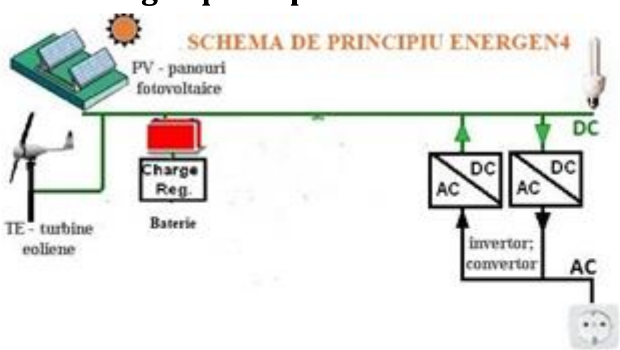


Figure 4.10. Schematic diagram of the Enegen4 type system

The Energen4 energy system uses both types of primary energy generation sources, i.e. solar radiation and wind speed, and to compensate for the intermittent nature of wind and solar energy to meet consumer requirements, excess energy is stored in rechargeable batteries The Energen4 system is shown schematically in Figure 4.10.

4.4.2. Energy performance Indicators

From the total renewable electricity production for the energy support of the virtual passive house, 22.98% is stored in batteries, 40.32% is used directly by the passive house consumer and the remaining 36.70% represents excess energy produced by the system, which can be used in other applications or fed into the national grid.

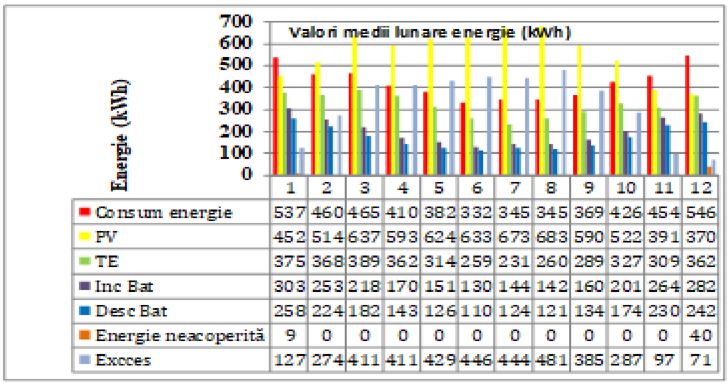


Figure 4.11. Monthly average energy values of the Energen system4

4.4.3. Performance indicators for CO_2

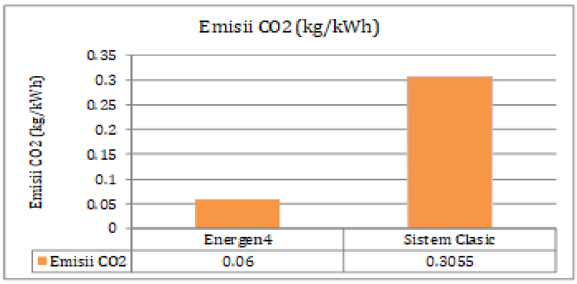


Figure 4.12. Performance indicators for CO_2

The passive house supported by the Energen4 system studied generates carbon dioxide emissions embedded in the system in the amount of 0.06 $kgCO_2$ /kWh, which is 19.64% of the average value calculated for a standard building supported by conventional energy generation systems.

4.4.4. Financial performance indicators

In this hypothesis it is observed that the wind energy conversion technology has the highest share in the cost diagram, the first place is occupied by the wind speed electricity generation unit, i.e. 34.52%, followed by the solar radiation conversion unit, i.e. photovoltaic panels with a share of 23.58%.

4.5.1. Energen principle scheme5

The Energen5 energy system uses solar radiation as a renewable primary source of energy generation and hydrogen delivered through a hypothetical centralised distribution network, converted to electricity through a fuel cell-to-electricity array, as a secondary resource [12]. The analysis of this type of hybrid energy system [13] is carried out in the perspective of the future hydrogen economy [14], in which there will be a hydrogen transport and distribution network. The Energen5 system is schematically shown in Figure 4.13.

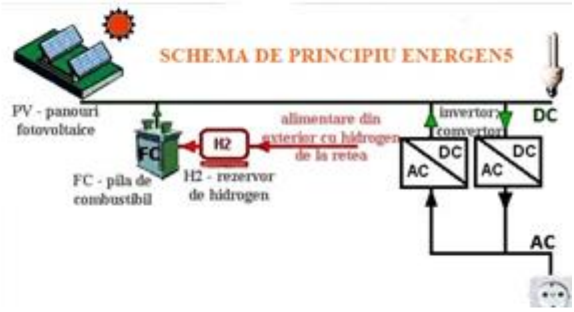


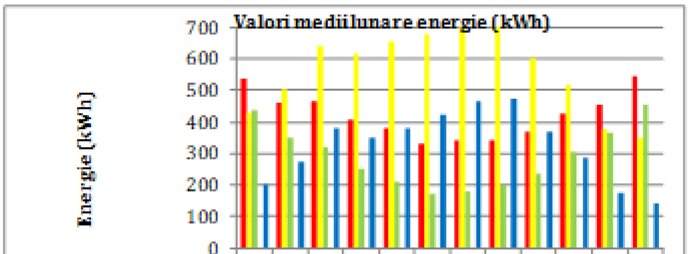
Figure 4.13. Schematic diagram of the Energen system5

Based on the input data presented in the previous subchapters, the simulation was performed with the *iHOGA* software and the resulting configuration is shown in Table 4.25. The component equipment that make up the Energen5 system are: ***photovoltaic panels*** with a total installed nominal power of 6.16 kWp, ***fuel cell*** with nominal power of 2 kW, inverter 1800 VA .

4.5.2. Energy performance indicators

It was found that the configured Energen5 hybrid power system generates an amount of electricity that fully meets the electricity demand at the consumer level. There are no periods of unmet demand throughout the year.

The operation of this system produces an amount of energy in excess of demand, which, given the configuration of the system, which does not include a storage solution, can be exported to the national grid. In contrast to the previously studied cases, the advantage of combining the two types of energy completely eliminates the shortcomings due to the intermittent nature of solar radiation, in particular that of day/night alternation, due to the fact that hydrogen is available on demand from the centralized grid and thus disappears the disadvantage of hydrogen production conditional on the availability of renewables.



	1	2	3	4	5	6	7	8	9	10	11	12
Consumenergie	537	460	465	410	382	332	345	345	369	426	454	546
PV	431	501	641	616	656	677	723	715	602	517	378	352
Pila de combustibil	440	352	319	250	209	170	180	197	237	304	367	455
Energie neacoperită	0	0	0	0	0	0	0	0	0	0	0	0
Exces	204	274	380	350	381	421	463	472	370	286	176	142

Figure 4.14. Monthly average energy values of the Energen system5

By calculating the degree of use of alternative energy resources for the purpose of energy support of the passive house under the conditions specified above and using the established component equipment configuration, it can be stated that the degree of energy autonomy of the system from the centralized electricity distribution network is a function of this. The degree of autonomy of the passive house powered by an Energen5 system is 100%.

4.5.3. Performance indicators for CO_2

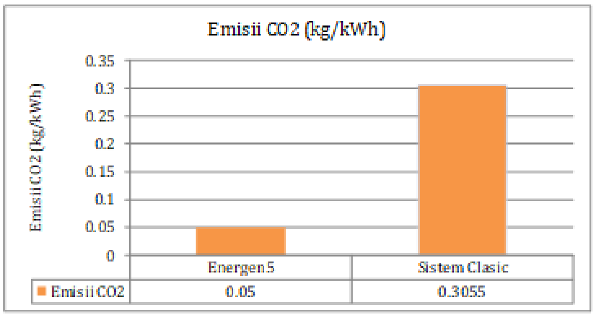


Figure 4.15. Performance indicators for CO_2

The passive house supported by the Energen5 system studied generates carbon dioxide emissions embedded in the system in the amount of 0.05 $kgCO_2$ /kWh, which is 16.36% of the average value calculated for a standard building supported by conventional energy generation systems.

4.5.4. Financial performance indicators

In this hypothesis it is observed that the hydrogen technology has the highest share in the cost diagram, the first place is occupied by the electricity production unit - fuel cell, i.e. 44.25%, followed by the hydrogen purchase cost with a percentage of 38.24%. As we have pointed out in the previous statements hydrogen electricity generation technology is in continuous development, and as research results are validated, it is expected that costs will decrease so that in the near future these types of equipment and technologies will be competitive with other technologies in the field of energy generation and storage.

4.6.1. Energen principle scheme6

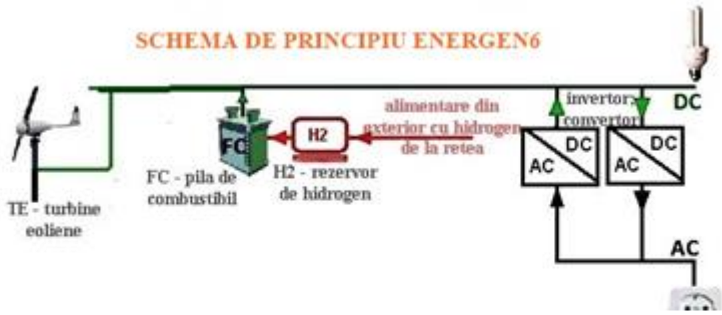


Figure 4.16. Schematic diagram of the Enegen6 type system

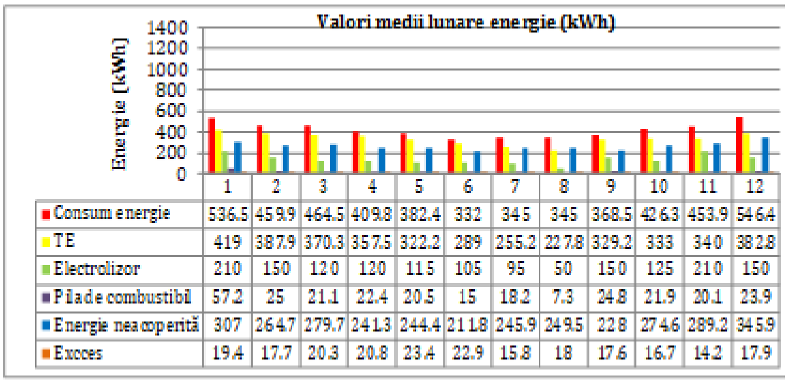
Based on the input data presented in the previous subchapters, the simulation was carried out with the *iHOGA* software. The equipment components that make up the Energen6 system are: ***wind turbine*** with a total installed rated power of 3.26 kWp, ***fuel cell*** with a rated power of 2 kW, inverter 1800 VA.

4.6.2. Energy performance indicators

The Energen6 hybrid energy system was found to generate an amount of electricity that fully meets the consumer's electricity demand. The operation of this system produces an amount of energy that exceeds demand, which can be exported to the national electricity grid.

In contrast to the previously studied cases, the advantage of combining the two types of alternative energies completely removes the shortcomings due to the intermittent nature of the wind speed, due to the fact that hydrogen is available on demand from the centralized grid.

By calculating the degree of utilization of wind and hydrogen resources for the purpose of energy support of the virtual passive house under the previously specified conditions and using the established component equipment configuration, it can be stated that the resulting degree of energy autonomy of the system from the centralized power grid is 100%.



	1	2	3	4	5	6	7	8	9	10	11	12
Consum energie	536.5	459.9	464.5	409.8	382.4	332	345	345	368.5	426.3	453.9	546.4
TE	419	387.9	370.3	357.5	322.2	289	255.2	227.8	329.2	333	340	382.8
Electrolizor	210	150	120	120	115	105	95	50	150	125	210	150
Pila de combustibil	57.2	25	21.1	22.4	20.5	15	18.2	7.3	24.8	21.9	20.1	23.9
Energie neacoperită	307	264.7	279.7	241.3	244.4	211.8	245.9	249.5	228	274.6	289.2	345.9
Exces	19.4	17.7	20.3	20.8	23.4	22.9	15.8	18	17.6	16.7	14.2	17.9

Figure 4.17. Monthly average energy values of the Energen system6

4.6.3. Performance indicators for CO_2

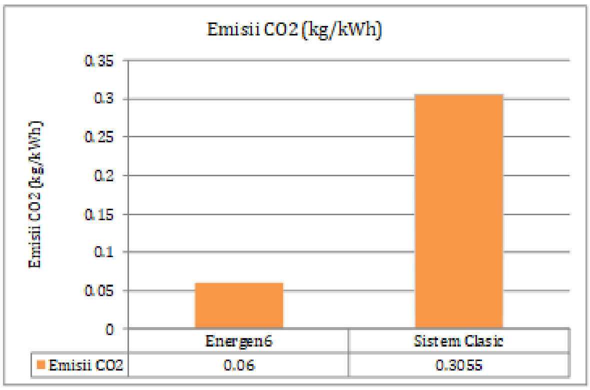


Figure 4.18. Performance indicators for CO_2

The passive house supported by the Energen6 system studied generates carbon dioxide emissions embedded in the system in the amount of 0.06 $kgCO_2$ /kWh, which is 19.64% of the average value calculated for a standard building supported by conventional energy generation systems.

4.6.4. Financial performance indicators

In this hypothesis, it is observed that the hydrogen technology has the highest share in the cost diagram, the first place is occupied by the hydrogen fuel cell electricity generation unit, i.e. 46.05%, followed by the hydrogen fuel purchase cost with 36.90%.

4.7.1. Energen principle scheme7

The Energen7 system uses solar radiation and wind speed as renewable primary sources of energy generation, and *hydrogen delivered through a hypothetical centralized distribution network,* converted to electricity via a fuel cell array into electricity [15], as a secondary resource. The analysis of this type of hybrid energy system is carried out in the perspective of the future hydrogen economy, in which there will be a hydrogen transport and distribution network. The Energen7 hybrid energy system is shown schematically in Figure 4.19.

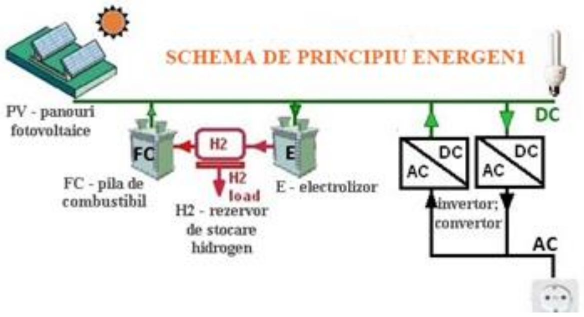


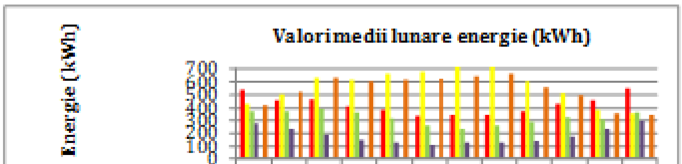
Figure 4.19. Schematic diagram of the Energen system7

Based on the input data presented in the previous subchapters, the simulation was performed with *iHOGA* software. The component equipments that make up the Energen7 system are: ***photovoltaic panels*** with a total installed rated power of 6.16 kWp, ***wind turbine*** with a total installed rated power of 3.26 kWp, ***fuel cell*** with a rated power of 2 kW, inverter 1800 VA .

4.7.2. Energy performance indicators

It is found that over a year of operation of the Energen7 system, photovoltaic panels produce 53.05% and wind turbines produce 29.97% of the total energy generated by the system. 50.38% of the total renewable electricity production for passive house energy support is used, and 16.98% of the total fuel cell power is supplied to the system.

In contrast to the previously studied cases, the advantage of combining the two types of alternative energy completely removes the shortcomings due to the intermittent nature of solar radiation and wind speed, due to the fact that hydrogen is available on demand from the centralized grid [16] and thus the disadvantage of hydrogen production conditional on the availability of renewable source disappears



	1	2	3	4	5	6	7	8	9	10	11	12
Consum energie	537	460	465	410	382	332	345	345	369	426	454	546
PV	431	501	632	616	661	677	723	715	602	517	378	352
TE	375	368	389	362	314	259	231	260	289	327	309	362
Pila de combustibil	274	228	189	146	128	113	127	126	139	180	235	294
Energie neacoperită	0	0	0	0	0	0	0	0	0	0	0	0
Exces	415	518	631	608	619	624	642	661	562	489	353	344

Figure 4.20. Monthly average energy values of the Energen system7

4.7.3. Performance indicators for CO_2

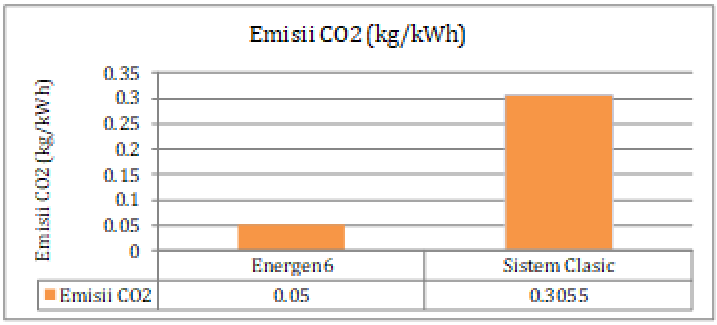


Figure 4.21. Performance indicators for CO_2

The passive house supported by the Energen7 system studied generates carbon dioxide emissions embedded in the system in the amount of 0.05 kgCO_2 /kWh, which is 16.36% of the average value calculated for a standard building supported by conventional energy generation systems.

4.7.4. Financial performance indicators

In this hypothesis, it is observed that the hydrogen technology has the highest share in the cost diagram, the first place is occupied by the hydrogen fuel cell electricity generation unit, i.e. 36.62%, followed by the hydrogen fuel purchase cost with a share of 26.52%.

Chapter 5. Comparative analysis of performance parameters of hybrid energy systems

Given the results of the running simulations of the seven hybrid energy systems considered in the case studies presented in Chapter 4, it becomes necessary to determine the optimal hybrid energy support option for the virtual passive house building analysed. The present chapter is dedicated to the comparative analysis of the recorded performance parameters, in which the results have been addressed in parallel and comparative graphs have been prepared and critically analyzed.

In order to substantiate the selection decision of the optimal hybrid energy system [17] the results obtained were compared in a multi-criteria analysis. **The** analysis and selection method used is based on the Analytical Network Process (ANP) model, [18] and the calculations were performed using Super Decisions V3.0 software.

Table 5.1. Alternatives and criteria used in multi-criteria comparative analyses

Nr crt	Alternative / Criteria	Energen 1	Energen 2	Energen 3	Energen 4	Energen 5	Energen 6	Energen 7
1	Annual energy RES	5549	4013	8784	10525	6804	3845	10651
2	Degree of autonomy	53,10	44,08	79,8	99,10	100	100	100
3	Back-up energy	562	277	946	2419	0	0	0
4	Purchased energy	2739	3210	1172	50	0	0	0
5	Excess energy	124,2	205	456	2366	2843	1154	4133
6	Total CO_2	1371	1469	898	439	435	413	484
7	CO_2 emissions /kW	0,16	0,12	0,1	0,06	0,05	0,06	0,05
8	Investment value	35910	39805	47279	26808	21818	32858	31712
9	Cost back-up	44046	45865	45492	8889	51003	56929	31959
10	Cost 25 years	91409	101002	107946	37650	116622	146545	96992
11	Unit price / kW	0,63	0,7	0,75	0,26	0,81	1,02	0,67

Analysis of performance parameters using comparative graphs

In order to compare the results of the running simulations of hybrid energy systems, comparative graphs were drawn up based on the *energy, environmental and economic parameters* obtained in the case studies in the previous chapter [19]. The purpose of these comparative graphical analyses is to select the optimal hybrid energy system variant [20] among the seven types studied. The best application for the passive house power supply is to obtain electricity using systems that offer maximum efficiency, minimum pollution and minimum cost [21].

5.1.1. Energy performance analysis

As the main energy indicator, the *average annual amount of energy used from renewable energy resources* (sun or wind). Comparison *criterion 2* refers to the *degree of consumer autonomy from the national conventional electricity grid*,[22]. *Criterion 3* refers to the back-up *energy* needed to support the consumer [23]. Comparison criterion 4 is the *energy purchased from the national* electricity *grid* required to support the consumer. Comparison *criterion 5* refers to the *excess energy resulting from the operation of the systems* and is comparative.

Analysis of environmental performance

Parameters related to environmental protection elements [24] that are comparatively analyzed refer to the carbon dioxide emissions generated by the studied hybrid energy systems, in particular the CO_2 emissions embodied in the equipment of these systems.

Analysis of economic performance

The financial indicators considered as comparison criteria in the benchmarking analysis are: the value of the initial investment, the cost of energy storage and/or reserve, the cost of the system over a 25-year lifetime and the unit price per kWh energy.

Analysis of performance parameters using the ANP method

The multi-criteria analysis was based on the application of the ANP method and involved ***14 steps.***

In this chapter, a case study on the ***choice of the best hybrid energy support solution for the virtual passive house consumer*** sized in Chapter 2 was presented. Comparative analyses of the performance parameters recorded by the hybrid energy systems configured and simulated in operation in Chapter 4 involved a parallel approach to the results and comparative graphs were drawn up and analyzed. In order to inform the decision on the selection of the optimal alternative energy system to be implemented for hybrid energy consumer support, the *results obtained were compared in a multi-criteria analysis*. The analysis and selection method used is based on the Analytical Network Process (ANP) model and the calculations were performed using Super Decisions V3.0 software.

In the case study seven alternatives are analyzed based on eleven decision criteria. The decision criteria considered for the basis of the decisions were: annual energy generated by locally available alternative resources; degree of autonomy from the conventional electricity grid, battery back-up energy or hydrogen energy; energy purchased from the conventional grid; excess energy generated by hybrid energy systems; total CO_2 emissions; CO_2 emissions per kWh; investment value; cost of storage, energy back-up or hydrogen purchased from outside the hybrid energy system; total cost calculated for 25 years of system life; and unit price per kWh electricity.

The comparative analysis leads to the following conclusions: considered individually, each type of energy, environmental or economic indicator can argue for and against each of the seven power generation systems analyzed. Overall, these indicators provide arguments in favour of the Energen4 system, followed by Energen7 because they offer the highest energy efficiency both in meeting the energy consumption of the passive house consumer studied and in exploiting the potential of the non-conventional energies available in the situation of the site studied. The compared environmental performances recommend the Energen4 - hybrid system with energy storage in rechargeable batteries, as well as the independently produced hydrogen systems Energen5, Energen6 and Energen7 - as the best option.

From a financial perspective, the Energen4 system that stores renewable energy in rechargeable batteries is recommended as the optimal option, followed by Energen7 the system that supports the passive house consumer by hybridizing the three types of energy - solar, wind and hydrogen-based electricity. At the other end of the scale are systems with local production of hydrogen through electrolysis which, given the low degree of autonomy, purchase electricity from the conventional grid and yet have calculated financial indicators similar to those of systems providing 100% autonomy.

The ANP multi-criteria analysis assisted by Super Decisions V3.0 software supports the arguments made by the graphical analysis and leads to the following conclusions:

Based on the maximum overall priority, it is recommended as the optimal option to choose alternative A4, i.e. the Energen4 energy system which supplies the consumer with electricity through the conversion of solar and wind energy, and the storage for backup energy is done through rechargeable batteries, in the case of the passive house consumer located in Rm. Vâlcea, Romania, which has a calculated electricity consumption of 5070 kWh/year.

The mathematical model presented is flexible allowing the introduction of new criteria and sub-criteria as well as other alternatives. The methodology described in this case study can be modified and used according to the specific situation.

Chapter 6. General conclusions. Original contributions. Research trends and perspectives

6.1. General conclusions

The research topic of passive house and hybrid energy systems is in line with ensuring the sustainability of housing, contributing to the diversification of energy sources used, energy saving and pollution reduction.

This PhD thesis presents solutions for the use and integration of alternative energy sources - sun and wind together with energy storage technologies, in the energy support of *passive houses*. In this regard, the energy, environmental and economic performance of energy systems with different ways of energy hybridization and different alternative energy storage solutions (rechargeable battery, hydrogen) were analyzed. The alternatives chosen for the study were simulated under different assumptions and conditions of operation and use in order to highlight the performance of these hybrid energy system solutions in supporting the *passive house* with energy.

Virtual operating conditions of hybrid energy systems were realized by means of case studies set up, and then simulations were carried out in operation for a period of one year in order to demonstrate the overall usefulness of these systems and their component equipment. Calculations and simulations of the carbon dioxide emissions embodied in the systems were also carried out, as well as financial analyses of investment costs, running costs for a period of 25 years and the unit cost of a kWh of hybrid energy.

Given the results of the running simulations of the hybrid energy systems configured in the case studies, it becomes necessary to determine the optimal hybrid energy support option for the passive house building under analysis. One of the research directions addressed in the thesis was dedicated to comparative analyses of the recorded performance parameters, where the results were addressed in parallel and comparative graphs were drawn up and critically analyzed. Also, in order to substantiate the decision of selecting the energy system that represents the optimal alternative to be implemented for the hybrid energy support of the consumer, the obtained results were compared in a multi-criteria analysis. The analysis and selection method used is based on the Analytical Network Process (ANP) model and the calculations were performed using Super Decisions V3.0 software.

The research carried out on electricity generation with hybrid energy systems in the energy-efficient building sector, in particular passive houses, led to the following conclusions:

- the use of hybrid energy systems and alternative energy conversion technologies (sun, wind) in electricity generation can achieve 100% autonomy from the national grid;
- excess energy generated from the operation of solar irradiation and wind speed conversion equipment can be harnessed locally in hybrid energy systems by producing hydrogen through electrolysis, thus becoming an energy storage element, as hydrogen can be reconverted into electricity through fuel cells.;

- Local electrolytic hydrogen production in hybrid energy systems is directly influenced by the availability of renewable energy resources and is variable over the course of a year, which in turn influences the electricity production of the fuel cell, which is also directly proportional to the availability of hydrogen fuel;
- Carbon dioxide emissions from energy systems that power a passive house energy efficient building with hybrid energy are significantly lower, averaging over 55% less than conventional energy systems powering a standard residential building with electricity;
- The costs of solar and wind energy conversion equipment that are part of hybrid energy systems are competitive, but the technology for hydrogen production, storage and conversion to electricity and the costs of purchasing hydrogen fuel are high on the financial graph. Hydrogen power generation technology and ways of producing, storing and distributing hydrogen are subject to continuous research and development, which will influence and drive the continuous reduction of costs, and will make this equipment and hydrogen fuel competitive with conventional energy production and storage technologies.

6.2. Original contributions

Main *own contributions* to the thesis:

- Summary on the current state of hybrid energy systems internationally;
- Summary on the passive house concept;
- Making bibliometric maps in the field of hybrid energy systems;
- Estimate the total energy consumption of the virtual passive house consumer for: heating, domestic hot water preparation, lighting installation, household and auxiliary equipment;
- Drawing up daily/hourly energy consumption schedules for the virtual passive house;
- Synthesis of virtual software in the field of hybrid energy systems;
- Presentation of iHOGA software modules and technological equipment used;
- Establishing performance indicators for hybrid energy systems: energy, environmental and financial indicators;
- Virtual simulation of the seven hybrid energy systems;
- Evaluation of the energy performance of seven hybrid energy systems;
- Assessment of the environmental performance of the lifetime CO_2 emissions of each of the seven hybrid energy systems;
- Evaluation of the financial performance of the seven hybrid energy systems;
- Analysis of energy, environmental and financial performance;
- Analysis of performance parameters using the ANP method;
- Identify the optimal solution based on multi-criteria analysis;
- Technical specification sheet for a passive house supported by a hybrid energy system

6.3. Research trends and perspectives

The topics studied and analyzed during the present PhD thesis as well as the results obtained lead to the identification of future research directions in the field of the topic:

- proposing specific hybrid energy systems according to the energy potential of the consumers' location;
- configuration, optimization, design and simulation of real-time parameters of new energy hybridization solutions;
- extending research into other types of alternative energy sources and non-conventional energy conversion technologies (heat pump) that ensure high efficiency and reliability through hybridization with solar and wind renewables;

- configuration, optimization, simulation and design of new high-efficiency hybrid energy systems that can support stationary applications with energy for various functions, e.g. an nZEB residential building.
- development of a computational application such as software for the design of hybrid energy systems, which facilitates the configuration, optimization, calculation and sizing of equipment for the conversion of energy produced from renewable energy sources, depending on the energy consumption of the consumer so as to ensure its energy independence.

Starting from the definition of the passive house, it is considered that the combination with a new concept (smart house) can bring benefits to energy management (due to automation) through energy efficiency and conservation, but can also be the way to another research direction, the combination of the two concepts (passive house, smart house) being the way to the "house of the future".

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