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A Preliminary Environmental Assessment of Power Generation Systems for a Stand-Alone Mobile House with Cradle to Gate Approach

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ABSTRACT

Due to the sporadic characteristics of solar and wind power it has been a challenge to generate a highly reliable power with photovoltaic and or wind turbines alone. A fuel cell as a supplementary energy source is an alternative to overcome this challenge. PV/wind/fuel cell hybrid power system may be a feasible solution for stand-alone applications. In this study, which is a preliminary work of a comprehensive Life Cycle Assessment (LCA), comparison of the power generation alternatives in terms of environmental impacts by evaluating their environmental and energy efficiencies and impacts during the productions of the system components was given. Also, impacts during the production of wind turbines, PV panels, fuel cells and diesel generators were inspected. Eco-Indicator 99 impact assessment method was used as the impact assessment method. It was shown that the in human health and ecosystem quality damage categories the PV panels are less environmentally efficient when compared with other power generation technologies with similar capacities.

Keywords: *Wind, Photovoltaic, Fuel cell, Life Cycle Assessment, Stand-alone*

1. INTRODUCTION

As the interest among the general public towards environment grows, society has become more concerned about natural resource depletion and environmental pollution. Through this attention, industries and businesses were compelled to supply "greener" products by exploiting "greener" processes. The companies are obliged to look into changes for their processes to minimize the environmental effects of their products due to the fact that the environmental performance became an important factor of the competition [1].

Increasing eco-efficiency, reducing energy and raw material consuming per product, is an important way to meet the global environmental problems. To achieve this goal, the Life Cycle Assessment (LCA) is used for the evaluation of the eco-efficiency of the product. LCA investigates environmental impacts of e.g. systems or products from cradle to grave throughout the full life cycle, from the exploration and supply of the materials and fuels, to the production and operation of the investigated objects, to their disposal/recycling. LCA can also be applied to compare products or processes and to analyze the contribution of the life cycle stages to the overall environment load to prioritize the improvements on products or processes [2 – 4].

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2. LIFE CYCLE ASSESSMENT OF RENEWABLE ENERGY SYSTEMS

Renewable energy sources often presented as 'clean' sources without the consideration of their environmental impacts during the manufacture and transport. Although power generation from renewable resources is free from fossil fuel and greenhouse gas emissions, a considerable amount of energy is consumed in manufacturing and transportation of the elements of the systems. Also, the energy consumption and emissions from decommissioning phase of the systems must be taken into account for making a fully informed environmental study, that is to say when their entire life cycle of energy production taken into account, it would show that there is GHG emission and energy use throughout the stages of the life of renewable just as conventional electricity generation technologies have. Renewable energy sources provide several beneficiary management strategies from economic as well as environmental [2-6].

To evaluate future energy systems at early stage of market development has many advantages. Conduction of an LCA study will give the opportunity to evaluate the environmental and energetic impacts of alternative combinations of stand-alone power generation systems. The importance of LCA becomes apparent if one considers industrial processes (metallurgical, chemical, etc.) for products (metals, plastics, glass, etc.) and services, since almost all currently rely on fossil fuels, the consumption of which leads to a range of environmental impacts [7-8].

Stand-alone systems will hold an important share in developing countries, where there are still large rural areas without an available electrical grid. Stand-alone hybrid systems hardly have to justify their primary energy use since they are usually located in places where there is not competing energy source (e.g. remote areas, rural homes in developing countries, etc.). However, an LCA study can be very useful to keep track of the different system components and to identify the energetically and environmentally most expensive elements [5].

Solar radiation and wind are considered the most preferred renewable energy sources for their availability and inexhaustibility [9]. However, due to the sporadic characteristics of natural resources, it has been a challenge to generate a highly reliable power with photovoltaic and/ or wind turbines alone [10]. Theoretical and experimental studies have shown that using a fuel cell as another energy source had overcome this challenge. Also, in recent studies, the simulated results showed that a PV/wind/fuel cell hybrid power system may be a feasible solution for standalone applications [11-13]. Since a multi-source hybrid power system increases energy availability significantly, it becomes advantageous for practical applications that need highly reliable power regardless of location [14].

Most of the LCA studies hybrid power systems focus on wind-PV hybrid system. On the other hand, LCA studies that addresses fuel cells mostly focus on the use of fuel cells in transportation sector.

LCA consist of goal and scope definition, inventory analysis, impact assessment and interpretation phases (Figure 1).

In goal and scope definition phase the product/service that is going to be assessed is defined, data sources, system boundaries and the functional unit are stated.

Inventory analysis step contains the data collection and calculation procedures for the quantification of the relevant input and outputs [15].

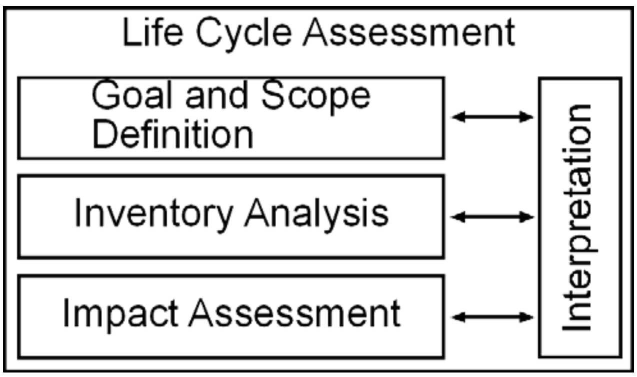


Figure 1. Steps of Life Cycle Assessment [15]

3. SYSTEM, GOAL AND SCOPE DEFINITION

Stand-Alone Mobile House project is a demonstration of the use of a PV/wind/fuel cell hybrid power system to supply electricity to a mobile house. The demonstrated system shows that it is compatible to use hydrogen as an energy carrier with other renewable energy sources such as PV and wind energy. The hybrid power system was designed based on the data of solar radiation and wind availability in the city of Istanbul, Turkey. PV and wind energy are used as the main energy sources for the system and the fuel cell performs as a backup power for the continuous generation of high quality power. The proposed mobile house demonstrates that it can be used as a stand-alone power system in areas where there is no access to grid and also as a backup power system to cover electricity shortage in certain situations such as natural disasters. Figure 2 shows the aforesaid mobile house and the team of engineers that worked on it [14].

Figure 2. The mobile house with hybrid power system

The main goal of this preliminary study is to conduct a comparative environmental study on the power generation alternatives of the stand-alone mobile house which uses electricity for air conditioning and home appliances. The study takes the power generation systems individually not the whole hybrid into account.

PV panels, wind turbine, fuel cell and diesel generator which are the alternatives for main and supplementary power resources are assessed with the cradle to gate scope; only the productions of these components are evaluated, the use and disposal phases are not taken into account.

The emissions from the power generation systems are scaled to the functional unit of the study, which is 1kW power generation capacity. Since the scope of this study only includes the production of the system components, cradle to gate, the positive or negative impacts that can be caused by the disposal and/or recycling of the components are not taken into consideration.

4. STUDIES

The components used in the mobile house's power generation are selected by load analysis and availability study made on solar radiation and wind speed.

System design starts with deciding whether the mobile house is connected to grid or not. Since the system is mobile, it has to be designed as a stand-alone application, independent from grid. Moreover, the load profile of the mobile house is analyzed to ensure that energy sources generate sufficient energy throughout the year. Equation (4.1) shows the estimation of average daily energy consumption [14].

$$E_d = \sum_{i=1}^{n} I_n V_n D_n \qquad (4.1)$$

Where I_n V_n, and D_n are the current, voltage and duty cycle of each appliance used in one day, respectively and Ed shows the total energy demand for the mobile house.

The average daily energy consumption of the mobile house is calculated as 4220Wh according to (4.1).

As one of the power generation systems PV panels consist of six panels which are composed of 72 polycrystalline cells and have an area of 125*125 cm2 and 166W power capacity. The data from ecoinvent database includes production of the cell matrix, cutting of foils and washing of glass, production of laminate, isolation, aluminum frame of the panel and AC-DC converter [16].

The city of Istanbul has the lowest daily irradiance and sun hours in December, as shown in Figure 3. The average radiation in December was calculated as 2030 Wh/m2/day when PV panels are tilted at 41°. Total area on the roof of the mobile house available for PV panels is 8.4m2 and the total energy generated in a day of December can be calculated with (4.2).

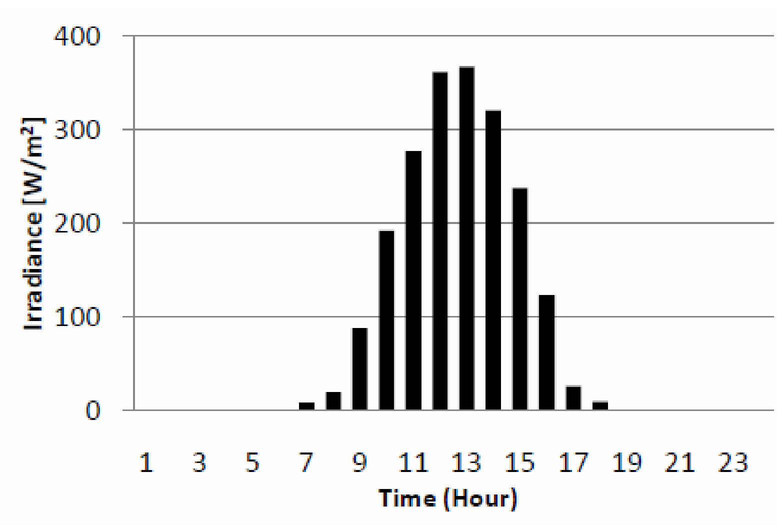


Figure 3. Solar irradiance data for December (41°N, 29°E) [14]

$$E_{pv} = \left(\int_0^{24} I_r dt \right) S \eta_{pv} \eta_b \eta_i \qquad (4.2)$$

Where:

S surface area of PV cells, η_{pv} efficiency of PV panels, η_b efficiency of batteries, η_i efficiency of inverter, I_r irradiance (W/m2), E_{pv} AC power generated by PV panels

The wind turbine has 1kW rated power with a permanent magnet synchronous generator. The data is scaled from another wind turbines data in the literature which has similar characteristics. Since the output of the wind turbine used in the project is DC, an inverter is also included to the calculations.

As shown in Figure 4, the availability of wind was determined by the average daily wind speed in December in Istanbul at 10m altitude [14].

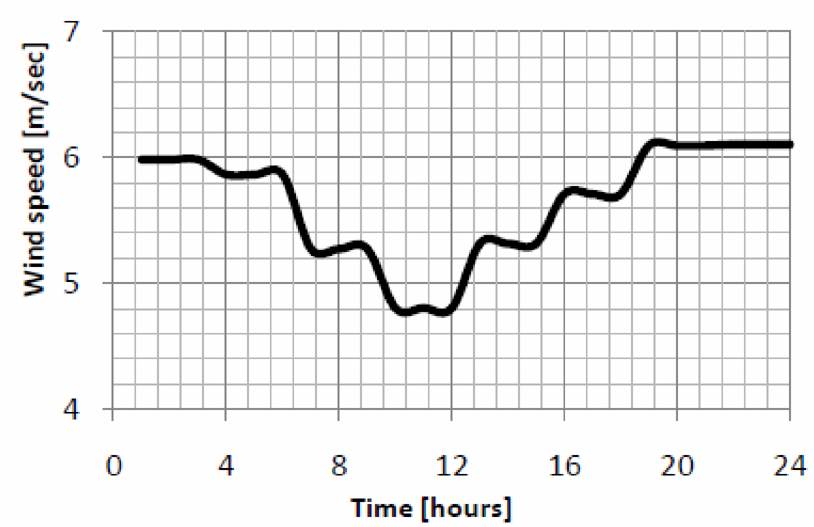


Figure 4. Average daily wind speed in December [14]

The instantaneous power produced from wind is

$$P_w = \frac{1}{2} \rho A C_p (\lambda, \theta) \upsilon^3 \qquad (4.3)$$

Where:

ρ air density (kg/m3), A rotor sweep area (m2), C_P power coefficient, a function of tip speed ratio and pitch angle, v wind velocity (m/sec),

The energy produced from wind can be determined as follows.

$$E_W = \left(\int_0^{24} P_W dt \right) \eta_S \qquad (4.4)$$

Where:

P_w instantaneous power produced (W), η_S system efficiency with battery and inverter included, E_W wind turbines' generated power to AC Bus in a day.

Diesel generators with 1kW rated power on the market have an average of 20 kg weight. The proportions of this weight to the materials used can be adopted as 60% steel, 35% aluminum, and 5% copper [17]. Since classical diesel generators have AC outputs system does not need an inverter or a control unit.

The fuel cell system is a 2 kW backup power system from a German company Future-E. Fuel cell system consist of a 2 kW fuel cell stack, a control panel and start up battery bank with power of 600W. The environmental burden of the fuel cell is calculated with the data obtained from literature as the emissions per kW rated power and control unit data from ecoinvent database [16, 18].

As the impact assessment method Eco-indicator 99, which is the state of the art impact assessment method, is used. In the modeling of the system SimaPRO 7 LCA Software is used for its wide database collection, intuitive interface following ISO 14040 and the ability to compare impact assessment calculations from each stage of the product.

In this study, at the impact assessment phase only classification and characterization steps, which are the mandatory steps according to ISO 14044 standards, are elaborated, yet the results are interpreted only via the results from characterization step.

The data collected from several literatures used to create individual models for power generation systems. With the necessary calculations made by software the emissions of the systems are reached. Using the characterization method of Eco-Indicator, emissions are grouped into eleven impact categories and these impact categories classified into three damage categories [19].

Table 1. Classification and characterization according to Eco-Indicator 99 [19]

Damage Category	Unit	Impact
Human Health	DALY	Carcinogenesis, radiation, respirator organics and inorganics
Ecosystem Quality	PDF x m^2 x yr	Climate change, ozone layer, acidification/eutrophication, and Ecotoxicity
Resources	MJ SE	Land use, minerals and Fossil Fuels

DALY: Disability adjusted life years – Lifetime loss or years to adjust disabilities caused by the impact
PDF: Potentially disappeared fraction – Proportion of the species that might be loss because of the impact
SE: Surplus energy – The extra energy needed to extract resources used

The single score results of the Eco-Indicator impact assessment methods facilitates the comparison. The values of the impact categories mentioned above are normalized with a reference system defined by Blonk T. J. et al and the results weighed with the weighing coefficients of the individualistic perspective of the method [20]. The weights of the damage categories according to individualistic perspective are: 55% Human Health, 25% Ecosystem Quality and 20% Resources [19].

5. RESULTS

The results of the study is evaluated in the damage categories mentioned above; Human Health, Ecosystem Quality and Resources.

As it seen in Figure 5, the impact of PV panels is much higher than impacts of diesel generator and wind turbine. However, the impact of PV panels does not show a big difference when compared with polymer electrolyte membrane fuel cell (PEMFC). The emissions from PV panel production like volatile organic compounds (VOC), sulfuric peroxide mixture (SPM) etc. which directly and/or indirectly affects human health, are more than diesel generator and wind turbine. According to LCI studies for PV panel production in the literature energy input is an important factor on environmental impacts of the PV systems. The primary energy that is used for Si feedstock and wafer production is the most important factors on environmental impacts of PV production [16, 21].

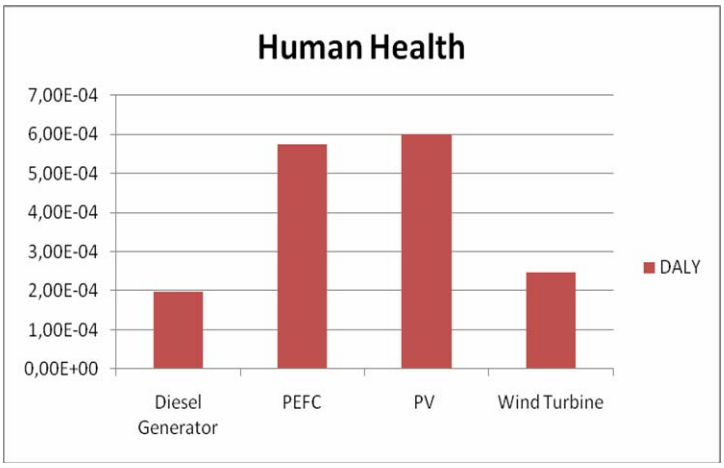


Figure 5. Impacts of the systems in damage category Human Health

However, when diesel generator and PEMFC compared, both of which can be used as a supplementary power source to ensure the reliability of a PV/wind hybrid system, the impacts of PEMFC on human health is obviously are more than diesel generators.

In Figure 6, the results are investigated according to resources damage category. It can be seen from the figure that the wind turbine and diesel generator looks like the least efficient alternatives. But since as the criteria in this category is extra energy needed to extract the resources from nature by the next generations and the scope of the study, which does not cover the recycling procedures, should be taken into consideration before evaluating the results. Although, the energy needed for re-extraction of the sources that is used for the production of diesel generator and wind turbine are more, the recycling of these resources are more feasible and easier than of the PEMFC and PV panels. On the other hand, the resources used for the systems are considered as new materials not recycled. Consequently a study with a full life cycle scope might show that bigger effect from PEMFC and PV panels on this category.

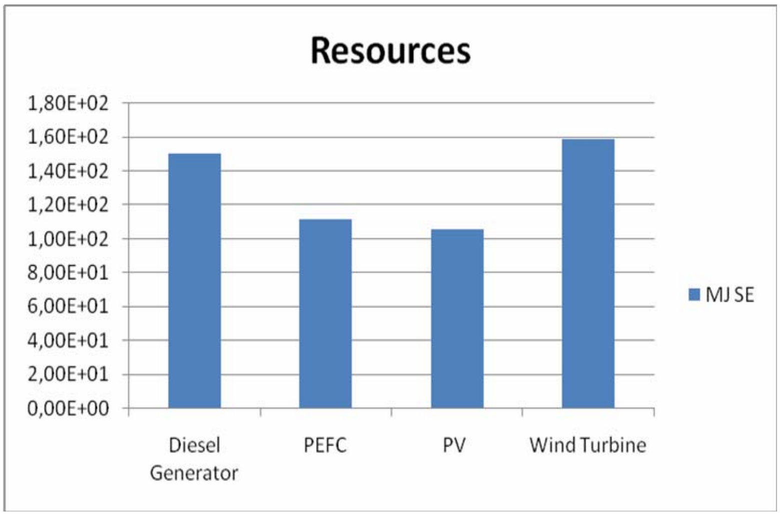


Figure 6. Impacts of the systems in damage category Resources

Calculation of Ecosystem Quality damage category includes land use, pesticides, heavy metals and concentration changes of these in water and soil. As it seen in Figure 7 the effect of PV panels in this category are higher than the other power generation systems.

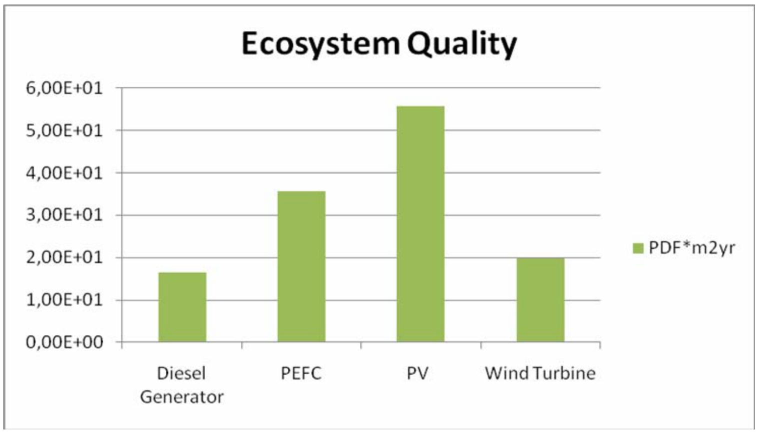
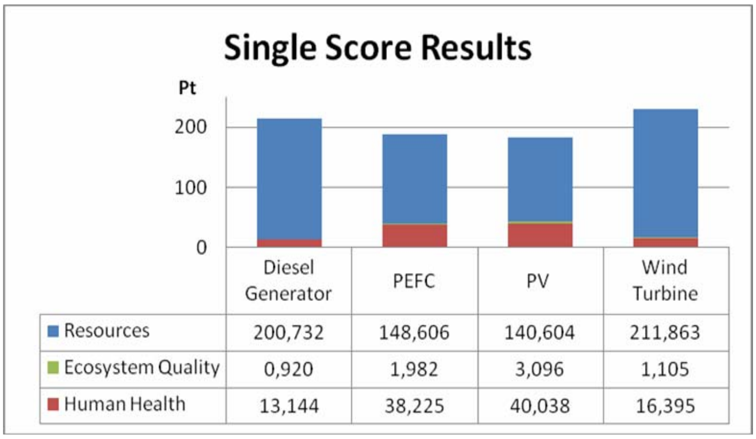


Figure 7. Impacts of the systems in damage category Ecosystem Quality

The results in Figure 8 shows that the biggest burden from the system productions is caused by wind turbine, diesel generator, PEMFC, and PV panels, respectively. However, as it is seen from the graph clearly the biggest impact for all power generation systems are in resources damage category. As it was mentioned above, disposal/recycling/reuse of the systems which causes a great deal of distortion in the category was not included in the calculation part.



	Diesel Generator	PEFC	PV	Wind Turbine
Resources	200,732	148,606	140,604	211,863
Ecosystem Quality	0,920	1,982	3,096	1,105
Human Health	13,144	38,225	40,038	16,395

Figure 8. Single score results according to individualistic perspective

6. CONCLUSION

LCA comparison of the power generation alternatives in terms of environmental impacts by evaluating their environmental and energy efficiencies and impacts during the productions of the system components was presented. The critical environmental issues were pointed out in these systems according to their impact on human health, resources, and ecosystem quality. It was shown that the highest impact on environment was from resources category for all power generator system. The present work also aimed at presenting a preliminary paper on the life cycle assessment of hybrid power systems to supply electricity to a mobile house and it is hoped that this will motivate more comprehensive and specialized researches in the future.

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REFERENCES

[1] Curran M.A., "Life Cycle Assessment: Principles and Practice, Scientific Applications International Cooperation Report", EPA/600/R-06/060, ***Nation**al **Risk Management Research Laboratory Office of Research and Development - U.S. Environmental Protection Agency Cincinnati***, Ohio, (2006).

[2] Ardente F., Beccali G., Cellura M. ve Lo Brano V., "Life Cycle Assessment of a Solar Thermal Collector", ***Renewable Energy*** 30:1031–1054 (2005).

[3] Pehnt M.: "Dynamic Life Cycle Assessment of Renewable Energy Technologies", ***Renewable Energy*** 31: 55 – 71(2006).

[4] Goedkoop M.; Schryver A. D.; Oele M.: "Introduction to LCA with SimaPRO 7", ***PRé Consultants, Amersfoort,*** Netherlands, (2008).

[5] Garcia-Valverde R.; Miguel C.; Martinez-Béjar R.; Urbina A.: "Life Cycle Assessment Study of a 4.2 kWp Stand-alone Photovoltaic System", ***Solar Energy*** 83:1434 – 1445 (2009).

[6] Varun; Prakash, R., Bhat, I.K., "Energy, economics and environmental impacts of renewable energy systems", ***Renewable & Sustainable Energy Reviews*** 13: 2716 – 2721 (2009).

[7] Granovskii, M., Dincer, I., Rosen, M.A., "Exergetic life cycle assessment of hydrogen production from renewables", ***Journal of Power Sources*** 167: 461 – 471 (2007).

[8] Lee, J.Y. et al., "Life cycle environmental and economic analyses of a hydrogen station with wind energy", ***International Journal of Hydrogen Energy*** 35:2213 – 2225 (2010)

[9] Deshmukh, M.K. ve Deshmukh, S.S., "Modeling of Hybrid Renewable Energy Systems", ***Renewable and Sustainable Energy Reviews*** 12(1):235–249 (2008).

[10] Zahedi A., "Technical Analysis of an Electric Power System Consisting of Solar Pv Energy, Wind Power, and Hydrogen Fuel Cell", ***Universities Power Engineering Conference AUPEC***, 1-5, September (2007).

[11] Alam M.S.; Gao D.W.: "Modeling and Analysis of a Wind/PV/Fuel Cell Hybrid Power System in HOMER Industrial Electronics and Applications", ***2nd IEEE Conference on ICIEA,*** 1594-1599 (2007).

[12] Tafreshi S.M.M.; Hakimi S.M.: "Optimal Sizing of a Stand-Alone Hybrid Power System via Particle Swarm Optimization (Pso)", ***Power Engineering Conference IPEC***, 960-965 (2007).

[13] Lagorse J.; Simoes M.G.; Miraoui A.; Costerg P.: "Energy Cost Analysis Of A Solar-Hydrogen Hybrid Energy System For Stand-Alone Applications", ***International Journal of Hydrogen Energy, 2nd World Congress of Young Scientists on Hydrogen Energy Systems*** 33(12):2871-2879 (2008).

[14] Eroglu M. et al., "A Stand-alone Mobile House Using PV/Wind/Fuel Cell Hybrid Power System", ***3rd World Congress of Young Scientists on Hydrogen Energy Systems,*** (October 2009).

[15] ISO. ISO 14040. Environmental management – life cycle assessment – Principles and framework, (1997).

[16] Ecoinvent Centre, 2007 Ecoinventnext term Centre, 2007. previous termEcoinventnext term Data v2.0 (2007) – The Life Cycle Inventory Data Version. Dübendorf, CH. http://www.ecoinvent.org/de/.

[17] Schleisner L., "Comparative life-cycle assessment of a small wind turbine for residential off grid use", ***Renewable Energy*** 20, 279 – 288 (2000)

[18] Pehnt M., "Life-cycle assessment of fuel cell stacks", ***International Journal of Hydrogen Energy*** 26, 91 – 101 (2001).

[19] Goedkoop M., Spriensma R., "Eco-Indicator 99 – A damage oriented method for life cycle impact assessment", PRé Consultants, ***Amersfoort, Netherlands,*** (2001).

[20] Blonk T. J. et al., "Drie referentieniveaus voor normalisatie in LCA [Three reference levels for normalisation in LCA]", ***RIZA and the Ministry of Environment, Lelystad, the Netherlands*** (1997).

[21] Alsema E.A., De Wild-Scholten M.J., "Environmental impacts of crystalline silicon photovoltaic module production", ***13th CIRP International Conference on Life Cycle Engineering***, (June 2006).