Net-Zero Energy Building Implementation through a Grid-Connected Home Energy Management System

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***Abstract*—Considering fast depletion of fossil fuels and consequently draining their sources on the other side, energy issue tended to be the main concern of the worldwide future policies. Due to new statistics and investigations, domestic buildings consume around 40% of global used energy. So, investigation and investment on this sector could lead the energy plans to advance rapidly. Through recent years, renewable energy sources (RES) considered as inevitable replacement for consisting fossil fuels. In future buildings, the electricity is generated from harvested RES in building itself. In this kind of buildings; known as Net-Zero Energy Building (NZEB), the annual net energy of the building is zero, meaning the building produces exact or even more energy as it consumes during a year. Emergence of the NZEB is tied to extensive research, prediction and planning on their elements which fortunately most of its needed element have developed sufficiently. In this paper a grid-connected NZEB is simulated in order to obtain the optimized constructional design in terms of availability and system costs.**

***Index Terms*—Net-Zero Energy Building (NZEB), Distributed Generation, Optimal Sizing, Sensitivity Analysis, Photovoltaic, Wind Turbine.**

I. INTRODUCTION

In the last decades, the price of oil and other fossil fuels has increased quickly and most of the world countries have developed new rules and strategies to reduce the energy costs and subsequent conservational impacts. Due to 2013 global energy statistics, which is depicted in Fig. 1, total energy consumption has increased dramatically during last decade and tends to keep its slope upward in future [1]. As International Energy Outlook 2013 (IEO2013) reference case exposes, world energy consumption increases from 524 quadrillion Btu in 2010 to 630 quadrillion Btu in 2020 and it has predicted to pass 800 quadrillion Btu in 2040, which means a 56-percent increase for 30 years. On the other side, most of this huge amount of energy is supplied by fossil fuels; which are the world's slowest-growing and most environmentally harmful energy sources, while due to Fig. 2, the share of RES energy production in 2013 has stayed only 11 percent [2].

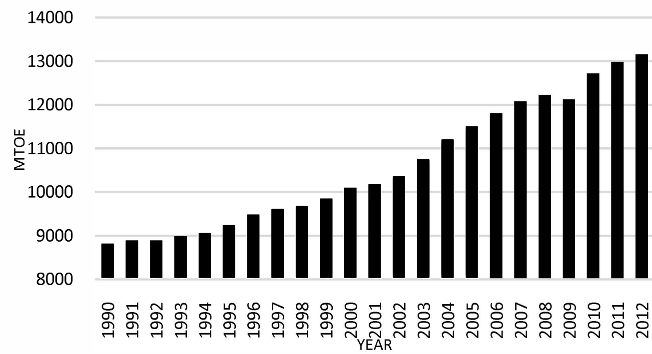

Fig. 1. World Overall Energy Consumption [1].

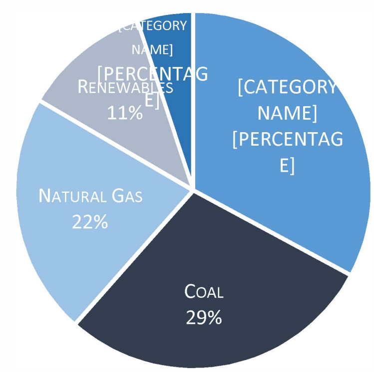

Fig. 2. 2013 Global Energy Sources [2].

To prevent energy crisis in upcoming decades, limit global warming to 2 degrees Celsius, which would require about 80 percent reduction in fossil fuel sources have been settled by the governments around the world [3]. 40 percent of the global energy is consumed by residential and commercial buildings [4]. This sector is blamed for having a share of 25-percent of worldwide greenhouse gas emission too [5]. In a typical

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buildings, electricity is providing about 70 percent of all energy needs. About half of this electricity which is generated in distant power plant is lost through transmission lines [6]. To mitigate and overcome these problems, future generation of building are planned to be designed with high efficincy energy standards, and on the other side, be powered by integration of RES. These kind of buildings are called Net-Zero Energy Building (NZEB), which generates approximately as much energy as it consumes over a period of year. A NZEB can save about 40% energy compared to a typical existing building with the same size. About half of these savings come from energy efficiency features and the other half come from the RES [7]. The most important part NZEB is energy question. Renewable power plants transform the energy of RES to electricity and deliver it to energy storage system (ESS). There must be an operative computer in NZEB to manage the flow of energy. In brief, this new step in mankind living calls for most up-to-date and newest technologies to be successful. There must be extensive research, investigation and examination on its relative field. So, in order to facilitate this case, this paper aims to simulate a NZEB to analyze its feasibility and cost-effectiveness in an expected circumstances from the electrical aspects and energy issue and to present the most optimized construction design with lowest costs and highest viability. The rest of paper is sketched as follows: Section II describes the components and elements of the studied NZEB and environmental and economical affecting factors. In section III Simulation and results are presented and discussed. Finally the paper is concluded in section IV.

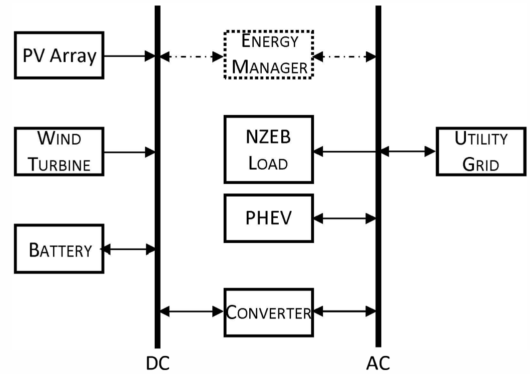
II. PROPOSED NZEB ENERGY COMPONENTS

First step for constructing a new NZEB is to consider how much energy the building consumes our different periods of a year, based on the application of the building, how many persons are living in the building, where the building is located, etc. Table 1 presents the average household electricity usage of Australian Energy Regulator (AER) survey of almost 5000 households [8]. It is assumed that our simulation model has a similar energy demand and this table is set as our base data which all the building parts and required energy system elements will be calculated on this data. It is assumed that the NZEB is located in a suburban, mild climate place and the implementation of other RES like hydropower, biomass and thermal power are impossible and just solar and wind energy remain as two feasible and cost effective RES. Due to erratic nature of solar and wind energy sources, electricity generation from them is approximately unpredictable and unreliable. So energy storage devices is always coupled to renewable energy electricity generators.

TABLE I. *ENERGY CONSUMPTION DETAILS OF THE PROPOSED MODEL*

Spring September-November	Summer December-February	Autumn March-May	Winter June-August
19.3 kWh/day Total: 1757 kWh	16.4 kWh/day Total: 1495 kWh	17.4 kWh/day Total: 1589 kWh	19.5 kWh/day Total: 1776 kWh

ANNUAL ENERGY CONSUMPTION:
18.1 kWh/day - 6617 kWh/year



- **ENERGY MANAGER UNIT**: MONITORING, SMART METERING,PROGRAMMING,MANAGEMENT,...

Fig. 3. Electrical System Architecture of the Proposed NZEB

The energy system architecture of the proposed NZEB is depicted in Fig. 3. Except Photovoltaic (PV) arrays and wind turbines, the other fundamental devices are converters, which are used to adjust the on-site generated electricity to appropriate level of energy storage and again to convert it to building's appropriate electricity level. It is very essential and important to monitor and save all the energy flow data to have a comprehensive administration and management on NZEB energy flows. Following, all reviewed elements are classified in three parts, including Energy Producers, Energy Consumers and Energy Management Unit, in order to be discussed more in detail.

A. *Energy Producers*

The first class stands for energy producers, which mutually have the duty of providing all energy needs of the building. The chosen photovoltaic and wind turbine are complement to each other since as the solar resource peaks in the summer, the wind resource peaks in the winter. The model is designated to be grid-connected in order to be able to sell surplus generated electricity to utility grid and to buy electricity when the stored energy is not sufficient. Following, the capacity and related price of three introduced elements are presented.

A.1. Photovoltaic

Typically, the average capacity of PV module for a domestic home is 4kW and costs lie between 6,000-9,000 US dollars [9]. The output power of a PV array is defined as follows:

$$P_{PV}(t) = ins(t) \times A_{PV} \times \eta_{PV} \quad (1)$$

where *ins(t)* is solar radiation data (kW/m^2), A_{PV} is the efficient surface of a PV cell (m^2), η_{PV} is the overall efficiency of PV and relative power adapters. In the proposed model, the cost of each 4kW PV array is set to be 7,000 dollars with the replacement cost of 6,000 dollars. Since PV modules are stationary equipment and they only need to be dusted, their maintenance costs supposed to be zero.

A.2. Wind Generators

If wind speed be between lowest limit and highest limit of wind turbine's nominal wind speed, the output power of wind turbine will be defined as follows:

$$P_{WG}(t) = \frac{1}{2} \times \rho \times A_{WG} \times v(t)^3 \times C_p \times \eta_{WG} \quad (2)$$

where ρ is wind density (m/s), A_{WT} is swept area (m^2), v is the wind speed (m/s), C_p is the power coefficient of the wind turbine and η_{WG} is the overall efficiency of the wind turbine and its power converters. Frequently, C_p is expressed as a function of rotor tip-speed ratio (TSR) with maximum theoretical value of 0.59 that its practical quantity depends on the employed wind turbines [10]. Size and the method of mounting, define the installation and equipment cost of a wind generator system, which for a 6kW typical home wind turbine is estimated to be between 20,000 and 30,000 dollars [9]. In the proposed model, it is supposed that wind turbines with 3kW rated power will be employed. The capital cost for each wind turbine is 12,000 dollars and replacement cost is 10,000 dollars. A high-quality manufactured turbine which is well-installed and well-maintained should work correctly up to 20 years without any critical need for service. In total, for proposed system, yearly maintenance checks with an approximate cost of 100 dollars per year are predicted.

A.3. Electricity Grid

NZEB is supposed to be connected to the electricity grid to be able to purchase electricity when the amount of produced and stored energy is not satisfactory for energy needs, and to export the on-site produced electricity when the generated electricity surpluses the storage capacity and the energy needs of building. By this method, NZEB is beneficiary of dependable backup of utility grid, a source of income for home owner by exporting surplus electricity and an assistance to grid to decrease *CO2* emissions. Since the proposed NZEB is planned to be constructed in a suburban area, there is no need to pay extra money to install power transmission instructions to transmit electricity to building. Electricity prices are discussed later.

B. Energy Consumers

Similar to other typical buildings, appliances, computers, lightning system, etc. are the main energy consumers of a NZEB. These elements are classified in group of domestic load, which in other parts of this paper, NZEB load refers to them. Domestic load defines the hourly and annual energy consumption of building and for our study is a fundamental data which all other energy system will be designed base on this. Undeniably, Plug-in Hybrid Electric Vehicles (PHEVs) are inseparable parts of the next generation of buildings. So in order to have a more comprehensive simulation, the effect of having PHEVs in NZEB should be studied. Since PHEVs consume a huge amount of energy during charging and they different behavior of charging time, they are categorized in a separate part which both are described following in detail.

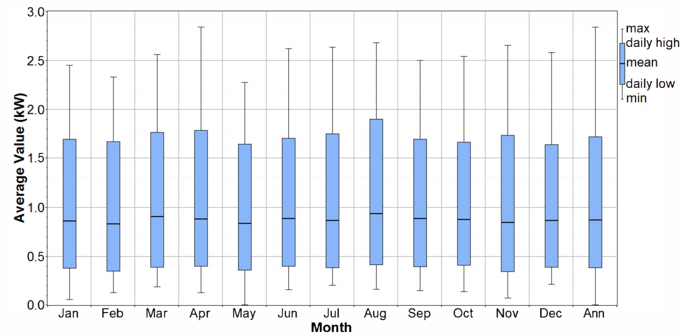


Fig. 4. Monthly Average Electricity Demand.

B.1. Domestic Load

All the electric appliances and lights are accounted in domestic load category and it is assumed that home habitants have a typical energy behavior like most other customers. A sample domestic load profile with average electricity demand of 18.1 kWh per day is assumed for proposed building. Fig. 4 represents load profile respectively on monthly scale.

B.2. PHEV

Based on high energy demand during charging PHEVs, they should be charged only through a coordinated charging scenario. Due to the extensive research and investigations during recent years about PHEV and procedure of connecting them to grid, the best time for charging is off-peak times (i.e. night), when electricity demand and respectively electricity price, power system tension, electricity losses are lowest [11]. On the other side, since PHEVs are charged via stored energy of NZEB's batteries, when on-site electricity production aims to surplus the capacity, is another best time for charging them. In proposed model, Toyota Prius Plug-in Hybrid with 4.4kWh lithium-ion (Li-ion) battery pack is supposed as PHEV. The PHEV battery will be fully charged via 10kW onboard charger in about 1.5 hours using a 240v outlet [13]. It is supposed that through a period of year, PHEV consume approximately 3.5kWh per day for charging batteries. The PHEV charging time is planned to be on times when RES produce enough energy and if not, when the local electricity demand from grid is minimum, the PHEV will be charged by utility grid.

C. Energy Manager, Battery and Power Electronic Devices

Since the nature of most RES is erratic and unpredictable, the electric power generated by renewable power plants is highly erratic and may affect both the power system quality and planning. Energy storage system (ESS) are regarded as main parts of renewable power plants by bringing reliability into the system and controlling them. Consequently, in any NZEB, the presence of ESS is so crucial too and since batteries are the most common energy storage devices and are easy to implement among the other types of ESS, they are used in our studied NZEB as energy storage. The output of PV cells and most of wind turbines is DC and cannot be used as household electricity. So it needs to be passed through a proper power electronic device to convert it to proper level of batteries to prevent any damages, and from the output of batteries, be sent to an inverter to be inverted to AC, 220V, 50Hz electricity and be used by NZEB. On the other side, there is an inevitable need for a processor to measure all the energy flows to have management on it. Following all the described elements are discussed more in detail.

C.1. Batteries

In order to store the produced electricity form the sporadic sources of solar and wind, energy storage should have enough capacity. For our studied case, batteries with 6V, 460Ah, 2.76kWh technical specification, is supposed to support the electric energy needs of building. Stored energy in the battery is calculated as follows:

$$E_{batt}(t) = N_{WG} \times P_{WG}(t) \times \Delta t + N_{PV} \times P_{PV}(t) \times \Delta t + P_{Grid}(t) \times \Delta t \quad (3)$$

where N_{WG} and N_{PV} Are the number of active wind turbines and PV arrays respectively and Δt is total time when they are providing energy to battery. Capital and replacement costs both meant to be 400 dollars per each battery cell [12]. Since batteries are stationary elements, no maintenance cost is assigned for them.

C.2. Power Electronic Devices

Due to new extensive advance in the field of power electronic, they could be used not only as adaptors of electricity levels, but as the smart elements which are coupled to microprocessors which can increase the reliability of the system. In our model, a variety of power electronic devices like inverters, rectifiers are used widely to adapt the electricity levels for each sector and for measurement tools as well.

C.3. Energy Manager

All the produced, stored, consumed, exported and purchased energy, in addition to maintenance and service times of the system elements should be measured, monitored and saved, in order to have a wide management on energy flow. Fig. 5 depicts the flow chart of the energy managing process. Based on it, produced electricity from RES will be stored in the batteries first. For increasing reliability, it is planned at least 10 percent of battery capacity be full, and if the state of charge (SOC) of batteries is less than 15 percent and RES are not providing energy, system automatically import energy from utility grid to power the NZEB and keep SOC of batteries at 10 percent. On the other side it is planned to sell energy to grid when batteries are fully charged. Charging PHEV batteries depends on the owner decision. The owner connects PHEV to NZEB charging outlet and determines how much the PHEV should be charged until a specific time. Then then energy manager unit decides how to charge it by on-site produced energy or by utility grid.

D. Environmental and Economical Factors

Obviously, the most important part of an energy building, is its energy provision, which the quality of the energy is dependent to a lot of environmental and climate factors. Since the studied model is going to be supported only by PVs and wind turbines as RES, the most important weather factors would be wind and solar circumstances, which along with import and export electricity prices are discussed below.

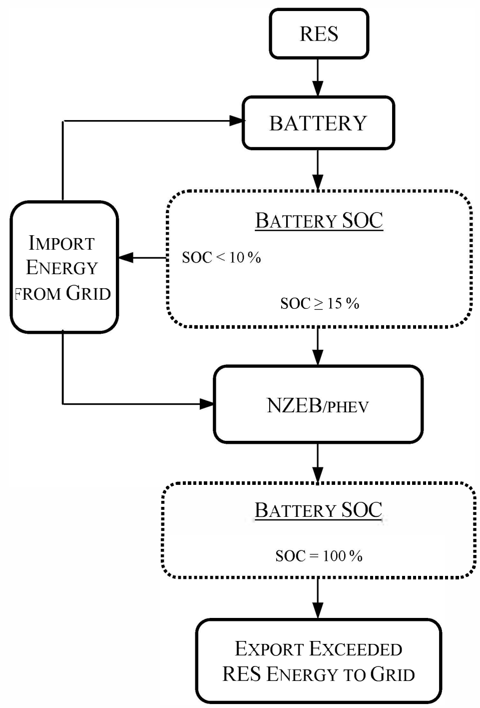


Fig. 5. Coordinated NZEB Energy System Scenario.

D.1. Solar Factor

Different global solar energy profiles studied widely to obtain an average solar profile and in order to achieve more trustworthy and reliable simulation results, four of them used in simulation. The annual average of proposed solar profile is 2.125 kWh/m^2/d, and as is depicted in Fig. 6, it is evident how sporadic solar power is. The prosed solar profile reaches its maximum level in June, meaning that PV arrays produce much energy in this month.

D.2. Wind Factor

As another most important sources of renewable energy, annual wind reports from various parts of the world have been collected and studied. In order to have a more reliable and factual simulation and results, average wind profile of a mild climate place has been selected for the base of simulation. On the other side, in support of an ideal simulation, five annual average wind speeds went under simulation. Fig. 7 illustrates the nominated annual wind profile. By comparing wind and solar profiles, it is evident that they are almost complement to each other in different periods of a year, which decrease the NZEB dependency on electricity grid.

D.3. Electricity Price

Since the proposed NZEB is connected to grid, it is important to comprehend the electricity prices for both importing and exporting electricity. For our studied case, electricity price is supposed to be 0.10 dollars per kWh and for selling energy back to grid, the price is assumed to be 0.05 dollars per kWh.

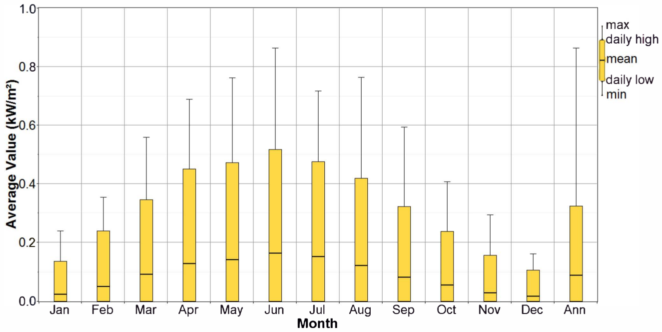


Fig. 6. Annual Solar Energy Profile.

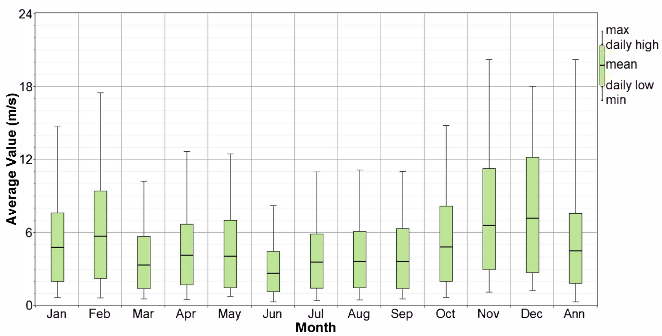


Fig. 7. Annual Wind Profile.

III. Simulation and Results

All the discussed parts went under simulation, and several optimization schemes obtained. Fig. 8 depicts the best optimization arrangements based on variable wind speeds and solar conditions regardless to costs. Based on the cost data, the implementation of wind turbines is absolutely restricted when average wind speed is less than 3.1 m/s. simultaneously, implementation of PV arrays are not described as optimize plan when the annual solar is less than 2.125 kWh/m^3/d. Implementation of wind turbines alone with battery and electricity grid is limited to a small range too. For average solar energy more than 2.125 kWh/m^3/d, PV arrays, coupled with batteries and electricity grid offers the most optimized design. Between several optimized arrangements, those which were based on 4.5 m/s for wind speed and average solar energy of 2.125 kWh/m^3/d are opted and two grid-connected NZEB architectures are presented following.

Design I. PV and Utility Grid

Considering cost aspects, the most cost effective construction of NZEB is implementation of PV arrays in combination with electricity grid. Table II represents the system architecture and cost summary of the obtained system, which consists of 12kW PV arrays, 4kW battery and two 6kW inverter and rectifier. Total net percent cost of system is 34,503 dollars, leveled cost of energy is 0.253 dollars per kWh and yearly operation cost is 696 dollars. Based on Table III, which outlines the capital, replacement, operation and maintenance and salvage costs of the system through a year, total costs of the system in a period of year is 2,699 dollars.

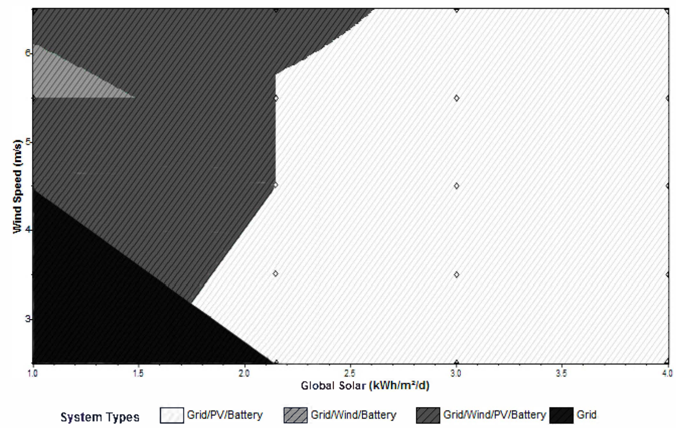


Fig. 8. Optimal Energy System Coupling Type.

Finally all imported and exported flows of energy through a year are represented in Table IV. By a comparison between Fig. 6; the annual solar energy profile, and Table IV, it is understood that in some periods of year, when the proposed solar profile is not proving enough energy, like January, November and December, the system is importing more energy, but the net-purchases energy is -188 kWh, meaning that NZEB has sold 188 kWh further energy to the grid in addition to the amount of purchased energy.

TABLE II. *Archtecture and Cost of Design I*

System Architecture					
PV Array	Wind Turbine	Grid	Battery	Inverter	Rectifier
12 kW	n/a	500 kW	4 kW	6 kW	6 kW
Cost Summary					
Total Net Present Cost		Leveled Cost of Energy		Operating Cost	
34,503 $		0.253 $/kWh		696 $/year	

TABLE III. *Annualized System Costs of Design I*

Component \ Cost	Capital ($/year)	Replacement ($/year)	O&M ($/year)	Salvage ($/year)	Total ($/year)
PV	1,643	439	0	-246	1,836
Wind Turbine	n/a	n/a	n/a	n/a	n/a
Grid	0	0	-9	0	-9
Battery	125	159	0	-26	258
Converter	235	98	300	-18	614
System	**2,003**	**696**	**291**	**-290**	**2,699**

TABLE IV. *Annualized System Energy Flows of Design I*

	Purchased Energy (kWh)	Sold Energy (kWh)	Net Purchases (kWh)
Jan.	424	145	279
Feb.	302	274	29
Mar.	294	434	-140
Apr.	240	487	-247
May.	192	455	-263
Jun.	177	478	-301
Jul.	186	465	-279
Aug.	258	361	-103

Sep.	298	243	55
Oct.	348	217	131
Nov.	384	123	260
Dec.	458	67	391
Annual	**3,561**	**3,749**	**-188**

Design II. PV, Wind Turbine and Utility Grid

In case of the energy system of a NZEB constructed from the combination of three sources of wind turbines, PV arrays and electricity grid, the most optimized architecture is represented in table V. This system architecture is consisted of 8kW PV array, 3kW wind turbine, 4kW battery and two 4kW inverter and rectifier. The total net percent cost of this architecture is 40,843 dollars, leveled cost of energy is 0.253 dollars per kWh and yearly operation cost is 696 dollars. Annualized system costs are represented in Table VI, which in comparison to design I, total yearly costs of the system has increased about 18 percent from 2,699 to 3,195 dollars. Due to Table VII, which represents the annual energy flows, the system is more reliable in comparison to design I, since the system is supported by both PV and wind turbine, and as mentioned earlier, in different periods of year faces less shortage of RES respectively. On the other side, the net-purchases has changed from -188 kWh in design I to -22 kWh in design II, meaning that though the system has been equipped with wind turbines besides to PV arrays and with more total net-percent cost respectively, the system is delivering less energy to electricity grid. But since annual energy export quantities in both designs are insignificant, they are not so different from each other. Finally choose of design I or II depends on environmental factors and owner desire.

TABLE V. *ARCHITECTURE AND COST OF DESIGN II*

System Architecture					
PV Array	Wind Turbine	Grid	Battery	Inverter	Rectifier
8 kW	3 kW	500 kW	4 kW	4 kW	4 kW
Cost Summary					
Total Net Present Cost		Leveled Cost of Energy		Operating Cost	
40,843 $		0.320 $/kWh		880 $/year	

TABLE VI. *ANNUALIZED SYSTEM COSTS OF DESIGN II*

Component \ Cost	Capital ($/year)	Replacement ($/year)	O&M ($/year)	Salvage ($/year)	Total ($/year)
PV	1,095	293	0	-164	1,224
Wind Turbine	939	326	100	-61	1,304
Grid	0	0	-1	0	-1
Battery	125	159	0	-26	258
Converter	156	65	200	-12	410
System	**2,316**	**843**	**299**	**-262**	**3,195**

TABLE VII. *ANNUALIZED SYSTEM ENERGY FLOWS OF DESIGN II*

	Purchased Energy (kWh)	Sold Energy (kWh)	Net Purchases (kWh)
Jan.	342	145	197
Feb.	201	314	-112
Mar.	308	241	67
Apr.	243	309	-65
May.	201	276	-75
Jun.	220	241	-21
Jul.	218	262	-44
Aug.	283	199	83
Sep.	311	137	175
Oct.	299	196	103
Nov.	204	344	-139
Dec.	194	384	-190
Annual	**3,025**	**3,047**	**-22**

IV. CONCLUSION

Worldwide stimulating demand for energy led to huge daily depletion of nonrenewable fossil fuels in addition to emitting a huge amount of harmful gases into the atmosphere. Undoubtedly, this energy crisis could be the most critical challenge of twenty first century which underestimating its consequences could lead to a real disaster. Renewable energies are considered as replacement for fossil fuels during recent years. They are clean and free and the only expense goes to their construction. Photovoltaic arrays and wind turbine as two major devices of transforming the solar and wind energy to electricity have advanced and developed suitably. Now another step could be bearing in mind the extensive consumers of electricity, like transportation sector and household sector. In case of renovating household sector, Net-Zero Energy Buildings could be an advantageous substitute of typical buildings which have a low energy efficiency and are consuming nonrenewable energies. Assembling the energy system of a Net-Zero Energy Building calls massive fundamental investment and extensive study, arrangement and forecasting of ambient weather condition. By having a well-designed energy system, the initial expenses would come back after some years of free energy.

REFERENCES

[1] Enerdata; Global Energy Statistical Yearbook 2013. Available: http://yearbook.enerdata.net/.

[2] US Department of Energy. International Energy Outlook 2013. Accessed February 2014.

[3] UK Government Official Website, Availeable: https://www.gov.uk/government/collections/fossil-fuel-price-projections.

[4] M. Singh, V. Khadkikar, A Chandra, and R. K. Varma, “Grid Interconnection of Renewable Energy Sources at the Distribution Level with Power-Quality Improvement Feature,” 2011, IEEE Transactions on Power Delivery, vol. 26, no 1, p. 307-315.

[5] U.S. Department of Energy. Building Energy Data Book. Available: http://buildingsdatabook.eren.doe.gov.

[6] H. Saboori, H. Abdi, “Application of a Grid Scale Energy Storage System to Reduce Distribution Network Losses,” 18th Conference on Electrical Power Distribution Networks (EPDC), p 1-5, 2013.

[7] A. Bedir, B. Ozpineci, and J. E. Christian, “The Impact of Plug-in Hybrid Electric Vehicle Interaction with Energy Storage and Solar Panels on the Grid for a Zero Energy House,” Transmission and Distribution Conference and Exposition, 2010 IEEE PES, April 2010.

[8] Energy Made Easy, Australian Government website maintained by the Australian Energy Regulator (AER). Available: http://energymadeeasy.gov.au/bill-benchmark/results/3660/4.

[9] Energy Saving Trust Foundation. Available: http://www.energysavingtrust.org.uk/Generating-energy/Choosing-a-renewable-technology/Solar-panels-PV.

[10] M. R. Patel, “Wind and Solar Power Systems,” U.S. Merchant Marine Academy,Kings Point, New York, U.S.A., 2006, ISBN 0-8493-1570-0.

[11] G. Li and X.P. Zhang, “Modeling of Plug-in Hybrid Electric Vehicle Charging Demand in Probabilistic Power Flow Calculations,” 2012, IEEE Transactions on Smart Grid, vol. 3, no 1, p. 492-499.

[12] Trojan Battery Company. Available: http://www.trojanbattery.com/markets/renewable-energy.

[13] Toyota Prius, Toyota official website. Available: http://toyotanews.pressroom.toyota.com/releases/toyota+introduces+2012+prius+plug-in+hybrid.htm.