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Development of power system designs for a net zero energy house

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ABSTRACT

This study compares various power design options and their optimized schemes for a net-zero house considered in a location in Lebanon, to cover its all electrical needs while maximizing renewable energy usage and minimizing the greenhouse gases emissions. The study starts by outlining the necessary measures needed to reduce the total electrical load connected to the house through efficiency gains, after which comprehensive simulations are carried out to establish the best possible power design options with the least total net present cost and maximum renewable energy fraction, as they achieve a sustainable net-zero energy house. The simulation results show that the optimum renewable energy system for a total connected load to the house of 90 kWh/day requires a combination of PV, wind turbine, batteries, convertor and diesel generator at a total net present cost of $56,558.00 and a renewable energy fraction of 0.998. Moreover, simulations for the same connected load are carried out with different configuration of renewable energy resources and the optimum results are obtained. On the other hand, a set of simulations is performed for different areas of the house, and a sensitivity analysis is then conducted for these obtained results. An exergetic assessment is carried out to compare the efficiencies of a PV system to that of a PV/T, where water is heated by the thermal part supplied. The energy efficiency of the PV/T system is then improved by about 23% while the exergy efficiency increases by 10% with an additional cost of $8442.00.

1. Introduction

Energy shortages have been increasing due to population growth and increased industrial activities in developing countries. This makes a sustainable supply of energy a critical need for the developing world. Once the maximum rate of global oil production is reached, a decline in the supply occurs. This is expected to cause a significant increase in oil prices and their byproducts and some socio-economic implications in the world. Delaying the time of peak oil can be achieved by resorting to other alternatives for producing energy such as, nuclear, renewable, unconventional oil resources like oil shale, oil sands and by producing hydrogen fuel from the electrolysis of water. Moreover, fossil fuels are treated as a major contributor to air pollution and global warming. Hence, reducing the usage of fossil fuels is considered as important as achieving a sustainable energy supply. Therefore, switching to sustainable energy options becomes an ultimate goal and helps reduce carbon dioxide emissions. The importance of using renewable energy is best described by the following quote: “Achieving solutions to environmental problems that we face today requires long-term potential actions for sustainable development. In this regard, renewable energy resources appear to be the one of the most efficient and effective solutions” [1].

As stated in the literature, buildings consume lots of energy, for example in the US; buildings consume 40% of the primary energy and 71% of the total electricity [2] while in the UK, 47% of total national energy [3]. These values constitute a real challenge to economic sustainability, electrical production and emissions which can be avoided if new buildings aim to achieve the zero energy designs, and old buildings are retrofitted as much as possible to implement net-zero energy solutions and reduce green gases emissions. The concept of net zero energy houses is best described by the U.S. Department of Energy (DoE) building technologies program: “A net zero energy building (NZEB) is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies”.

Torcellini et al. [4] presented a study case based on using PV placed on the roof and analyzed the performance of buildings with implementing readily available energy conservation measures. They conclude their document by claiming that serious energy

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Nomenclature

A	anisotropy
C	clearness index
f	factor
F	horizon brightening factor
k	battery rate constant (1/h)
$\dot{q}$	solar radiation (kW/m^2)
$\dot{p}$	power (kW)
r	reflectiveness
R	ratio of radiation (Tilted surface/Horizontal surface)
T	temperature (°C)
Δt	unit of the time step (h)
x	battery capacity ratio

Subscripts

a	ambient
anem	anemometer
b	beam
batt	battery
cell	photovoltaic cell
chg	charge
d	diffuse
disch	discharge
elec	electrical
G	global
g	ground
i	index
L	length
mp	maximum power
PV	photovoltaic
theo	theoretical
turb	wind turbine
s	solar
Tot	total
o	out
STC	standard test conditions

Greek letters

∂	temperature coefficient of power
η	efficiency
β	slope of the surface
$\varnothing$	latitude
$^\circ$	degrees
α	absorption coefficient
θ	incidence angle
τ	solar transmittance
α	solar absorbance
Ψ	exergy efficiency

savings is achieved, by using the roof to place solar cells and using advanced technologies combined with integration and control of systems.

Li et al. [5] made a review paper on the design strategies used to achieve a NZEB and identified them as “Minimizing the need for energy use in buildings by undertaking energy efficient measures for the NZEB to curb down heat loads from internal, external sources and building services mechanisms. Resorting to renewable energy for power supply to meet the remaining energy needs such as photovoltaic/building-integrated systems, photovoltaic/thermal systems, wind turbines, solar water heaters, ground source heat pumps, and district heating and cooling. They conclude their research by stressing that there is need to cut down on energy consumption if we were to sustain our environment and economy, by resorting to achieving zero energy buildings”.

Masoso et al. [6] concentrate on building envelopes for energy reduction and efficiency measures by utilizing optimum thermal insulation, to prevent heat gains and losses which will sharply reduce the electricity demand for heating and cooling. They assert that careful consideration should be taken in climates where cooling is dominant not to over insulate to the point of thermal inflexion.

Jentsch et al. [7] and Artmann et al. [8] studied the effects of thermal mass on delaying heat transfer to a building during day light where the peak temperatures and heat transfer occur. They claim that cooling requirement can be reduced with an integration to mechanical ventilation and that passive cooling can be achieved.

Wang et al. [9] presented a case study for zero energy house (ZEH) in the UK. They used simulation software Energy Plus to muster a design through different building envelopes and layers to maximize energy reduction needs and resorted to TRNSYS software to study the feasibility of using renewable energy technologies to provide electricity and achieve a ZEH. The authors performed their own simulated study on a typical house in the UK occupied by two people, where the total yearly electrical consumption was estimated at 6008.9 kWh while the annual electricity generated with PV and wind turbine is estimated at 7305.9 kWh. They conclude that it is possible to achieve a ZEH in the UK if energy efficiency measures are taken and the right renewable technology is used.

Graca et al. [10] conducted a feasibility study on solar powered net zero energy houses (NZEH) for single family house in southern Europe by using dynamic thermal simulations of two different architectural configurations powered by PV and thermal solar collectors. They recommend the following measures to be followed if an ideal NZEH is to be achieved, namely: (i) design the house to utilize maximum natural light and ventilation with optimal passive heating and cooling, (ii) use high-efficiency appliances, (iii) adequately sized renewable energy systems and (iv) proper design of electrical infrastructure with flexible grid connection.

- Christian et al. [11] studied at the thermal performance of a NZEH, built in Tennessee USA, with structural insulated panels and powered with 2 kW grid-tied photovoltaic system while geothermal heating and cooling of the space is used. They concluded that all five houses that cost \$100/ft^2 can reach zero energy status if the PV system is extended over the free area on the roof.
- Ramesh et al. [12] conducted an extensive study on the life cycle energy analysis of buildings and concluded that operating (80–90%) and embodied (10–20%) phases of energy use are major contributors to life cycle energy demand.
- Leckner et al. [13] did a study on the life cycle cost and energy analysis of a NZEH with solar combi-system and reported that the energy payback time is 8.4–8.7 years, when compared with an average house that complies with the provincial code while the combi-system is 3.5–3.8 years compared with the heating system of conventional house.

Most of the researchers on NZEB has worked on the measures to reduce energy by increasing the efficiencies of the house envelope, proper construction design and architecture along with adequate sizing of the renewable energy systems to meet the remaining electricity demand. It is worth noting that human understanding and awareness of the need to curb energy use and sustain the environment would come beneficial to this transformation. Many concluded their work by ascertaining that NZEB will play an important role in energy, environmental and economic sustainability. They emphasized that more work on improving technologies to