Energy and Buildings 130 (2016) 465–476

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Getting to net zero energy building: Investigating the role of vehicle to home technology

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A R T I C L E I N F O

Article history:
Received 3 March 2016
Received in revised form 30 July 2016
Accepted 12 August 2016
Available online 13 August 2016

Keywords:
Net zero energy building
Vehicle to home technology
Energy consumption
Renewable energy sources

A B S T R A C T

95 percent of American households own at least one car, and with the help of newly introduced Vehicle to Home technology, it is now possible for buildings, vehicles, and renewable energy sources to work together as a single techno-ecological system to meet the requirements of a net zero energy building. Vehicle to Home technologies use idle electric vehicle battery power as a grid storage tool to mitigate fluctuations from renewable electric power sources and to help supply backup power in the event of an emergency. This study aims to investigate the role of Vehicle to Home technology in satisfying the energy requirements for a net zero energy building. For this purpose, an optimization analysis is performed first to select the best design alternatives for an energy-efficient building under the relevant economic and environmental constraints. Next, solar photovoltaic sources are used to supply the building's remaining energy demand and thereby minimize the building's grid reliance. Finally, Vehicle to Home technology is coupled with the renewable energy source as a substitute for power from the grid. The results indicate that, with the help of this system, it is possible to not only lower the monetary value of the required grid electricity for such a building to zero in certain months of the year but also to earn money to compensate for the installation costs of solar panels and other technologies necessary for a net zero energy building, while grid electricity consumption for the rest of the year can still be effectively reduced by up to 68% compared to that of a conventional building design.

1. Introduction

The world's rapidly growing energy consumption rates, coupled with the associated environmental impacts of such energy consumption, has raised concerns in different communities and among researchers, engineers, and even politicians [1]. As buildings are responsible for more than 40% of primary energy usage and 70% of overall electricity usage in the U.S., policy-makers must quickly take action to reduce the energy demand of buildings [2]. The energy consumption of buildings is responsible for 38% of CO_2 emissions to the atmosphere, 52% of SO_2 emissions, and 20% of NO_x emissions [3]. At the same time, the energy usage of buildings faces an increasing trend in the future, considering its existing nexus with population and economic development [1]. Therefore, moving toward sustainability requires minimizing the resource consumption of buildings, meaning that the energy performance of buildings should be maximized without sacrificing their comfort levels [4]. To design energy-efficient buildings, several studies are available that have investigated factors such as thermal insulation and building envelope, age, size, lighting and lighting control systems, outdoor weather conditions, HVAC equipment, building orientation, urban texture, and other applicable factors in an effort to reduce the energy consumption of a particular building [5–8]. Among these is a study by Balaras et al., who investigated the effect of a building's thermal insulation (including floor, window, wall, and roof insulation) on the energy performance of the building [9]. Other studies investigated the potential of smart occupancy sensors to reduce a building's energy consumption [10–12]. In addition, since HVAC system management is another major concern when designing an energy-efficient building, some studies have specifically investigated the influence of HVAC system management on the energy consumption of buildings [13–15].

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http://dx.doi.org/10.1016/j.enbuild.2016.08.044
0378-7788/

Most of the abovementioned studies have focused on specific aspects of a typical building's energy consumption, and have tried to simulate and analyze the effect of those specific components on the energy demand of such a building. However, since one of the goals of this study is to design an energy-efficient building, it is therefore necessary to simultaneously consider all of the most important factors affecting a building's energy consumption in an optimization analysis to select the best design alternatives. In this regard, it is necessary to optimize the parameters that influence the energy and investment costs and the thermal comfort of such a building (envelope, HVAC, etc.) [16]. However, achieving this goal requires a thorough study to find better design alternatives that satisfy a variety of conflicting criteria, such as those pertaining to economic and environmental performance [3], so as to help designers overcome the drawbacks of trial-and-error with simulation alone.

There are several studies in available literature on optimization approaches and their suitability for minimizing a building's energy consumption [17]. For instance, Fesanghary et al. investigated the application of a multi-objective optimization model based on a harmony search algorithm to find an optimal building envelope design to minimize life cycle costs and emissions [18]. In addition, Hamdy et al. proposed a modified multi-objective optimization approach based on a Genetic Algorithm to design a low-emission, cost-effective dwelling [19]. It has also been noted that minimizing energy consumption should be taken into consideration along with other constraints such as costs and the comfort levels within buildings [20]. Therefore, this study uses an optimization approach through the use of a built-in optimization tool developed by Designbuilder [21]. With this optimization tool, it is possible to identify different design alternatives with various combinations of costs, energy consumption rates, and comfort levels, using the Genetic Algorithm (GA) method to perform a multi-objective optimization analysis. Consuming less energy through an optimization process and the selection of the best available design alternatives will be a major step toward a sustainable community. However, in order to fully implement the concept of sustainability, new plans must be devised to integrate renewable energy sources into the energy portfolio of a building. Therefore, developing a new methodology with which to minimize the energy consumption of a building and integrating renewable energy sources with the main electricity source (the power grid) will both contribute greatly to a more sustainable community [22]. In this regard, when moving toward sustainability, it is important to not only reduce the required energy of the building in question but also to find ways to implement new and cleaner energy sources whenever possible. For this reason, shifting the building's energy sources away from the electricity grid (which tends to be the most likely source to emit air pollutants) in favor of onsite renewable energy sources seems to be inevitable. The concept of the net zero energy building (NZEB), as explained further in the next section, has evolved primarily from this idea.

1.1. *Net zero energy building (NZEB)*

The goal of the NZEB concept is to reach a point where a building's onsite electricity production can supply its entire electricity demand [23]. The NZEB concept is no longer perceived as a purely theoretical ideal for future applications, but as a realistic and achievable goal to reduce buildings' energy consumption levels and to subsequently mitigate CO_2 emissions from the building sector [24]. Growing attention to the NZEB concept can be seen in a number of buildings constructed based on this theory as practical examples thereof [25–28]. The Energy Independence and Security Act (EISA) of 2007 authorizes the Net-Zero Energy Commercial Building Initiative to support the goal of net zero energy consumption for all new commercial buildings by 2030, and to extend this goal to reach a net-zero-energy target for 50% of U.S. commercial buildings by 2040 and for all U.S. commercial buildings by 2050 [29]. The Energy Performance of Buildings Directive (EPBD), published in 2002, obliged all EU countries to enhance their buildings' regulations and to introduce energy certification schemes for buildings [30]. To this end, the EPBD Directive of 2010 has set a target of "nearly zero energy buildings" by 2018 for all public buildings and by 2020 for all new buildings [31]. As can be seen from these goals, the international community now regards the NZEB concept as a viable solution to the increasing energy consumption levels and CO_2 emissions of today's buildings.

Across all definitions and classifications for the NZEB, one basic design rule remains constant; address demand first, and then supply [29]. Different methods to reduce the energy consumption of buildings have already been discussed in previous sections, and hereafter the main focus of this paper is on energy supply. New types of renewable energy sources should be employed for a NZEB, and in this regard, many studies have investigated the use of various renewable energy sources (solar panels, wind turbines, geothermal heat pumps, etc.) to supply the energy demand of buildings. For example, Charron investigated the use of thermal and solar photovoltaic (PV) technologies to generate as much energy as a typical home would need on annual basis, in what can be referred as a net zero energy solar home [32]. The life cycle costs of such homes is also an important topic to discuss, and has been investigated in different studies [33]. Another study by Iqbal investigated the feasibility of using wind energy in a net-zero-energy home, taking into account critical parameters such as wind speed [34]. Some studies have even tried to combine different types of renewable energy sources to design a NZEB. For instance, Melissa et al. investigated the power generated through solar thermal energy and wind power to supply the energy demand of a building [35], while Noori et al. investigated the socio-economic and environmental impacts of producing electricity for buildings using wind power plants [36].

In addition to renewable energy sources, the role of vehicles in supplying the energy demand of buildings is now yet another possibility to be investigated. With the help of newly introduced technologies, it is possible to use vehicles (esp. household vehicles) as potential energy sources for buildings. These technologies and their applications are discussed in further detail in the next section.

1.2. *Vehicle to home (V2H) technology*

In addition to renewable energy sources (solar panels, wind turbines, etc.), alternative-fuel vehicles can also be considered as viable energy sources to supply the power demand of a building. Existing bi-directional charging technology allows intelligent charging to be taken to a new level; with the help of vehicle-to-home (V2H) and vehicle-to-grid (V2G) technologies, the use of electric vehicles (EVs) can be considered an opportunity to use EV networks as power sources in and of themselves [37]. Using this technology in conjunction with other renewable energy sources makes the overall system more energy-efficient by storing excess energy generation during off-peak hours for use whenever the available power generation is not sufficient to meet the energy demand. Moreover, V2H technologies use idle EV battery power as a grid storage unit with which to handle fluctuating renewable electric power supply.

Different studies in this regard have examined this technology from different perspectives. One such study by Haines et al. developed a simple V2H model for a home's daily energy demand [37]. Another study by Liu et al. introduced different methodologies for using V2H, V2G, and vehicle-to-vehicle (V2V) technologies [38]. Cvetkovic et al. presented a small grid-interactive distributed energy resource system consisting of photovoltaic sources, plug-in hybrid electric vehicles (PHEVs), and various local loads [39]. More-

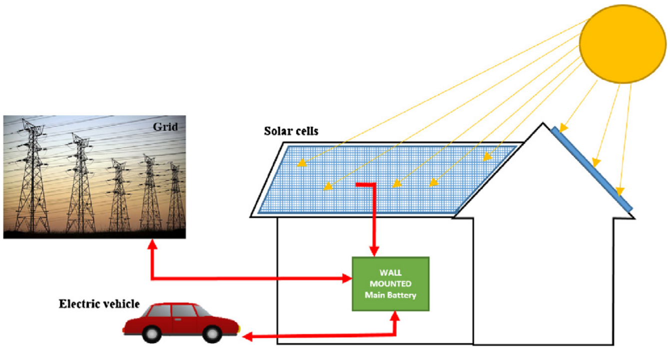

Fig. 1. Net Zero Energy Building.

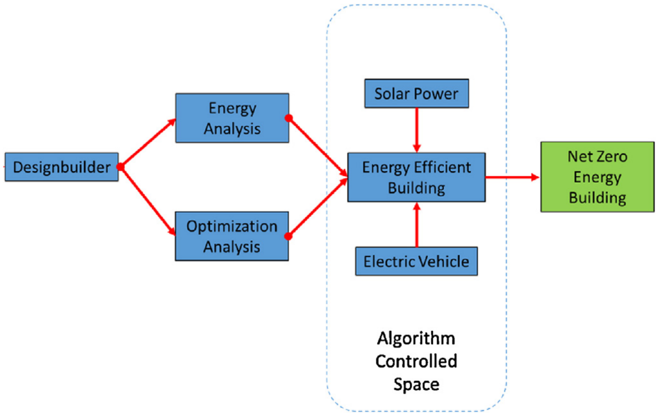

Fig. 2. Developed Methodology.

over, Noori et al. investigated the regional net revenue and emission savings that may be possible with the use of V2G technology [40]. The life cycle cost (LCC), environmental impacts, and market penetration of EVs are also important areas to consider when performing a thorough life cycle analysis of the system as a whole [41,42].

V2H technology enables users to connect a variable number of vehicles to a building's power distribution board, making it possible to supply the building's power demand at nighttime (when the building's electricity usage is usually at its peak). This is accomplished by depleting the stored power in the batteries of electric vehicles and then charging the battery when the power demand is low, using electricity from the power grid or from other renewable energy sources (solar panels, wind turbines, etc.). This system can also be used as a reliable energy source in case of an emergency such as a power outage. In this regard, government incentives can be implemented to compensate individuals and businesses for the increased initial costs of this technology. From the consumer's viewpoint, this means that cars are usable for mobile energy storage and not just for transportation purposes, being able to provide power to a building and thereby alleviate the corresponding stress on the conventional power grid. A schematic of the overall concept considered in this study is shown in Fig. 1 below.

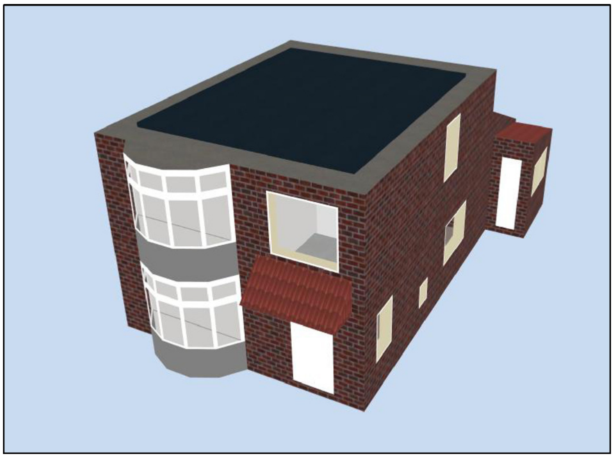

Fig. 3. Developed Model in Designbuilder.

Table 1
Modeled Building's Specifications.

Parameters	Values and types
Gross Wall Area	1239 sq ft [115 sq m]
Window Opening Area	295 sq ft [27.4 sq m]
Gross Window-Wall Ratio [%]	23.80
Gross Roof Area	632.60 sq ft [58.77 sq m]
Skylight Area	50.30 sq ft [4.67 sq m]
Skylight-Roof Ratio [%]	7.95
Weather File	Orlando Sanford Airport FL USA TMY3 WMO# = 722057
Latitude [deg]	28.78
Longitude [deg]	−81.3
HVAC system	Ground Source Heat Pump (GSHP)
Lighting system	Fluorescent, Compact (CFL)

2. Methodology

The general methodology of this study is illustrated in Fig. 2 below, which summarizes the different steps taken in this research to achieve a completed NZEB design. These steps are described in detail in the following sections. As shown in Fig. 2, the overall process starts with modeling the building itself, followed by an energy analysis and an optimization analysis in order to design an energy efficient building. Next, solar power and an EV battery are integrated in conjunction with the main energy source of the designed building (grid electricity), and the resulting interactions within this system as a whole are controlled using an algorithm introduced in the following sections.

2.1. Model development

For modeling purposes, the building modeled in this study is a two story residential building with a total area of 1184 square feet and a net conditioned building area of 1074 square feet. This model can be seen in Fig. 3. The detailed specifications of the modeled building are summarized in Table 1.

In the next step, the developed model is used to evaluate the energy performance of the building. The Department of Energy (DOE) recommends a complex variety of tools and software for different design purposes, and one of the most comprehensive software programs currently available is EnergyPlus, which is designed to simulate and assess the energy consumption of the entire building [43]. Architects, engineers, and researchers have been able to use EnergyPlus to model the energy consumption of a designed building, (including energy consumption from heating, cooling, ventilation, lighting, and water usage) while also providing users with a broad range of alternatives for each component [44]. However, EnergyPlus reads inputs and writes outputs to text files, which can make it somewhat difficult and time-consuming to work with. In order to increase the usability of this software and make it more understandable for ordinary engineers, several graphical interfaces for EnergyPlus have been introduced. The graphical interface for EnergyPlus used in this study is Designbuilder, which accounts for the weather conditions of a particular region when performing an energy performance analysis, allowing the analysis in this study to account for average annual sunshine, wind speed, temperature,

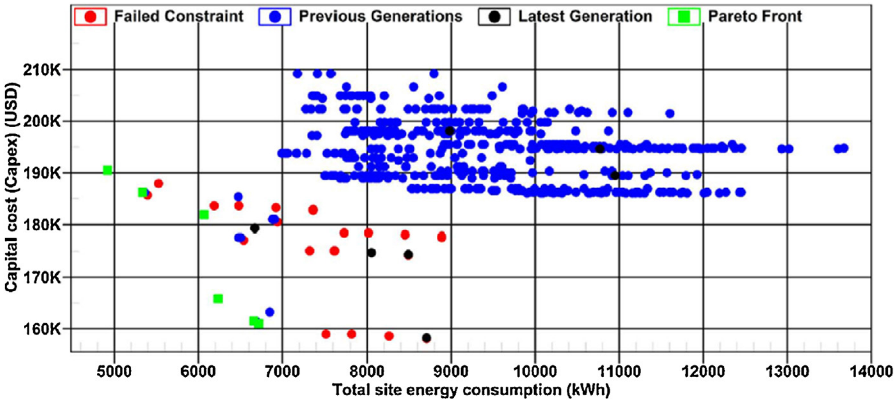

Fig. 4. Optimization Analysis Results.

and all weather-related situations in addition to the other factors previously discussed [45].

2.2. Optimization of the building's energy performance

Once the model is defined and the applicable weather database file is imported, the next step is to analyze the building's energy performance. As mentioned earlier, the process of choosing the best design options is a time-consuming process that requires a powerful database to enable designers to choose the best design alternative, while also considering relevant design constraints during the search for an optimal solution. Regarding the energy performance of a building, many different factors should be considered simultaneously in order to find an optimal solution; for purposes of this study, an optimal design should provide a high-quality, comfortable building fully compliant with the applicable standards and codes while also reducing the initial cost, operational energy usage, and environmental impacts of the building [46]. In this regard, an optimization analysis is performed in order to select the best building design options with which to minimize the energy consumption of the building in question without compromising any more than necessary in terms of cost, environmental impacts, or (more importantly) the comfort of the residents.

The process of finding the best design alternatives can be very difficult, especially with respect to conflict areas such as those related to economic and environmental performance levels [47]. The method used for this purpose should be chosen in a way that allows for a multi-objective optimization and also works relatively well given the non-explicit nature of the applicable objective functions [48]. Designbuilder provides a user-friendly interface that enables engineers to compare a set of different alternative design options for building envelopes (wall insulation, glazing type, etc.) as well as different heating and cooling systems, using the Genetic Algorithm (GA) multi-objective optimization method to select the best design alternatives. It is worth mentioning, however, that the Genetic Algorithm method does not guarantee the optimal solution, but instead finds an approximate solution to the optimization problem [42,43,49].

In this regard, more than 66% of the energy consumption of residential buildings is related to HVAC and lighting systems [2]. In this specific case study, considering the weather conditions in Orlando, cooling and lighting loads are expected to have dominant shares in the overall energy consumption of the building, which would match with the preliminary results of the energy analysis of the building in question. Therefore, in order to optimize the energy consumption of the building, more emphasis is placed on testing different HVAC and lighting systems to find an optimal solution that reduces energy consumption as much as possible. Fig. 4 shows the results of this optimization analysis with different design variables and objective functions. In this figure, the results of the GA optimization method are shown as a set of optimal solutions, but the best design method with the least amount of energy consumption and the lowest cost can still be derived as a result of the aforementioned optimization analysis.

As seen in Fig. 4, a set of different colorful points is illustrated in this graph, with each point representing a separate design method with different HVAC and lighting systems. In general, three main areas must be considered when optimizing the energy consumption of the building: total site energy consumption, capital cost, and comfort level. For this purpose, the parameter values of the optimization analysis are set in a way that minimize the capital cost and total onsite energy consumption of the building. Clearly, as the system becomes more efficient, the energy consumption of the building decreases, but the capital cost may increase. On the other hand, ASHRAE Standard 55–2013 states that, for thermal comfort, the temperature in the building may range between 67 °F and 82 °F (approximately 19 °C and 27 °C, respectively) [50]. In order to ensure an acceptable level of comfort in the building, the comfort level is considered as a constraint in the optimization analysis, meaning that the only acceptable design methods are those that can ensure a comfortable temperature within the specified ranges; the green points in Fig. 4 indicate the solutions corresponding to these designs. The red points represent the design methods that are optimal in terms of both capital cost and energy consumption, but fail to provide the desired comfort level.

During the optimization analysis, approximately 1990 design set points were tested, and based on the results, 6 of these points are found to be acceptable for consideration as the optimal design methods. The specifications and optimization results for these 6 designs are summarized in Table 2.

The above table describes the most optimal design points, such that their respective capital costs and energy consumption levels are both optimized while also ensuring that the basic requirements in terms of thermal comfort are met. In order to select the most efficient system among these 6 designs, the results of a separate energy analysis have first been derived for each design. Afterward, by comparing the discomfort hours of different systems based on ASHRAE 55-2004, the system with the lowest amount of total discomfort hours has been selected as the final optimal design. Now, after reducing the energy consumption of the building, the next step is to devise a system with which to supply the required power to the building.

Table 2
Optimization Analysis Iterations.

HVAC template	Lighting template	Cooling system (COP)	Onsite energy consumption (kWh)	Capital cost (Capex) (USD)	Comfort Temp (°C) in building
Air to Water Heat Pump (ASHP), Convectors, Nat Vent	T8 Fluorescent – triphosphor – with STEPPED dimming daylighting control	2.63343	5336	186,203	27.75
Natural ventilation – No Heating/Cooling	T8 Fluorescent – triphosphor – with STEPPED dimming daylighting control	3.57576	6659	161,514	27.69
Natural ventilation – No Heating/Cooling	T8 (25 mm diam) Fluorescent – triphosphor – with ON/OFF dimming daylighting control	3.31574	6719	170,000	27.71
Electric Convectors, Nat Vent	LED with linear control	2.76246	6069	181,917	27.6
Air to Water Heat Pump (ASHP), Convectors, Nat Vent	LED with linear control	2.68622	4918	190,489	27.6
Natural ventilation – No Heating/Cooling	LED with linear control	3.12023	6235	165,800	27.54

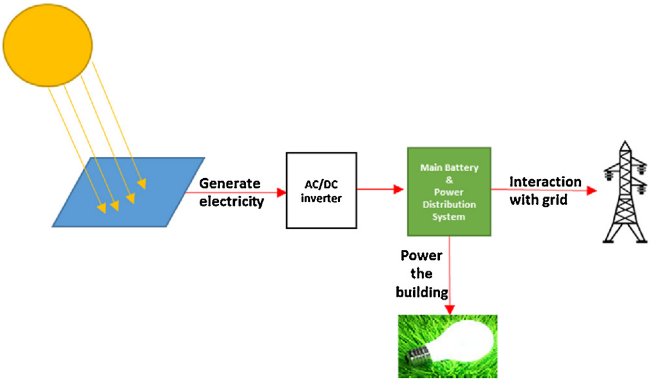

Fig. 5. PV System Components.

2.3. Power supply system

In the following two sections, each of the energy sources chosen for the hypothetical building in this research (solar power and electric vehicles) are described in further detail.

2.3.1. Solar power

The sun has produced energy for billions of years, and the energy in the sun's rays as they reach the earth can be converted into electricity through Photovoltaic (PV) cells, often better known as solar cells [51]. Solar energy is no longer viewed as a minor contributor to the nationwide energy grid mixture of the U.S., as it used to be in previous years due to high costs and other practical constraints [52]. Photovoltaic (PV) systems are like any other electrical power generation system, with some differences in the equipment used as opposed to the standard equipment for conventional electromechanical generation systems [53]. A basic diagram of PV systems is presented in Fig. 5 below.

In order to convert solar energy to base-load power, excess power produced during sunny hours must be stored for use during nighttime (on-peak) hours [52]. In this study, in order to consider solar energy as a part of a power supply system, a series of solar panels with a total area of 108 square feet is modeled on the roof of the building, as indicated by the dark blue areas in Fig. 3, and each solar panel works as a separate electricity generator. The modeled solar panels generate DC electricity, which must be converted to AC electricity so that the generated power can be used for the building's appliances and stored in a battery designed to store AC power, which is the most widely available battery type for consumers. In short, the operation scheme of the solar panels is designed to generate electricity regardless of the energy demand at any particular time, while any excess amount of this generated electricity can be transferred to an EV battery and then stored in the main battery.

Table 3
Solar Panel Characteristics.

Parameter	Characteristics
Solar collector type	Photovoltaic
Performance type	Simple
Performance model	PV with constant efficiency of 0.15
Heat transfer integration mode	Decoupled
Material	Bitumen felt
Area	108 sq ft [10 sq m]

In this study, the solar panels are placed on top of the roof of the building in order to simulate the worst-case scenario in which the building in question is surrounded by other buildings, although it must be noted that, in many cases, it is possible to use the backyard and/or the front yard of the building to install these panels and generate electricity. The amount of solar energy generated with the solar panels depends on the properties of the modeled solar panels; detailed specifications for the solar panels in this study are presented in Table 3.

Moreover, the amount of generated solar energy depends on the time of day, the amount of incoming solar radiation, and the angle of the solar panels with respect to the sun. All of these parameters have been considered when analyzing the solar power generation for the building. In order to better understand the way that the modeled system interacts with the position of the sun, a schematic view of the analysis is shown in Fig. 6. In the example illustrated in the figure, the position of the sun (sun-path diagram) is shown for July 15th at 11 A.M.

Cost-related issues pertaining solely to solar power are beyond the scope of this study, and are not included in the results because the results can vary significantly depending on the boundaries of the cost analysis, and so a separate study is needed to fully investigate costs specific to solar electricity. That said, it is worth mentioning that the production price of solar energy has continuously decreased over the past few years, having dropped from 21.4 cents/kWh in 2010–11.2 cents/kWh in 2013 [54]. In order to make solar power more cost-competitive with traditional energy sources, a target has been set to reduce this price to 6 cents/kWh, which is now an achievable target given the current decreasing

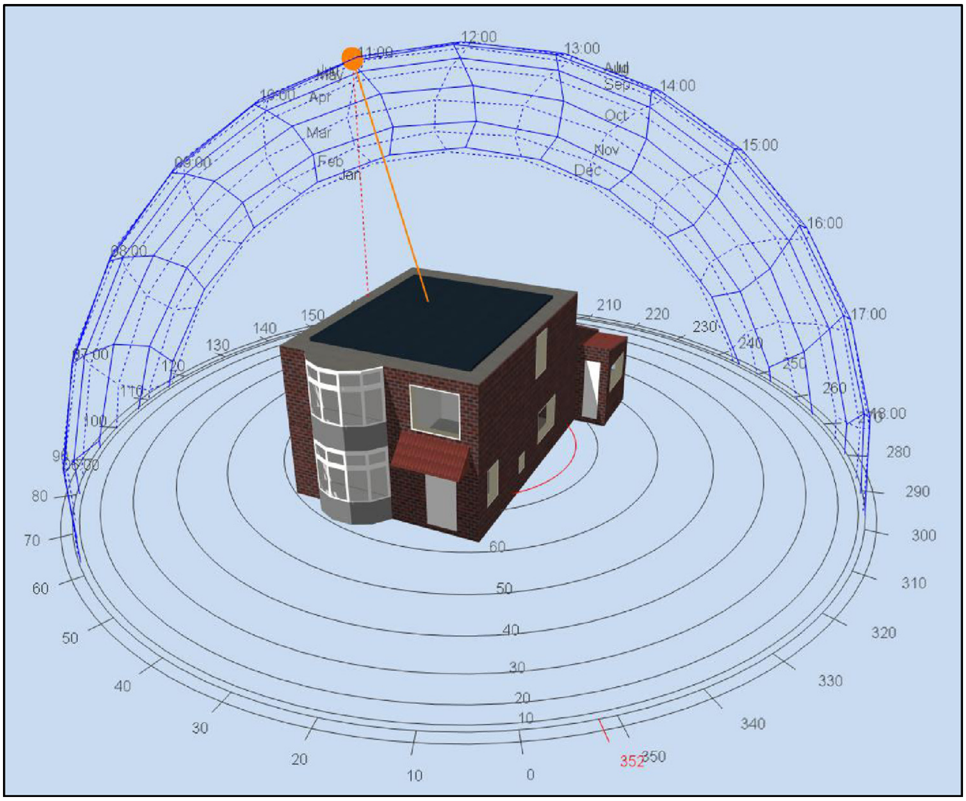

Fig. 6. Schematic View of Sun-Path Diagram.

trend in prices as observed from 2010 to 2013 [54]. However, generating solar power can also have direct economic benefits in addition to the indirect economic advantage of reducing utility bills. For example, in Orlando, FL, some utility companies offer a credit to customers who generate solar energy ($0.05 per kWh of solar power generated), and if any such electricity can be transferred to the main power grid, utility companies typically buy this electricity for the same retail price.

Table 4
Model Parameters.

Parameter	Source	Values & Ranges
EV Battery Capacity (kWh)	[55]	19–30
Hourly EV Charge (kW/h)	[57]	3–6
Solar Photovoltaic Production Incentive ($/kWh)	[58]	0.05
Electricity to Grid Price ($/kWh)	[59]	0.0757

2.3.2. Electric vehicle

As discussed earlier, EVs are included in this study as part of the energy supply system for the modeled NZEB. The EV is modeled as a battery that can be connected to the home during certain hours of the day and certain days of the week. This study assumes that the vehicle is used to go to work between 9:00 AM to 5:00 PM, and is then connected to the building for the rest of the day. For modeling purposes, some specifications with respect to the EV in this study should be defined before starting the analysis, including EV battery capacity, state of charge, hourly EV charge (EV battery charging rate per hour), and other specifications as applicable.

EV battery capacity is highly dependent on the characteristics of the vehicle, and can range from 19 kWh for a mid-sized sedan to 30 kWh for a full-sized SUV [55]. This study assumes that the lithium–ion batteries is used as described for a Nissan EV, the EV batteries of which are said to be able to store up to 24 kWh [56]. The hourly EV charge depends on the battery size, the charging level, and other important factors. Assuming an average vehicle range, it generally takes 4–8 h for an EV battery to be fully charged [57], so the hourly EV charge in this study is assumed to range from 3 kW/h to 6 kW/h.

The electricity that can be transferred to the building from the EV battery and vice versa is highly dependent on the amount of electricity that is left in EV battery when it reaches home. In this analysis, the state-of-charge (SOC) variable is used to determine how much electricity is still in the EV battery when the EV returns home. The SOC when the vehicle returns home depends on the distance that the vehicle needs to travel to reach home, which in turn may vary depend on the specific characteristics of each region. This study therefore uses the average returning SOC value as a starting point, and different ranges are applied to the analysis afterward to see the effect of this parameter on the required electricity from the power grid. All of the EV-related data and assumptions used in this study are summarized in Table 4 below.

3. Power distribution system

The role of Building Energy Management Systems (BEMS) is becoming more significant as the importance of providing the necessary thermal comfort, visual comfort, and indoor air quality is receiving more attention, especially in situations where fossil fuel consumption, GHG emissions, and price fluctuations are major obstacles to meeting the need for an energy-efficient building [60]. While the concept of BEMS generally applies to controlling HVAC systems and determining the operation times in order to reduce energy consumption without compromising comfort [60], this study attempts to use this management tool to establish a connection between different energy sources within the building and determine the flow of electricity between the main battery, the EV battery, and the power grid. In a NZEB, different types of energy sources should be used in conjunction with each other and with the conventional power grid. This study assume that all of the power generated through the solar panels and the electricity from the EV battery are stored in a main battery already designed for this purpose. However, the specific technological advancements to be used in such a power distribution system are beyond the scope of this study.

This study attempts to develop an algorithm in which different energy sources interact with the grid in order to provide enough electricity to meet the energy demand of the building, while also transferring any surplus generated electricity to the grid and obtaining any additional required electricity from the grid during off-peak hours. In this algorithm (Fig. 7), two possible situations are considered:

a.) **The EV is connected to the building.** In this case, the EV is considered as part of the energy supply system of the building. This study assumes that the vehicle is used to drive the owner to work every day at 9:00 AM and then return home by 5:00 PM; during this time, the vehicle is therefore disconnected from the building. When the EV is connected to the building and is not fully charged, the algorithm checks whether or not the amount of onsite renewable generated electricity is greater than the amount of energy consumption for that specific hour of the day, in which case the excess amount of generated electricity is used to charge the connected EV. This process continues until the EV battery is fully charged.

The next step is to see whether or not the main battery is fully charged. If not, then the onsite generated electricity is used to charge the main battery so that it can be used during on-peak hours, when the price of electricity is higher. After the EV battery and the main battery are both fully charged, if there is still any excess of generated electricity, it is transferred to the grid. In all of these steps, the algorithm checks if the generated renewable electricity is enough to supply the energy usage of the building.

If at any point the amount of onsite generated electricity is not enough to supply the energy demand of the building (especially during on-peak hours), then the system checks to see if there is any available electricity stored in the main battery. If there is, then the stored power in the main battery is used to power the building until it is fully depleted, after which the system checks if there is any electricity in the EV battery. Any stored power available in the EV battery is also used to power the building until the EV battery is also depleted, and if there is still insufficient power to meet the energy demand, then the remaining required electricity is taken from the grid.

b.) **The EV is disconnected from the building**. In this case, the main battery and the power grid are considered as the only available energy sources. Like in the previous scenario, the system checks to see whether or not the amount of electricity generated is greater than the energy consumption of the building. If not, then the system checks the main battery to see if there is enough electricity available in the main battery to power the building. If at any point the main battery is depleted, the power grid is used to provide the remaining electricity demand.

If at any time the onsite generated electricity is greater than the energy consumption of the building, the excess of generated electricity stores in the main battery for use during on-peak hours. Once the main battery is fully charged, any remaining surplus energy transfers to the grid.

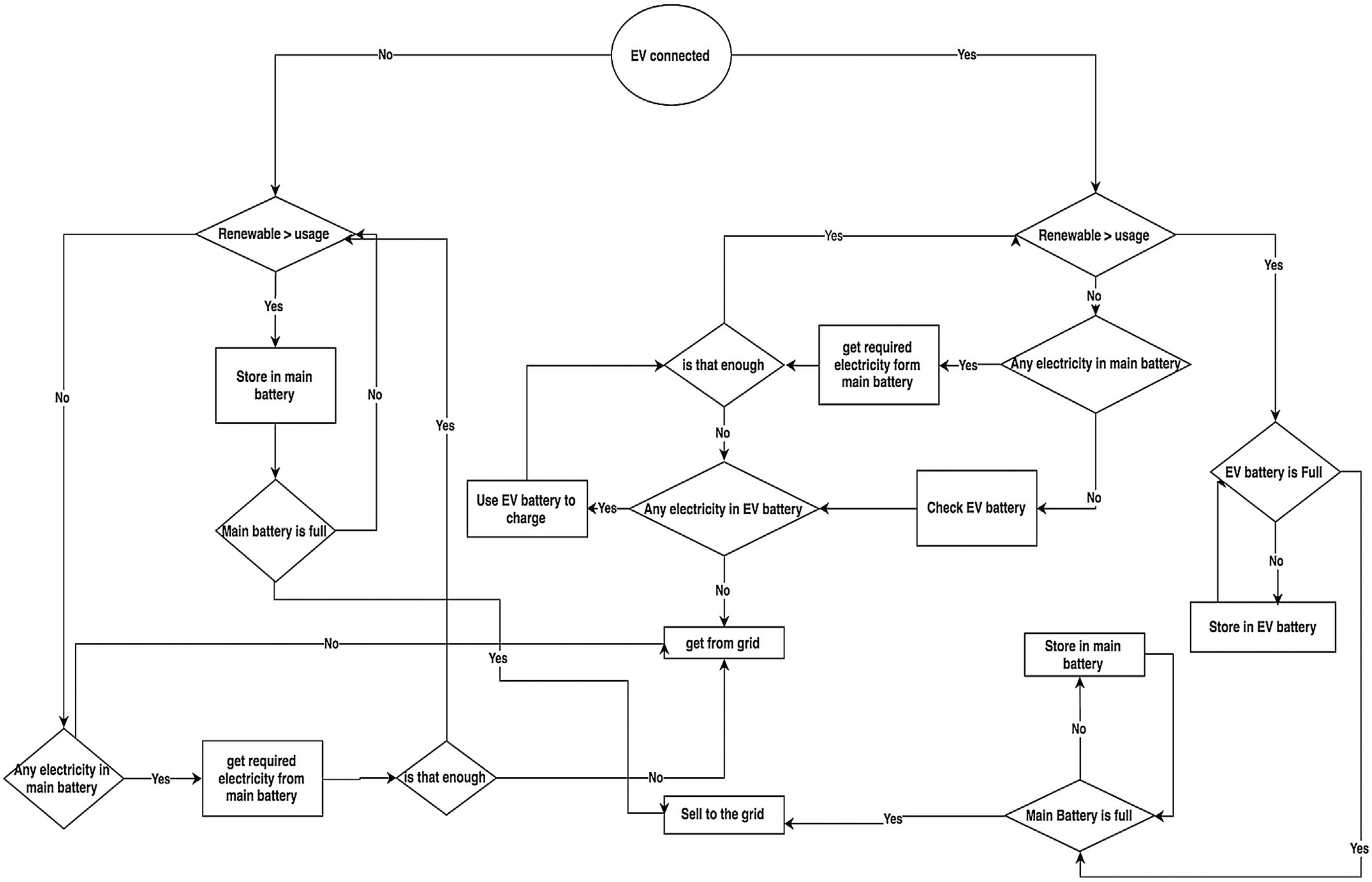

Fig. 7. Power Distribution System Algorithm.

Table 5
Hourly Electricity Pricing.

	Summer (April–October)	Winter (November–March)
Flat rate ($/kWh)	0.0757	0.0757
On-peak charge ($/kWh)	0.06124	0.03316
Off-peak credit ($/kWh)	−0.01125	−0.01125

4. Time-Based electricity pricing

Time-based electricity pricing is a pricing strategy in which power companies charge their customers extra for using electricity during certain time periods of the day (“on-peak hours”) and offer credits to their customers who consume electricity during any other time period (“off-peak hours”). Utility companies have introduced this strategy to their customers to save money by reducing peak power demand [61]. For this purpose, a flat rate is applied to electricity consumption regardless of the time of usage, and then (depending on the usage hour and season) an extra charge is added to the total bill for using electricity during on-peak hours, while bonus credits are subtracted from the total bill for using electricity during off-peak hours [62]. Different electricity rates used in this study for different hours of the day are presented in Table 5 below for different seasons; in this study, these seasons have been separated into “summer” from April to October and “winter” from November to March.

5. Results and discussion

The results of the analysis are presented in the following sections. First, the results of the energy analysis are presented in Section 5.1. Next, electricity consumption rates are compared and discussed in Section 5.2 for two scenarios, the first scenario being where the only available source of energy is grid electricity (the “conventional” scenario) and the second scenario being where renewable energy sources and the use of an EV battery are introduced as part of the energy portfolio (the “NZEB” scenario). Afterward, the amount of electricity transferred to the grid during different months of the year is presented in Section 5.3, followed by a price comparison for the two above-mentioned scenarios in Section 5.4. Finally, the results of a sensitivity analysis are presented in Section 5.5 to analyze the effects of input variables (main battery capacity and state of charge) on the annual electricity consumption of the building modeled in this study.

5.1. Energy analysis results

The results of the energy analysis are summarized in Table 6, including the monthly energy consumption of each type of power usage within the building (lighting, heating, cooling, etc.), as well as different sources of energy and/or energy savings, such as heat gain through windows and power generated through solar panels. Different parameters affecting the energy consumption of the building (outside temperature, humidity, building envelope, occupancy, heat gain through interior and exterior windows, etc.) have also been considered in this analysis, while Table 7 also summarizes the temperature and dry-bulb temperature for each month of the year. In Table 6, zone-sensible cooling and heating are defined as the sensible cooling and heating effect of any air introduced into the conditioned zone through the HVAC system [63]; for example, the heating effect of fans can be considered as a zone-sensible cooling load. Looking at Table 6, the results make sense in that, as the temperature increases from January to September (Table 7), the cooling load increases and reaches its maximum value in July, after which the temperature begins to decrease as the weather gets colder; although the month of February does not seem to follow this trend, this could be due to unusual weather conditions. The same trend can be seen in reverse for the heating load; as the number of cold days per month increases relative to the corresponding number of hot days, the heating load increases. The amount of electricity generated via the installed solar panels also can be tracked on a monthly basis (Table 6). This analysis shows that, as the number of sunny hours per day and/or the number of sunny days per month increase, the solar panels receive more sunlight and can therefore generate more and more electricity. This amount, as seen in Table 6, has an increasing trend until the end of July, after which it gradually starts to decrease until a sharp reduction us observed at the beginning of October. These differences in energy consumption trends are easily justifiable based on intuitive deductions from the surrounding environment. On the other hand, other contributors to the energy consumption of the building (room electricity, lighting and equipment components, etc.) have a nearly constant energy consumption rate with minimal variations during different months of the year, regardless of temperature changes or weather conditions.

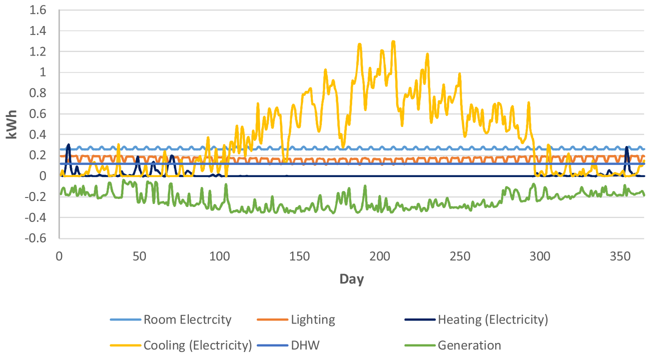

Fig. 8. Daily Energy Consumption of The Building.

Fig. 8 is presented below to better understand the results of the energy analysis of the building in question. In this graph, the energy consumption and generation for different months of the year can be observed for a quick visual comparison. The most significant variations occur for cooling load and electricity generation through solar panels during different months of the year, because unlike many areas in the U.S., heating load does not contribute significantly to the energy consumption of the building. As seen in this graph, as the hotter days of the year approach, the cooling load begins to increase significantly, while the opposite trend can be seen in the heating load. Except for the colder days in December, January and February, the heating load then becomes insignificant for the rest of the year. All other components (room electricity, lighting, hot water, etc.) have a relatively steady rate of variation for different months of the year. The negative values in the graph indicate the electricity generated via solar panels, which decreases the overall daily energy consumption.

5.2. Electricity consumption

The hourly and cumulative rates of purchased electricity from the grid for the studied building are presented in Figs. 9 and 10, respectively, each comparing the purchased electricity of the building with and without the integration of solar panels and the EV battery (“NZEB” and “conventional”, respectively).

The purchased electricity drops significantly in the NZEB scenario compared to the conventional scenario, with the average hourly decrease in grid reliance being roughly 61% year-round, while the most visible hourly decrease (93%) was in September. The gap in purchased electricity between the two scenarios is greatest during the summer due to increased solar power generation from

Table 6
Energy Analysis Results.

Energy analysis results (kWh)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Room Electricity	196.6	178.0	197.6	190.4	196.6	191.4	196.6	197.1	190.9	196.6	190.9	197.1
Lighting	133.4	117.1	123.2	117.4	115.3	106.9	113.6	117.4	117.5	129.5	125.1	132.2
Heating (Electricity)	28.7	24.5	34.7	1.4	0.0	0.0	0.0	0.0	0.0	1.8	5.2	25.9
Cooling (Electricity)	22.5	13.1	26.3	134.9	303.6	433.1	661.3	510.0	386.2	245.8	36.4	17.3
DHW (Electricity)	89.0	80.4	89.0	86.2	89.0	86.2	89.0	89.0	86.2	89.0	86.2	89.0
Generation (Electricity)	1280	1010	1797	2302	2509	2119	2336	2298	2221	1441	1446	1305
Computer + Equipment	196.6	178.0	197.6	190.4	196.6	191.4	196.6	197.1	190.9	196.6	190.9	197.1
Solar Gains Exterior Windows	811	564	831	1003	1046	920	977	972	990	731	868	864
Zone Sensible Heating	57.4	49.0	69.4	2.7	0.0	0.0	0.0	0.0	0.0	3.5	10.4	51.8
Zone Sensible Cooling	51.5	29.5	59.5	312.9	675.1	941.3	1392	1071	827.8	519.3	81.1	39.4

Table 7
Temperature Data for Different Months of the Year.

Temperature	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Air temperature (C)	19	21	22	24	25	25	25	25	25	24	23	21
Outside dry-bulb temperature (C)	14	17	18	21	24	26	26	26	26	23	20	16.3

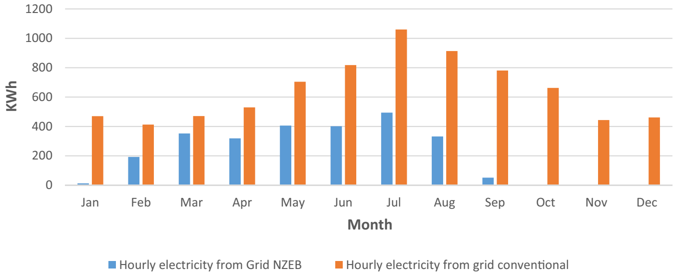

Fig. 9. Comparison of Hourly Energy Consumption of the Building for Conventional and NZEB Scenarios.

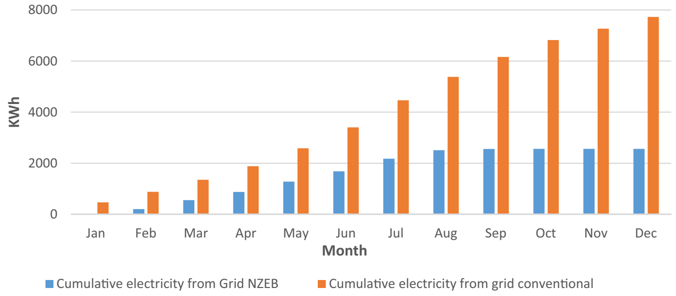

Fig. 10. Comparison of Cumulative Energy Consumption of the Building for Conventional and NZEB Scenarios.

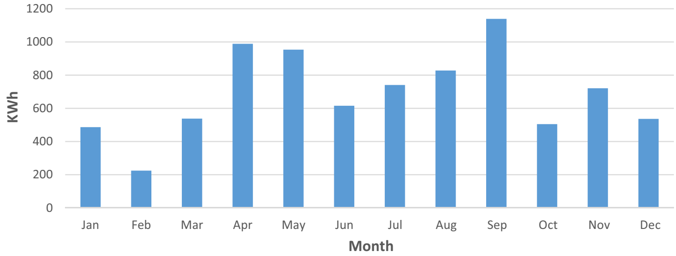

Fig. 11. Monthly Amount of Electricity Transferred to the Grid.

longer sunny periods compared to other months of the year. From Fig. 9, the overall year-round energy savings with the NZEB scenario is 66%.

5.3. Electricity to grid

As mentioned earlier, and as noted in the algorithm discussed in Section 3, any remaining excess amount of onsite generated electricity from the solar panels and from the stored electricity provided through the EV battery can be transferred to the power grid. Fig. 11 presents the amount of electricity that can be transferred to the grid in different months of the year. The amount of electricity transferred to the grid in each month is highly dependent on the electricity consumption of the building, as well as the monthly electricity generation rate from the solar panels, so finding a constant trend in this case is not possible on a yearly basis. However, jumps in the amount of electricity transferred to the grid from month to month can be better understood by looking at the electricity consumption of the building (Fig. 9) and the amount of solar energy generated (Table 6). In general, less electricity is transferred to the grid when the monthly energy consumption is higher and/or when the amount of generated solar energy is lower, in which case the main priority of the system is to supply the energy demand of the building first and then transfer any excess amount of generated energy to the grid. For example, the amount of electricity to grid is higher in September than October, November, or December, but looking at Fig. 9 and comparing electricity consumption rate in September with those in each of the last three months of the year, this may sound confusing. This confusion may be clarified by following the trend of electricity generation (Table 6) and analyzing the solar energy generation in each of the latter months.

5.4. Price comparison

A very important incentive for a NZEB is the potential economic advantages of such a building, as a true NZEB would effectively reduce its utility bills to zero. In the process, it is also possible to earn money to compensate for the installation costs of solar panels and other technologies required for the NZEB. Calculations regarding the monetary value of energy in this study are divided into two parts. The first part investigates how much in savings may be possible by reducing the energy consumption of the building, assuming that no credit is given to the customer for selling electricity to the grid or for producing renewable energy from solar panels or other energy sources. In the second part, however, a production credit is provided to customers who generate solar energy and then sell the excess amount of onsite generated electricity to utility companies such as the Orlando Utility Commission (OUC) [58].

The differences in conventional and NZEB electricity costs (with and without credits) are presented in Fig. 12, where it becomes immediately clear how much can be saved in electricity costs

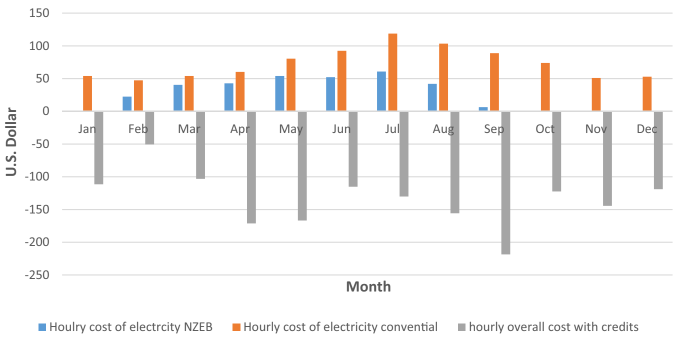

Fig. 12. Monthly Electricity Bill Comparison.

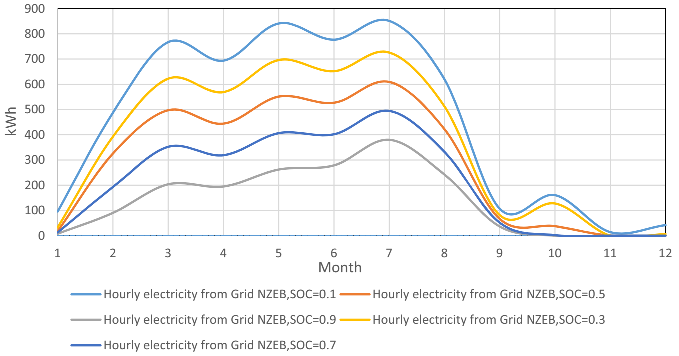

Fig. 13. Electricity from the Grid for Different Ranges of SOC.

with an NZEB. Many utility companies provide incentives for their customers to encourage the integration of renewable energy sources into their energy portfolios. Considering all of these credits together, the final electricity price for the NZEB in this study with all of the above-mentioned considerations and energy sources taken into account is shown in Fig. 12. This graph shows that, when the aforementioned credits are taken into consideration, the net electricity price is negative throughout the year, meaning that customers can effectively pay nothing for electricity and can even earn money as a result.

5.5. *Sensitivity analysis*

As previously discussed in Section 2.3.2, each of the aforementioned parameters in this analysis, (EV battery capacity, main battery capacity, hourly EV charge, SOC, etc.) have different ranges that must be considered in any practical analysis. The previous analyses described above used average values for each of the specified parameters. However, this section demonstrates the effect of these parameters (more specifically, the main battery capacity and the SOC) on the required electricity from the power grid and on the transferred electricity to the grid, and then compares the results as appropriate. For this purpose, two maximum and minimum ranges and three median values for main battery capacity (10 kWh to 90 kWh) and SOC (0.1–0.9) are tested, and the results are presented in Figs. 13 and 14. The values of the aforementioned parameters and the corresponding results are presented in Tables 8 and 9 for comparison.

The graph above (Fig. 14) shows that the lowest grid electricity demand is evident whenever the SOC is at its highest value. For instance, in January, the required electricity from grid is reduced by 92% as the SOC increases from 0.1 to 0.9, which shows how significant the effect of state of charge is on demand from the power grid. On a year-round basis, an average reduction of 80% in the required electricity from the grid is observed for the two maximum and minimum assigned values of SOC. This is because, based on the defined algorithm, after supplying the energy demand of the building and before storing any electricity in the main battery, the system stores the surplus onsite generated electricity in the EV battery. Having more electricity available in the EV battery when the vehicle returns home for the day means that less electricity can be stored in the EV battery afterward, meaning that more energy is available to be stored in the main battery and/or used to supply the energy demand of the building. The same rule also applies for the EV battery capacity; as the EV battery capacity increases, more electricity can be stored in the EV battery, and so more electricity is required from the grid to fully charge the EV battery. In other words, decreasing EV battery capacity has the same effect as increasing the state of charge.

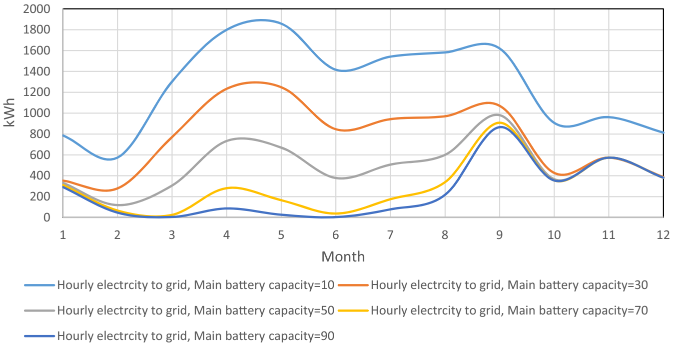

Fig. 14. Electricity Transferred to the Grid with different ranges of main battery capacity.

The results from Fig. 14 match the stated expectations as well, in that more capacity to store the surplus onsite generated electricity can justify less transferred electricity to the grid. As seen in Fig. 14, the highest amount of electricity supplied to the grid is observed when the capacity of the main battery is at its lowest value; hence, as the capacity of the main battery increases, the amount of electricity supplied to the grid decreases. For instance, as seen in Table 9 for the month of May, the observed reduction in electricity transferred to the grid is over 98%. On average, a 77% reduction in the amount of electricity transferred to the grid is observed for different months of the year as the main battery capacity increases from 10 kWh to 90 kWh. This is understandable because, based on the algorithm used, fully recharging the main battery is given priority over transferring electricity to the grid.

6. Conclusion

This study attempted to investigate the role of electric vehicles and renewable energy sources (e.g. solar power) as potential featured in a net-zero-energy building (NZEB). The main parts of the system analyzed in this study included solar panels for generating electricity, a main battery that interacts with these solar panels, an EV, and the main power grid. Using an inverter, the generated solar power was stored in the main battery, while the EV contributed to the overall system by providing electricity during on-peak hours and receiving electricity from the main battery and/or from the grid during off-peak hours. The mechanics of the system as a whole were based on a unique algorithm as described in Section 3 of this study, which assigned the energy sources to be used in the NZEB during any given hour of the day. The results showed that, with the help of this system, it is possible to reduce the amount of electricity required from the grid by up to 68% on average. The monetary value of reducing this grid reliance was also evaluated, and showed that the resulting electricity bill can be reduced by up to 62% without considering any of the various incentives and credits offered by

Table 8
Required Electricity from the Grid for Different Values of SOC.

State of Charge	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.1	95.8	487.4	767.2	693.8	841.3	776.8	851.1	619.8	106.6	160.5	13.9	41.8
0.3	32.5	392.4	622.2	568.8	696.3	651.8	725.9	512.1	81.2	127.6	0.0	6.3
0.5	17.7	325.7	497.2	443.8	551.3	526.8	609.4	422.1	66.2	37.6	0.0	0.0
0.7	12.7	192.7	352.2	318.8	406.3	401.8	494.4	332.1	51.2	2.1	0.0	0.0
0.9	7.7	90.3	203.6	194.8	262.0	278.5	380.0	242.1	36.2	0.0	0.0	0.0

Table 9
Amount of Electricity Transferred to the Grid for Different Values of Main Battery Capacity.

Main battery capacity (kW)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
10	786.2	574.4	1303	1799	1858	1415	1542	1582	1620	906.8	962.1	813.1
30	353.4	278.7	771.9	1233	1248	845.3	943.2	970.2	1071	426.7	573.9	387.6
50	331.7	118.7	306.7	733.6	670.2	378.2	507.1	600.2	981.0	366.5	573.9	381.3
70	311.7	66.6	25.0	281.5	165.6	37.5	175.3	338.6	908.0	354.4	573.9	381.3
90	291.7	46.6	5.0	86.5	26.2	3.5	78.1	217.2	866.2	354.4	573.9	381.3

different utility companies and government organizations; when these credits and incentives are taken into account, the resulting overall savings can increase drastically to as much as 2.83 times on average (Fig. 12). In fact, throughout the year, the net electricity price when credits are included is shown as a negative value, representing a net profit to customers from selling electricity to the grid. As stated in the introduction (Section 1), investigating the lifetime economic and CO_2 savings of this system is beyond the scope of this study. However, the relevant emission factor indicates that reducing 1 kWh of electricity consumption can reduce CO_2 emissions by 6.89551×10^{-4} metric tons [64], meaning that it is possible for this system to reduce overall GHG emissions by 3.56 metric tons by the end of any given year. From this perspective, the large-scale environmental impacts of reducing reliance on grid electricity can be significant.

In the last phase of this analysis, a sensitivity analysis was performed to investigate the effect of the different modeled parameters (specifically the capacity of the main battery and the EV battery's state-of-charge value) on the overall performance of the system. It is worth noting that this study was an attempt to apply V2H technology and solar power to a possible NZEB scenario; the results of this analysis showed that the net cost of electricity is negative by the end of the year, which can be interpreted as a net revenue for homeowners, but it should also be noted that having an energy-efficient building and installing solar panels can significantly increase the total capital cost. Even though the cost of solar panel installation has reduced noticeably in recent years, such costs should still be included in any complete life cycle cost analysis. Nevertheless, the significant reduction in electricity cost shows that this research can be used as a starting point for future efforts to design a NZEB. In the continuation of this study, efforts will be made to modify this algorithm and the applicable ranges for different variables to more adequately reflect regional differences, as each region of the U.S. has its own driving behaviors and weather patterns that can affect the energy consumption of a particular building. This study also attempted to discuss and present the potential feasibility of this system by developing an algorithm that can connect the different components of the system (the EV battery, the main battery, the power grid, and the building itself), although investigating the life cycle cost of the building and the related technical aspects were both beyond the scope of this study.

In future research, different pricing ranges will be also tested using an Agent Based Modeling (ABM) approach where, by applying different pricing scenarios, the life cycle cost of the system and the payback period will be simulated in a real-time analysis. Moreover, more focus will be given to a life cycle cost comparison between a standard code-compliant building and a NZEB by considering the payback period of increased costs incurred from making the system more energy-efficient and from the integration of photovoltaic solar panels into the building's energy portfolio. In addition, it is important to evaluate the co-costs and co-benefits [65] of getting to net zero energy buildings in future research.

Acknowledgment

This work was supported in part by an award to the University of Central Florida, as part of grant number DTRT13-G-UTC51 from the U.S. Department of Transportation's University Transportation Centers Program.

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