Energy Storage Requirements of a Transition to Renewable Energy

by

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ABSTRACT

The proliferation of grid-dependent, zero-energy buildings in a region will alter the diurnal electric power demand to a U-shaped demand curve that limits the role of base-load power plants and the flexibility of the electric grid to meet the power demand. Zero-energy buildings that are also grid-independent (GIB-ZEBs) ensure that carbon emissions are curtailed and that the electricity grid will retain its flexibility to make appropriate use of large, base-load power production units. Such buildings incorporate a reliable system for energy storage that supplies the needed energy when the renewable energy source does not. This paper offers a detailed analysis of the power needs, the seasonal energy usage, and the seasonal energy storage requirements of two GIB-ZEBs. The first is located in the South-West part of the USA, where the air-conditioning demand is very high and the second in the North, where the heating demand is very high and the irradiance/insolation is less. Hydrogen storage and battery storage systems were considered for the energy storage requirements of the buildings. Calculations for the two buildings include: the hourly electric power and total energy demand of the building throughout the year; the hourly energy production by a system of photovoltaics; the hourly energy storage needed throughout the year; the photovoltaics area requirements; the overall capacity and seasonal use of the energy storage system needed; and the effects of the various components and systems performance on the power production and storage parameters.

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Abstract

The proliferation of grid-dependent, zero-energy buildings in a region will alter the diurnal electric power demand to a U-shaped demand curve that limits the role of base-load power plants and the flexibility of the electric grid to meet the power demand. Zero-energy buildings that are also grid-independent (GIB-ZEBs) ensure that carbon emissions are curtailed and that the electricity grid will retain its flexibility to make appropriate use of large, base-load power production units. Such buildings incorporate a reliable system for energy storage that supplies the needed energy when the renewable energy source does not. This paper offers a detailed analysis of the power needs, the seasonal energy usage, and the seasonal energy storage requirements of two GIB-ZEBs. The first is located in the South-West part of the USA, where the air-conditioning demand is very high and the second in the North, where the heating demand is very high and the irradiance/insolation is less. Hydrogen storage and battery storage systems were considered for the energy storage requirements of the buildings. Calculations for the two buildings include: the hourly electric power and total energy demand of the building throughout the year; the hourly energy production by a system of photovoltaics; the hourly energy storage needed throughout the year; the photovoltaics area requirements; the overall capacity and seasonal use of the energy storage system needed; and the effects of the various components and systems performance on the power production and storage parameters.

1. Introduction

The rapid global growth of energy and electric power demand are causes of several detrimental environmental effects, most important of which is Global Climate Change (GCC) with the accompanied regional climate warming and sea-level rise. There is a recognized need to restrict the CO_2 emissions, as well as emissions of other greenhouse gases. This is accomplished by reducing the electricity consumption from centralized fossil fuel power plants – especially coal power plants – and promoting alternative energy solutions, such as solar energy, wind power, nuclear power, etc. [1]. The efforts to promote alternative energy solutions as well as the expected depletion of fossil fuel reserves in the future has placed renewable energy and, in particular, solar and wind energy in the forefront of technological and societal interest.

The total energy demand in buildings, for both residential and commercial use, is approximately 35% of the Total Primary Energy Supply (TPES) in the OECD countries [2]. The fraction of the electric power demand for residential and commercial buildings is even higher: buildings in the USA consumed more than 74% of the total electric power production in 2014, most of it for lighting and air-conditioning [3]. These numbers are typical of other OECD countries. Higher energy efficiency and the increased production of solar electric power in buildings have become principal objectives for the energy policies of several regional and national governments.

A high fraction of the electric energy consumed in buildings is spent on the electricity-voracious air-conditioning systems [4] and solar energy is highly correlated with the air-conditioning demand. A solution to the high peak seasonal and the diurnal electricity demand, which would alleviate the strain on the electricity production and distribution systems in the hotter climates, is to produce more electricity from solar energy. Solar power from photovoltaic (PV) systems has been touted as a very suitable source of electric power production for residential and commercial buildings. The continuously decreasing cost of PV cells since 1980 in combination with improvements in their manufacturing and energy conversion efficiencies make the significant production of electric power by solar energy more likely in the next decades [1, 5]. If distributed systems using solar power are readily used to satisfy the electric power demand of residential and commercial buildings (or any other electricity demand sector for that matter), the demand for electric power at daylight would lessen. Higher use of solar power during the hottest days will also decrease the use of low-efficiency, peak-demand fossil fuel units and will prevent a part of CO_2 emissions to the atmosphere. Futuristic ideas for electric power generation systems envision buildings with walls surrounded by PV membranes, which produce a large fraction of the electric power demand, not only for the buildings themselves, but also for other residential and industrial users in their vicinity [6].

The heating needs of residential and commercial buildings during the winter months are primarily satisfied by gaseous and liquid hydrocarbons – natural gas or the several forms of heating oil. A small but growing fraction of buildings use heat pumps, which are driven by electric power. In particular, the use of Ground Source Heat Pumps (GSHPs) has grown rapidly in the European Union and the USA in the last two decades [7, 8]. While being reliable and very efficient, GSHPs also shift the demand for hydrocarbons to demand for electric power, which may be provided by renewable sources. Since solar collectors cannot supply all the heating needs of a building during the colder days an alternative to fossil fuel combustion is to use PV-powered heat pumps with energy storage.

Residential and commercial buildings that independently meet their annual energy needs have been the subject of study by several researchers. The concept of the Zero Energy Building (ZEB) or Net Zero Energy Building (NZEB) has been studied for decades, even though there are several slightly different definitions and descriptions of such buildings [9]. A ZEB, in general, produces as much energy as it consumes annually. This implies that, during several time-periods the building will draw net power from the electric grid, while at other periods it will be a net producer of electric power and will contribute this power to the grid. Because of its connection to the electricity grid, a ZEB does not necessarily use storage for the excess energy it produces or demands. The building may simply draw this energy from the electricity grid and return it back at a later time. A review article [10] examined the impact of two design strategies currently used in the development of ZEB technology: a) the minimization of the buildings' energy need through energy-efficiency and conservation measures; and b) the adaptation of renewable energy and other technologies to meet the remaining energy needs. Another study examined the performance of such buildings under future, warmer climatic conditions that impose higher cooling requirements [11].

Optimizing the characteristics of renewable energy sources (generation, storage and flexibility of demand) with the selection and sizing of the systems for ZEBs has been the subject of several recent studies [12, 13, 14]. An integral part of the optimization of current ZEB technology is the high energy efficiency of the buildings, new or retrofitted. A related ASME-sponsored competition derived appropriate designs for solar houses using PV panels for electric power, that supplied all the needed building energy in the Washington DC area [15]. However, these prototype ZEBs are very small, in the range 450-800 ft^2 (42-74 m^2) and by far smaller than the detached houses in that region, which average more than 2,000 ft^2 (186 m^2) of heated and air-conditioned area. If the current standard of living is to be maintained with renewable energy supply, one has to examine the energy needs of existing designs of larger buildings with all their amenities. A combination of energy efficiency and conservation measures, together with the production of electricity from renewables may be proposed for such buildings. Lesser space and higher energy efficiency imply lesser need for electric power and lower investment for renewable energy production. Building owners may take all these under consideration and arrive to an informed decision for the systems and the overall technology to be adopted in their ZEB.

2. The Grid-Independent Buildings

While the ZEB concept is a good standard to aim, it has a noteworthy drawback: In urban locations with several ZEBs, when energy is needed from the electricity grid (e.g. at the dusk and night hours) there is a spike of electricity demand, which must be met immediately by conventional electric power plants that need to be on standby. When the irradiance/insolation[1] is high and the building does not consume all the power it produces – e.g. in the morning hours of the summer and during most days in the spring – the building feeds the excess energy it produces to the electric grid at times when the overall demand for electric power is low. This causes a shift of the electric power demand, which develops a substantial dip during the early daylight hours, when the demand is lower and the high insolation produces excess power in the PV cells. This type of power demand trend has been called *U-shape demand* or *duck curve* [16, 17] and limits the flexibility of the electricity grid to use the larger base-load units. Figure 1 depicts the transformation of a typical summer day demand for the city of San Antonio, Texas, if the number of ZEBs is high enough to account for the production by PV cells of 10%, 20%, and 25% of the electric energy demand during the summer days (data from [1]). The power denoted by the broken lines is the power demanded by the rest of the power production units, including base-

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[1] The words irradiance and insolation are often used interchangeably. While irradiance is defined as instantaneous power per unit area, insolation is used when the time-integral of irradiance is taken and the average is obtained. We mostly use the term insolation because the data for the instantaneous irradiance data are averaged over a period of one hour and the source of data [26] uses the same term.

load units. The area under the broken lines represents the total electric energy supplied by the rest of the units in the grid during the 24-hour period (90%, 80% and 75% in this case). Two observations are made in this Figure: a) the peak power demand is reduced from 4,296 MW to 4,115 a rather small decrease of 4.2%; b) the minimum power demand for the rest of the units, which is typically supplied by large, base-load units, is reduced from 2,219 MW (at 3 am) to 251 MW when the ZEB fraction increases to 25% of the total demand (at 10 am, when the insolation is high but the air-conditioning demand is not). Actually, the electricity "demand" between 9 and 11 am would become negative if the fraction of the ZEB's were to increase to 30%, which signifies higher electric energy production than the entire demand of the grid.

The second observation is very significant for the electricity production industry: Because large, base-load units – primarily nuclear and coal[2] steam power plants – cannot readily adjust their power production levels within short timescales, a region that heavily relies on solar (or wind) power for grid dependent ZEBs will have to do one or a combination of the following:

a) Reduce the number or completely eliminate the current base-load power plants and substitute them with gas turbines. This requires significant investment in new gas turbines.
b) Invest in utility-level storage capacity that would enable the base-load power plants to operate in conjunction with the solar units. This option also requires significant investment by the electric power production and transmission corporations.
c) Shift the storage capacity to the buildings, or districts with groups of buildings, and promote Grid-Independent Buildings (GIBs) or districts of buildings. The GIBs are

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[2] While it is desirable to retire several of the currently operating coal power plants, this should be done without disrupting the supply of electric power to the consumers and the reliability of the grid.

powered by renewable energy (solar or wind), they store the excess energy and use it when the renewable energy source is unavailable. Converting buildings to GIBs and developing the required storage systems requires investment by the owners.

The construction of more GIBs in the mix of residential and commercial ZEBs has two significant and beneficial effects on the electric power demand. First, it reduces the power produced by carbon fuels and reduces the CO_2 emissions. Secondly, it allows for the inclusion in the power production mix of large, base-load nuclear power units, which do not emit CO_2, but are not flexible enough to accommodate large diurnal power fluctuations. When the national economies make the transition from fossil fuels to periodically variable or intermittent renewable energy, the U-shaped demand curves may become a problem and will need to be addressed. Two of the available solutions are: significant energy storage at the utility level; and conversion of higher number of buildings to GIBs.

Two types of GIBs may be developed:

1. Completely zero-energy buildings that are also grid independent. These buildings satisfy completely both the electric power and heat rate demands by renewable energy without any reliance on the electricity grid.
2. Buildings that completely satisfy their electric power demand from renewable energy, but use conventional energy – e.g. natural gas – for their heating needs. In the warmer regions, where most of the residential energy is spent for air-conditioning, this would still result in the desired reduction of the CO_2 emissions.

This paper examines the conversion of two large residential buildings to GIBs powered with solar energy. The first building is in the Dallas/Fort Worth area of Texas, and has high air-conditioning demand in the summer. The second building is in Duluth, Minnesota, where the heat demand is higher during the winter and there is no need for air conditioning during the summer. The buildings produce energy from PV panels. We consider hydrogen storage and solid battery systems for the energy storage and perform calculations on the daily and hourly amount of energy that needs to be stored. We examine the hourly energy demand of the buildings – for both electricity and heat – for an entire year and match this demand with the local solar energy supply. We also conduct a parametric study and determine the needed area and rated power of the PV panels and the needed storage capacity, under several conditions related to the adoption of conservation and energy efficiency measures.

Wind is another available renewable source in the locations of both buildings. However, the available wind turbines for residential buildings generate noise and several homeowner association (HOA) regulations prohibit the use of wind turbines in residential areas. In addition, buildings and other structures increase the surface roughness and wind turbulence in residential areas, the wind velocity is significantly lower and wind turbines do not operate efficiently. For these reasons, it was decided to use solar panels instead of wind for the supply of electric power.

Some advantages and disadvantages of GIB systems are listed in Table A. While this paper examines the conversion of two buildings to GIBs and calculates the power and storage parameters that will make this possible, it does not imply that converting all buildings to GIBs is an ideal solution to our energy challenge. It is very likely that the ideal mix of electric power production to accommodate a higher fraction of renewable energy will include GIBs, utility-level storage, and reduction of the capacity of base-load plants.

It must be noted that this paper does not offer an economic analysis of a GIB-ZED building and does not provide any financial figures of merit, such as Net Present Value (NPV) and Pay Back Period (PBP). The reason for this is that GIB-ZEB systems are still at their infancy and, naturally their present costs are very high. Our experience shows that, when the technology of appliances and systems for buildings matures; the systems are optimized; the systems are adopted by the market, become household items/appliances and massively produced, then their cost drops significantly and their PBP improves dramatically. The significant decrease of the PV cell costs and performance improvement since 1980 (equipment that are parts of the GIB-ZEB systems) is another indication that current pricing will not offer a significant insight on the feasibility and future cost-effectiveness of GIB-ZEB systems.

3. Description of the Buildings and the Energy Systems

Figure 2 is a schematic diagram of a complete PV energy system for a building with energy storage. An array of PV panels is placed on the roof of the building. If the roof is not sufficient for the entire area of the panels, another open space (e.g. part of the yard) is chosen. The PV panels produce dc electric power from the insolation, which is either used directly for the electric needs of the building or is stored in the storage system. The latter consists of either stacks of solid-state batteries or a hydrogen tank with fuel cells for the supply of dc voltage. If a battery system is chosen, the fuel cell is not necessary and is omitted. A *voltage controller*, which maintains almost constant voltage, is placed before the storage system to regulate the dc voltage and avoid excess voltage input that would damage the storage system. Also a *Maximum Power Point Tracker (MPPT)* ensures that the power is produced at the maximum power point of the solar panels. If the equipment in the buildings operate with ac, an *inverter* is necessary to convert the lower dc voltage from the solar panel and the storage system to the 120 or 230 V ac used in the building's HVAC equipment and the other electric systems and appliances. If the equipment and appliances in the building use dc current, the inverter is not necessary and is omitted.

The two detached residential buildings under consideration, in Fort Worth and Duluth, consist of approximately 3,750 ft^2 (348 m^2) area that is heated and air-conditioned. The size of the two buildings represents larger residential dwellings in the two markets and was chosen for the following reasons:

a) Most of the studies for solar energy in residential buildings use very small buildings oftentimes attached to other buildings [15].
b) It is often touted in the popular press that, because larger residential buildings use more energy and require larger PV systems, it will be very difficult and very expensive to convert them to ZEBs.
c) The current trends in the USA are for the construction of larger residential, single-standing buildings. In 2015 the median floor area of new homes built in the USA was 2,467 ft^2 (222 m^2) 61% higher than in 1973 [18].[3]
d) Single-standing (detached) residences are surrounded by large yards and open spaces, where the PV panels may be easily placed.

The energy demand patterns of the two buildings are typical of large residential buildings in the two geographical regions considered: The Fort Worth building consumes annually approximately 23,600 kWh of electric energy and 112,200 MJ of thermal energy, which is supplied by natural gas. The building in Duluth consumes annually approximately 8,700 kWh of electric energy and 370,000 MJ of thermal energy, also supplied currently by natural gas. Both buildings have two

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[3] The median size of all residences, including apartments and duplexes is lower, approximately 1,800 ft^2.

floors and were originally constructed in the 1980's, when energy conservation was not a priority. For this reason, the annual energy consumption of both buildings may be reduced significantly with retrofitting and energy efficiency systems. The Fort Worth building has two floors, both air-conditioned by two independent HVAC systems, one for each floor. The building in Duluth uses a natural gas burner with circulating air for heating.

The hourly electric power demand of the Fort Worth building is shown in the graph of Figure 3, for two typical days in the summer and the winter. The hourly power demand was obtained from the Reliant® electric corporation, which supplies power to the building. The effect of the air-conditioning is apparent in this figure: while the electric power demand in the winter is almost constant, in the range 1-2 kW, the demand in the summer increases dramatically between noon and 9 pm when the two HVAC systems operate almost continuously. The electric power demand peaks at the maximum of about 14 kW at about 7:00 pm, when the local insolation has decreased to less than 40% of its peak.[4] It is observed in the Figure that the air-conditioning demand is not eliminated after the sunset (at approximately 8:30 pm) because of the still higher ambient temperature and of the heat storage capacity of the building, which is getting hotter during the day. This is very significant for solar houses, which must obtain the needed power from either the (highly loaded at that time) electric grid or from a local energy storage system.

The heating needs of the Fort Worth building – for hot water throughout the year and space heating in the winter months – are currently met by natural gas. Energy calculations for the building were performed for two cases:

1. Only the currently needed electric energy is supplied by the PV system.

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[4] The solar noon in Fort Worth is rather late, at 1:40 pm in July.

2. Both the electric energy and the thermal energy needs are met by the PV system with the installation of a heat pump, which supplies the hot water and the space heating demand of the building.

The residential building in Duluth, Minnesota, was chosen to be very similar to the one in Fort Worth. The summers are cool in that region and residences do not need to be air conditioned. The annual heating demand is very high and the residence needs to be heated for most of the year from September to May. In addition, the irradiance/insolation is weaker at the higher latitude of Duluth – at 47^o compared to 32^o of Fort Worth. The hourly heating demand for this building was also calculated for an entire year and a GSHP system was chosen to supply the heating demand. Because the GSHPs derive heat from the ground, which is at almost constant temperature throughout the year [7], their coefficients of performance (COPs) do not exhibit the variability of conventional heat pumps that use the ambient air in the evaporation process. Very efficient GSHPs in the region may reach COPs up to 6. The more conservative value for an average COP of 4.5 was chosen for the heat pump of this building. Because the temperatures in Duluth seldom exceed 26 ^{o}C, buildings in that area do not need air conditioning. The entire energy demand for this building, including the energy needed for the operation of the heat pump, will be supplied by a PV system, similar to the one shown in Figure 2. The effect of the energy conversion efficiency of the solar cells on the needed panel area and the nominal power required is one of the parameters that have been investigated.

4. The Energy Storage System

When solar power is low or unavailable, the energy storage system of the building supplies the needed electric power. Two types of storage are considered for the buildings:

1. A hydrogen storage system that produces hydrogen by electrolysis. The hydrogen is generated and stored under high pressure, 500 bar ($500*10^5$ Pa), in a tank. Several commercially available automobiles – among these, the *Honda FCX Clarity*, the *Kia Borrego,* the *Hyundai ix35 FCEV*, the *Ford Focus FCV,* and the *Toyota Mirai* – have hydrogen storage systems with operating pressures as high as 700 bar ($700*10^5$ Pa). A system of fuel cells, associated with the storage system supplies dc electric power to the building when additional power is needed.
2. Stacks of solid-state, lead-based or lithium-based batteries connected in parallel and in series that supply 24 V dc power to the building [19].In general, solid-state batteries have higher round trip efficiencies than hydrogen storage in the short term, e.g. the diurnal cycle, but have low specific energy (in kJ/kg or kWh/kg) and, in addition suffer from self-discharge over long periods of time.

Of importance for the performance of the energy storage system is the *round-trip efficiency*, defined as the ratio of the electric energy delivered by the storage system to the initial energy input. In the case of hydrogen storage, the round trip efficiency is the product of the efficiency of the electrolysis and the efficiency of the fuel cells. For the system of batteries, the round trip efficiency includes the charging efficiency and the energy lost because of self-discharge (the internal drift current) which depends on the duration of the storage period.

Typical self-discharge rates for common rechargeable cells are as follows [20]:

- Lead Acid 4% to 6% per month
- Nickel Cadmium 15% to 20% per month
- Nickel Metal Hydride 30% per month
- Lithium 2% to 3% per month

Given that the round trip efficiency of the electrolysis-fuel cell system is approximately 50%, and that the battery charging efficiency (for full charge) is approximately 80%, the benefits of the higher round trip efficiencies of batteries are nullified after 1 month for Nickel Metal Hydrate batteries; after 1.5 to 2 months for Nickel Cadmium and after 5-7 months for Lead Acid batteries.

The efficiencies of the other equipment associated with the energy storage, such as the MPPT and the inverter are higher than 95% [21]. Under the current state of technology, very small amounts of energy are dissipated in these systems. In the calculations of this paper these efficiencies are lumped together with the other efficiencies of the energy storage system that are significantly lower.

5. Range of Parameters, Calculations, and Data Used

One of the principal contributions of this study is the effect of the component efficiencies of the solar energy conversion and storage system on the overall power needed for the PV system, which operates in combination with the storage system. Mass-marketed polycrystalline PV panels currently have efficiencies in the range 12-20%. With the worldwide research effort in photovoltaics, efficiencies of marketable PV cells above 25% will become feasible in the near future and may become more economical and more prevalent to install for commercial applications [22]. PV cells that are less expensive and most commonly used in buildings have efficiencies in the range 15-22% at lower ambient temperatures. The PV cell efficiency depends on the ambient temperature and drops with increasing temperatures, by one percentage point for every 4-6 ^{o}C temperature rise above 25 ^{o}C. Thus, the efficiency of the PV system is given by the equation [23]:

$$\eta_{Tsc} = \eta_{sc}\left[1 - k_{sc}\left(T - 25\right)\right] \qquad for\ T > 25^{o}C\ . \tag{1}$$

Values for the temperature sensitivity coefficient, k_{sc}, are in the range 0.002 to 0.006 $^{o}C^{-1}$ [23]. In this study, the sensitivity coefficient value k_{sc}=0.0025 was adopted. The following range of the other parameters was used in the calculations:

1. The PV panel efficiency, k_{25}, is in the range 14-26% [22].
2. The efficiency for the electrolysis process, η_{el}, is in the range 50-80% [24].
3. The efficiency of the fuel cells, η_{fc}, is in the range 45-80% [25].

The last two ranges of parameters indicate that the round-trip efficiency of the hydrogen storage system is in the range 22.5% to 64%. This implies that between 36 and 77% of the energy produced by the PV panels is dissipated in the (needed) storage system. In addition, we considered the effects of the adoption of conservation and energy efficiency measures that would reduce the power demand of the two buildings.

Detailed tables on the hourly insolation (the average irradiance over a 1 hour period) data for the Fort Worth and Duluth areas are available from the *National Solar Radiation Database* [26]. In order to avoid the effects of fluctuations of insolation due to past weather phenomena, e.g. because of storms, the average of five years of data was obtained from this database and used in this study. The system of PV panels that has been considered is stationary (the additional expense of heliostats that track the sun disc is prohibitive for smaller installations), with the panels facing to the south and positioned at an angle that is approximately equal to the latitude of the location (32° in Fort Worth, 47° in Duluth). The total, hourly insolation received from this system of PV panels, due to both direct and diffuse radiation, is calculated from the available data in the national database [26].

At a given hour in the calculations the energy production of the PV system is:

$$E_{Pi} = A\eta_{Ti}\dot{S}_i T \quad , \tag{2}$$

where $\dot{S}_i$ is the total insolation/irradiance on the PV panels; η_{Ti} is the efficiency of the PV cells; A is the total area of the panels; and T the time of operation of the panels.

It must be noted that local effects other than the temperature would affect the efficiency of the irradiance-to-electricity conversion. Among these are: the electrical mismatch of the current-voltage curves of the PV modules; reflective losses on the glass of the panels; accumulated dirt and water on the surface of the panels; spectral mismatch, etc. A useful enumeration and analysis of these factors appear in an article [27], which was part of the PERSIL project and monitored thirteen PV systems in the EU and calculated the long-term (one to two years) performance of thirteen actual PV installations. The paper also offers recommendation for the optimum coupling of the array and the inverter, dust removal and the overall maintenance of the PV system to optimize the overall energy production. The focus of the present study is in avoidance of the U-shaped demand for the electric power demand and the need for storage, not so much in the irreversibilities of the PV system. For this reason all the irreversibilities were lumped together in the efficiency of the system, η_{Ti}. The wide range of the lumped efficiencies in the calculations covers all the other irreversibilities.

Since the timescale of all the calculations is T= 1 hour, when the irradiance and insolation are given in kW/m^2, the energy production is obtained in kWh. The hourly energy demand of the buildings, E_{Di}, is met either by the hourly energy production or by the storage system. If the hourly production is greater than the demand, the difference is added to the storage level. If the production is less than the demand, the difference is obtained and subtracted from the storage:

$$\begin{aligned} E_{Pi} &= E_{Di} + \delta E_{Si} \qquad if \quad E_{Pi} \geq E_{Di} \\ E_{Pi} &= E_{Di} - \delta E_{Si} \qquad if \quad E_{Pi} < E_{Di} \end{aligned} , \tag{3}$$

At the end of the ith hour the energy storage level, E_S, becomes:

$$\begin{aligned} E_{Si+1} &= E_{Si} + \left(\delta E_{Si}\right)\eta_{el} \qquad if \quad E_{Pi} \geq E_{Di} \\ E_{Si+i} &= E_{Si} - \left(\delta E_{Si}\right)/\eta_{fc} \qquad if \quad E_{Pi} < E_{Di} \end{aligned} , \tag{4}$$

It was stipulated that the energy storage system must store enough energy to power the building for a minimum of ten days. The reason for this is that if there is a system failure or malfunction, the owners of the building will have enough time to repair the system and/or purchase additional stored energy (hydrogen or batteries) to ensure that the buildings functions will continue uninterrupted.[5] This constraint was added to improve the reliability of the entire system, which is able to function even if there are storms and cloudiness that decrease substantially the insolation and production of electricity by the PV system, or if the system fails and needs repairs. This is actually one of the advantages of energy storage: because a great deal of energy is stored bad weather scenarios and worst case scenarios are alleviated by using the stored energy. This constraint implies that the energy stored in the system does not reach zero. A sensitivity analysis proved that small variations in the actual value of this constraint (e.g. five to twenty days) do not alter significantly the results of the study. At the end of the year (8,760th hour), the energy storage system contains the same energy it had at the beginning of the year. This condition is used in the calculation of the total area and nominal power of the PV system, which is obtained by iteration. The steps followed for this iteration are:

1. The year starts with an assumed quantity of stored energy E_{S0}.

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[5] In all countries it is easy to purchase and charge needed battery capacity. Most countries have also developed markets for hydrogen purchase.

2. An area A_i, for the PV system is assumed and inserted in the spreadsheet with the energy demand, the supply, and the storage data.
3. The stored energy at the end of the year, E_{S8760}, is calculated and compared to E_{S0}. If $E_{S0} < E_{S8760}$, A_i is increased. If $E_{S0} > E_{S8760}$, A_i is decreased, until $E_{S0} = E_{S8760}$.
4. The correct value for E_{S0} is obtained by a second iteration. This iteration uses the condition that, on the day of the minimum storage, the system still has in storage the equivalent of ten days energy demand.

5. Results and Discussion

In the case of the building in Fort Worth we considered two cases for its conversion to GIB: one as a ZEB and the second with the supply of the heat by natural gas, which means that the current heating system is left as is. Because Fort Worth is very close to the Barnett Field that contains vast proven quantities of shale gas, natural gas is part of the local economy and its retail price is expected to be well below the prices of other thermal energy sources.

A. The building in Fort Worth – electric power only

At first, we considered a base case and the current hourly demand for the building, which adds to 23,556 kWh for the entire year. Currently feasible efficiencies for the components were applied as follows: for the PV cells η_{25}=18% [5]; for the electrolysis η_{el}=70% [24]; and for the fuel cell(s) η_{fc}=65% [25] (round trip efficiency for hydrogen storage 45.5%). The calculations showed that, for this base case, the GIB must be furnished with 98.75 m^2 of PV panels that have nominal power 18.3 kW.

For hydrogen storage, the maximum storage level in this case is 109.5 kmol of hydrogen, the equivalent of 7,293 kWh stored. At the maximum pressure of 500 bar ($500*10^5$ Pa) the density of hydrogen is 15.64 kmol/m^3 [28]. This implies that a storage tank with 7.00 m^3 capacity is needed. While the annual energy demand for the building is 23,556 kWh per year, the PV system must produce 37,584 kWh because of the energy losses for any part of the energy that needs to be stored.

For solid-state battery storage, typical automobile and marine lead acid batteries make 0.336 kWh of stored energy available and weigh approximately 40 lbs (18 kg). For the 7,290 kWh stored energy, the building would need approximately 391 tons of lead acid batteries. Using two commercial types of lithium-based batteries the weight of the storage system is calculated at 171 and 212 metric tons [19]. Because the foundations of the two buildings cannot withstand such heavy weight it was decided that solid state batteries should not be used. Two other factors against the use of batteries for such type of energy storage are:

1. The self-discharge (drift current) of batteries that reduces the stored energy.
2. Environmental considerations if such systems are adopted by a large fraction of the population. All batteries contain heavy metals (Pb, Ni, Co, Mn, Cd, etc.) that have been proven to be harmful to living organisms, including humans. The transportation (for maintenance and periodic regeneration) of large number of solid-state batteries inevitably results to misplacement and discarding of the batteries, which will add significantly to environmental deterioration [8].

Figure 4 shows the monthly electric energy demand of the building, the energy supply from the PV system and the monthly maximum energy storage level (all in kWh) needed for the sustainable operation of the building throughout the year. It is observed that the PV system produces more energy than the building consumes in all months except in July, August, and September.

Figure 5 depicts the monthly-averaged level of the storage system during the entire year, in kWh, and in kmol of hydrogen. The minimum level of storage occurs in the middle of October, when the demand for air-conditioning decreases significantly for the PV panel to produce more electric power than the system needs. The maximum energy storage level of 7,213 kWh, which is equivalent to 109.5 kmol (7.0 m^3) of hydrogen, occurs in June, when the demand for air-conditioning increases significantly and the electric power system draws the energy that was stored in the winter and spring. The diurnal variations of insolation cause similar fluctuations of the energy stored in the system, which do not show in the Figure.

The effect of the efficiency of the PV system on the needed area and nominal power of the panels is shown in Figure 6 with η_{sc} being the parameter in the range 14% to 26% and all the other parameters as in the base case. The necessary PV area and power for this type of GIB has been normalized by the area of the base case, 98.75 m^2, where the nominal power is 18.3 kW. It is observed that there is approximately 6% less PV area and nominal power needed for every 1% improvement of the PV efficiency.

The effect of the efficiencies of the electrolysis and the fuel cells is depicted in Figure 7. The efficiencies of these storage components vary in the ranges $50\%<\eta_{el}<80\%$ for electrolysis and $45\%<\eta_{fc}<80\%$ for the fuel cells. It is observed that the two trends are very similar, reflecting the fact that both components are used sequentially in the energy storage system. It is also observed that the effects of η_{el} and η_{fc} on the PV area needed are lesser than the effect of η_{sc}: for every 1% improvement of the efficiencies of these two components the needed PV area and nominal power drop by approximately 1%. This occurs because a) not all the energy produced passes through the storage system; and b) the numerical values of these two efficiencies are significantly higher than the numerical value of η_{sc}. A similar observation was made about the various component efficiencies in two buildings monitored by NREL [29].

It is apparent from these results that such large residential buildings, will have to install large areas of PV panels with high nominal power, even if the component efficiencies improve significantly. This requires capital investment. Another way for the owners of such buildings to make the transition to renewable energy sources is to reduce the air-conditioning energy needs of the buildings by investing in energy conservation and efficiency measures. For the building examined in this case such measures may be achieved by a combination of the following:

1. The replacement of the air-conditioning units with more efficient units, either conventional or GSHP.
2. The better insulation of the building, primarily through improved fenestration.
3. The increase of the interior temperature during the summer months.
4. Conversion of all or part of the lighting to LEDs (all the lighting energy dissipates and must be removed by the air-conditioning).
5. For new buildings, the reduction of the total air-conditioned space.

The adoption of any set of these measures will reduce the peak power demand as well as the total annual energy consumption of the building. There is a relationship between these two quantities that is not necessarily linear. Because of lack of more accurate data on the effect of the higher efficiency measures, the assumption is made for the calculations that the electricity demand reduction in the building is uniform throughout the year.

It was determined that the application of a number of these measures – especially the installation of a GSHP – would reduce the demand associated with the air-conditioning of the building by as much as 60%. Figure 8 shows the PV panel area savings that may be achieved by conservation and higher efficiency measures in the HVAC system. It is observed that for every 10% decrease of this part of the electricity demand, there is 6% reduction of the PV panel area and nominal power. This is important for the owners of the buildings, because energy conservation measures are less capital intensive than higher efficiencies for the PV panels and the energy storage system processes. With higher HVAC efficiency and conservation measures that would reduce the power consumption by 60% – a feasible target with such older buildings in the region – the needed PV panel area is 64.2 m^2 and the nominal power 11.9 kW.

It must be noted that, because the components of the energy generation and storage systems operate independently, the demand reduction and efficiency improvement methods are independent of each other and their effects on the total area needed are cumulative. For example, if the owners of this building reduce the electric energy demand to 40% of its current level (PV area and power at 65.7% of the base case) and, in addition, install PV cells with 20% efficiency (PV area at 90% of the basis) and fuel cells with 80% efficiency (PV area at 89% of the basis) then the cumulative effect of the improvements will be 0.657*0.90*0.89 or 52.6% of the basis area and power (52 m^2 total area, corresponding to 9.6 kW nominal power).

B. The building in Fort Worth with heat included

We now consider the case when the building is converted to ZEB as well as GIB. Currently the building uses natural gas for hot water and space heating during the colder months, both low temperature heat needs with the maximum heating demand during the winter months, when air-conditioning is unnecessary. Two options were considered for the supply of this heat: solar thermal collectors and a heat pump system. The experience with solar collector systems in the region has proved that they are not capable to supply the entire needed heat during the colder winter nights and must be supplemented by a heat pump system or a gas burner. For this reason, it was decided that the HVAC system, which supplies air-conditioning during the hotter season, will also be used as a heat pump during the colder season from November to March. Based on the performance of similar systems in the area, the COP in the heat pump mode was chosen to be 4.5 (SEER 15.4). The heating needs of the building during the hotter season (April to October) are primarily for hot water and this may be easily satisfied by using the waste heat rejected by the condenser of the HVAC system or the excess heat dissipated by the PV panels. Supplying the heat by such systems does not increase the peak electricity demand of the building in the April to October season, but adds to the electric power during the colder season when the HVAC system operates in the heating mode.

Figure 9 shows the new monthly electricity demand for the building, which includes the energy needed for the operation of the heat pump and the monthly electricity supply from the PV system. The Figure also shows the maximum energy storage level for the month (in units of kWh for consistency) needed during the winter months. The total PV panel area needed to transform the GIB to a ZEB is 122.7 m^2 and the nominal PV power is 22.8 kW, 24% higher than in the base case. The addition of 24% power would be sufficient to make such large residential buildings totally energy independent.

Figure 10, shows the monthly-averaged storage level (in kWh and kmol) for the storage system that produces heat as well as electric power for the building. The maximum storage level for the system now is slightly lower, 106 kmol instead of 109.5 kmol. The minimum level of hydrogen storage occurs at the end of January instead of the middle of October. The maximum level of storage still occurs in June. At the maximum pressure of the system, the required volume of the storage tank is approximately 6.78 m^3 [28].

The effects of improving the efficiencies of the PV system, the electrolysis and the fuels cells are comparable to the effects of the previous case that are reported in Figures 6 and 7. The effect of reducing the consumed energy by improving the efficiency and operation of the HVAC system are higher. Because this system supplies both the electricity and heat, for every 10% reduction of the energy associated with the HVAC system there is a 7.8% reduction of the PV panel area and of the nominal power of the PV system. The installation of a more efficient GSHP alone with 21 SEER would result in PV area of 84.4 m^2 (from 122.7 m^2) and nominal PV power becomes 15.7 kW (from 22.8 kW). Other energy conservation and higher efficiency measures (e.g. attic insulation, LED lighting, improved fenestration and optimization of the entire supply-demand schedule [12, 8]) will bring the required power to lower levels, close to 7 kW.

As it is apparent in Figures 5 and 10, most of the seasonally stored energy is stored during the winter and spring months to be used in the summer. An alternative is a smaller storage system that provides only the nocturnal energy demand every day of the year. This system would store during the day only the energy needed for the night. Calculations for such a system prove that, because the seasonal storage of energy is lost, such as system with a diurnal cycle would need 22% higher PV panel area and nominal power. Because all the other components are necessary for both the diurnal and the annual storage systems, constructing a larger hydrogen storage tank would be significantly less expensive than the additional cost of the PV cell power. In addition, the diurnal cycle system would not be as reliable as the annual cycle system because it is very much vulnerable to weather phenomena.

C. The building in Duluth

Because of the low ambient temperatures in the summer months, this building does not need to be air-conditioned. However, the heating demand of the building is very high and the heating season extends to most of the year. The electricity demand of the building includes the demand for lighting and the operation of standard housing appliances. During the heating season, the GSHP system with the auxiliary equipment for the circulation of warm air (fans and blowers), consume most of the electric power and provide all the heating requirements of the building.

Figure 11 shows the daily electricity demand of the building and the supply for this GIB-ZEB during two typical days in January, one that is sunny and the second when intermittent clouds and rain affect the energy produced by the solar system. It is observed in the Figure that the average hourly electricity demand in the building is almost constant, between 4.9 and 5.8 kW, reflecting the fact that most of the electric power is used by the heat pump and the air circulation systems, which account for approximately 4.5 kW. The time period of energy supply is short, with most of the power produced between 9:00 am and 4:00 pm on both days. The very large difference of power produced during the sunny and the cloudy/rainy day is also apparent in the Figure. It is because of the prevalence of cloudy/rainy days during the colder season that a high amount of energy needs to be stored in this climate.

With the efficiency values stipulated for the base case of the Fort Worth building, the building in the northern climate needs approximately 161 m^2 with nominal power rating 29.1 kW – a very high nominal power by any means. Figure 12 depicts the monthly energy consumption and energy supply for the building as well as the maximum energy storage level for the month. It is observed in this Figure that the energy supply is higher than the consumption during eight of the months of the year. The total energy produced during the year is 53,900 kWh while the energy actually used is 31,500 kWh. The difference is due to the irreversibilities for the storage and supply of stored energy, which are modeled by the efficiencies of the electrolysis and fuel cell systems (70% and 65% for a round-trip efficiency of 45.5%).

Energy is stored during the spring and summer months to be used in the winter months. Figure 13 depicts the hourly storage level for the entire year that calculations were made. The maximum storage level for the hydrogen gas is 222 kmol. At the maximum storage pressure of 500 bar the hydrogen storage tank has 14.2 m^3 capacity. It is also observed in Figures 12 and 13 that the minimum storage level occurs in March, when the temperatures start rising and the heating demand of the building is reduced.

With the numbers for the efficiency of the several components, the panel area and the nominal power level of the PV system are rather high for this residential building to become a GIB. The higher investment for the PV system and hydrogen storage system are reduced considerably if conservation and energy efficiency measures are undertaken that would reduce the energy consumption of the building. Figure 14 depicts the reduction of the panel area and nominal power of the PV system that is required to convert this building to a GIB-ZEB. The most effective of these measures are:

- Deployment of a more efficient heat pump system with higher COP.
- Reduced fenestration area.
- Additional attic insulation.

It is observed that energy conservation measures will reduce significantly the PV panel area and nominal power, as well as the needed capacity of the energy storage system. In particular, and because of the high area of the windows in the building, improved fenestration and a heavy layer of attic insulation will cut the heat losses of the building by as much as 50%. This will also reduce the fan requirements for the recirculation of warm air in the building. The addition of a more efficient heat pump system and the optimization of supply and consumption of energy (e.g. by matching the periods of consumption to coincide with periods of supply during a day and reducing the quantity of energy stored) will enable the owners to reduce the annual electricity consumption to 70% of the level that Figures 11, 12 and 13 are based. When such level of energy reduction is achieved, the building only needs 61 m^2 of PV panel area with a nominal power 10.7 kW and a hydrogen storage system with 4.5 m^3 capacity to become a GIB-ZEB.

Table B summarizes the principal results of this study for the power rating and the storage system features of the three cases examined. It is observed that the areas for the PV panels and the power rating of the PV systems are very high. Energy conservation and higher efficiency measures reduce the area and power requirements in both locations, but still the area and nominal power requirements are significant. The building in the Duluth area needs approximately 50% higher PV nominal power and area, primarily because the irradiance/insolation in that region is much lower than that in Fort Worth. The conversion of the building in Fort Worth to a complete ZEB (and the avoidance of natural gas combustion for heating) may be achieved with 24% additional PV power. The energy storage requirements in Duluth are almost twice as much as that in the Fort Worth area, primarily because of the very large amount of energy that must be available during the winter days when insolation is very low. As expected, and because the peak energy demand in Fort Worth occurs in the summer, and in Duluth in the winter, the energy storage seasons in the two locations are reversed.

A significant observation from the data of Table B is the very large area required by the PV panels in both buildings. The volume of the hydrogen storage tanks is rather modest (cylindrical tanks of 1-1.5 m radii and 1-2 m heights that will fit unobtrusively in a yard). The two buildings considered in this study have sufficient roof area to accommodate the PV panels. Also, the current footprints of the two buildings and their yards are large enough to accommodate the GSHP systems as well as the hydrogen storage tanks. However, typical buildings in high density urban environments do not have that much roof area for the solar panels. Their roofs and yard areas are smaller and partly shaded by trees or by the buildings themselves. PV panels on the roofs of urban buildings would provide only a fraction of the needed energy and the remainder will need to be supplied by another source. In such cases it may be possible to convert a local park (or any other free and open space) to a "PV park" where the panels supply the extra energy or hydrogen needed by an entire district of GIBs. Alternatively, and given that hydrogen may be readily transported, the additional hydrogen that is needed by the buildings may be produced at another (more optimal) location and transported to supply the remaining part of the building energy demand.

Conclusions

The inevitable depletion of fossil fuels and widespread concerns about global and regional environmental change makes necessary the higher use of alternative energy sources and the adoption of energy conservation measures. Solar and wind power, the most abundant renewable energy sources are not available when energy is demanded and this necessitates the storage of a fraction of the energy produced. Residential buildings in the south part of the USA demand high quantities of power for air-conditioning during the summer and similar buildings in the north have very large heating loads during the winter. The conversion of buildings to ZEBs using solar energy substitutes a fraction of the power needed from the electricity grid. If practiced on a large scale the conversion to grid-dependent ZEBs has the effect of transforming the regional power demand curves to U-shaped, which reduces the grid flexibility and limits the role of large, base-load power plants, including nuclear power plants that do not emit CO_2. Converting the buildings to GIBs, reduces the annual energy consumption and the peak power demand, without impacting significantly the operation of large, base-load power plants.

The conversion of two large residential buildings, one in Fort Worth, TX, and the second in Duluth, MN, to ZEBs was studied. With the current state of technology and without added energy conservation measures, a large residential building in the Dallas/Fort Worth area needs approximately 100 m^2 of PV cell area with nominal power 18.3 kW and a hydrogen storage tank of 7.0 m^3 to perennially produce and store the electric power it currently consumes. The area and power requirements are increased by 24% if a heat pump is used to supply the winter heating load of the building. The conversion of the building in Duluth to ZEB-GIB with hydrogen storage and a heat pump for the generation of heat necessitates a PV system of 161 m^2 and 29.3 kW nominal power with a hydrogen storage tank of 14.2 m^3 capacity. The PV cell area and nominal power, and the hydrogen storage requirements for the conversion of the buildings to GIBs are very high. The requirements significantly drop with the adoption of energy conservation measures, supply-demand optimization, and higher PV cell efficiency. The increase of the efficiency of the electrolysis process that produces hydrogen gas for energy storage and higher fuel cell efficiency also reduces the power and storage volume requirements, but at a lesser rate. Energy conservation and higher efficiency measures have the greatest impact on the PV area and nominal power requirements. Other things being equal, it is advantageous to invest in energy conservation projects, especially GSHPs with very high COPs.

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Tables

Table A. Advantages and disadvantages of GIB conversion.

Advantages	Disadvantages
Owner has control of all energy consumed.	High capital expense for the owner.
Grid has the flexibility to make high use of base-load power plants.	Grid is not there for back-up if something goes wrong.
Zero variable cost for the energy consumed.	Storage system must be well-maintained.
Any renewable source may contribute to the mix.	Grid services become more expensive for those left in the grid.
Very low environmental impact.	Round-trip efficiency less than 1.

Table B Power rating and the storage system features of the three cases examined (for the PV cells η_{25}=18%; for the electrolysis η_{el}=70%; and for the fuel cell(s) η_{fc}=65%).

	FW GIB, Gas Heated	FW GIB-ZEB	Duluth ZEB
PV power rating	18.3 kW	22.8 kW	29.1 kW
PV area	98.75 m^2	122.7 m^2	161.0 m^2
PV power rating and area with 30% energy savings	15.1 kW 81.3 m^2	18.5 kW 99.6 m^2	21.4 kW 118.4 m^2
PV power rating and area with 50% energy savings	13.1 kW 70.5 m^2	15.7 kW 84.5 m^2	16.2 kW 89.6 m^2
Max. Storage Capacity at 500 bar	7.00 m^3	6.78 m^3	14.2 m^3
Maximum Storage in	Early June	Early June	Mid October
Minimum Storage in	Mid October	Mid October	Late March

Figures

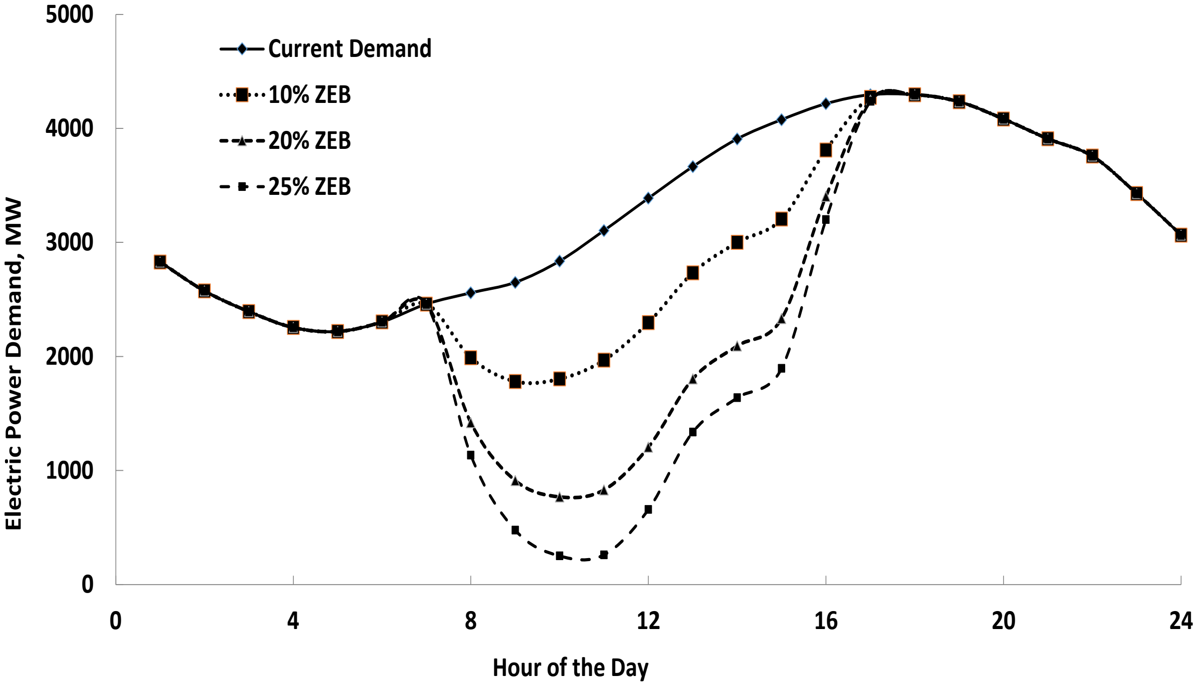

Figure 1. Summertime electric power demand in San Antonio, TX, and future demand with 10%, 20% and 25% ZEBs.

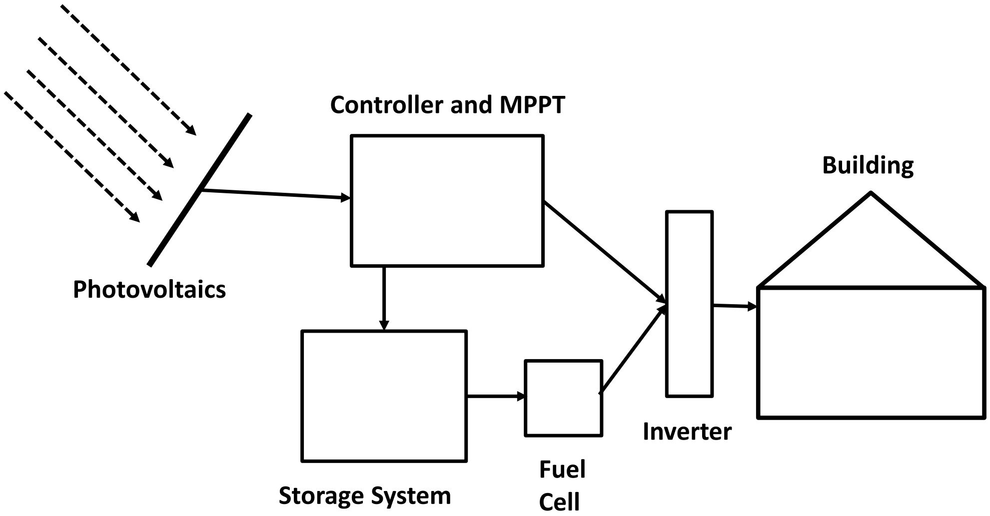

Figure 2. Schematic diagram of a solar system with energy storage.

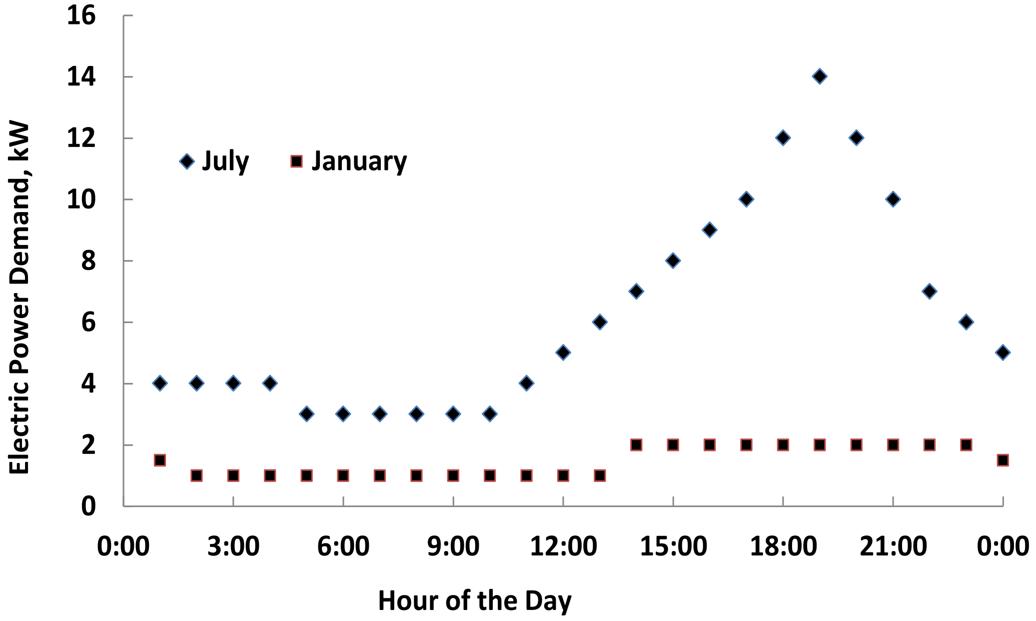

Figure 3. Hourly electric power demand trends of the Fort Worth building for two days in the winter and the summer.

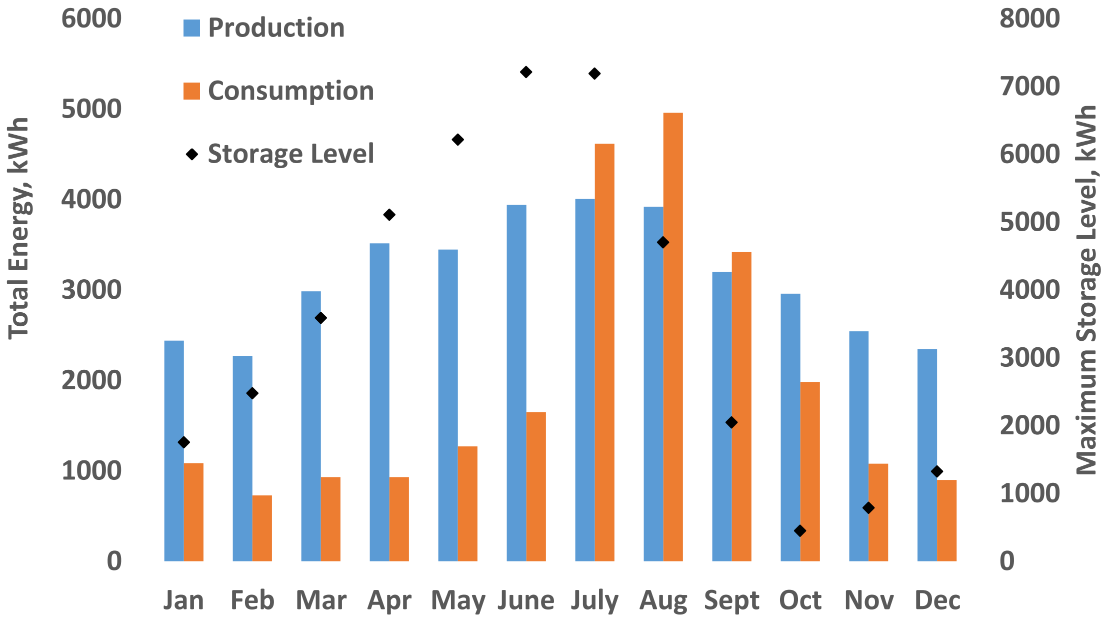

Figure 4. The monthly energy production, consumption, and maximum storage level during the month in kWh, based on the current electricity consumption.

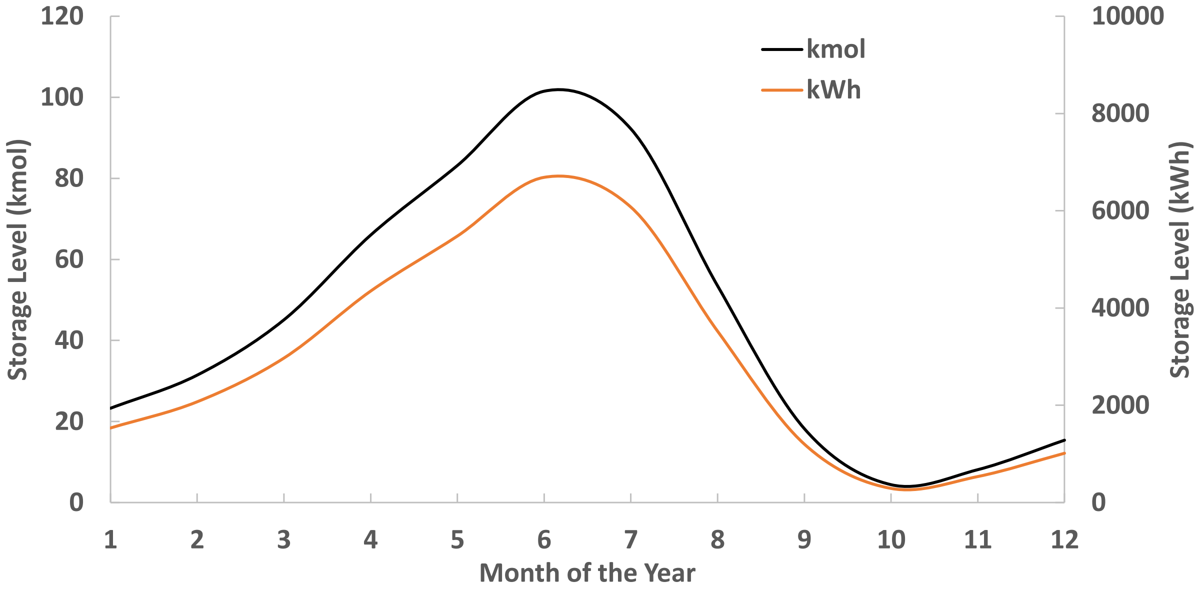

Figure 5. The storage level for the system in kmol of H_2 and kWh, based on the current electricity consumption.

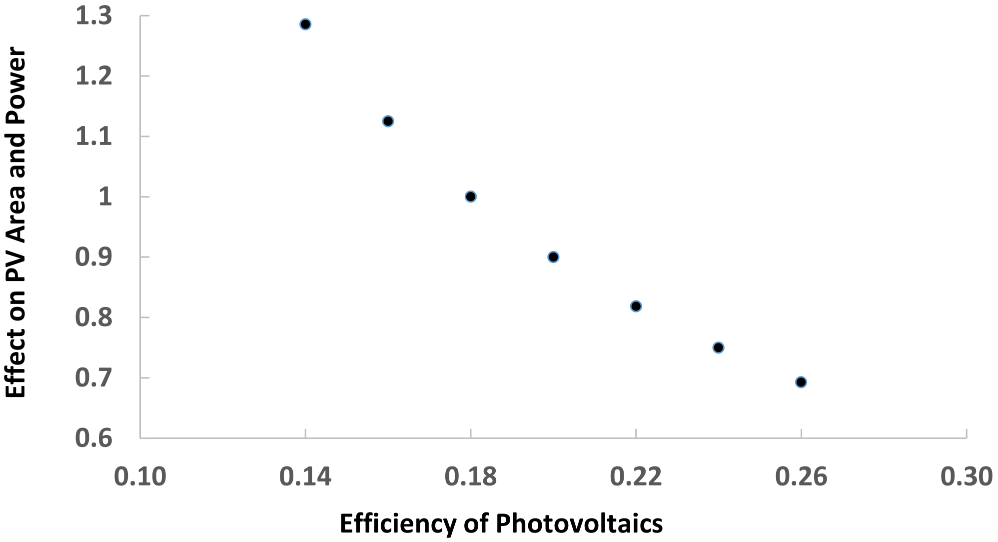

Figure 6. The effect of the PV panel system efficiency. The area for the base case is 98.75 m^2 and the nominal power of the PV system is 18.3 kW.

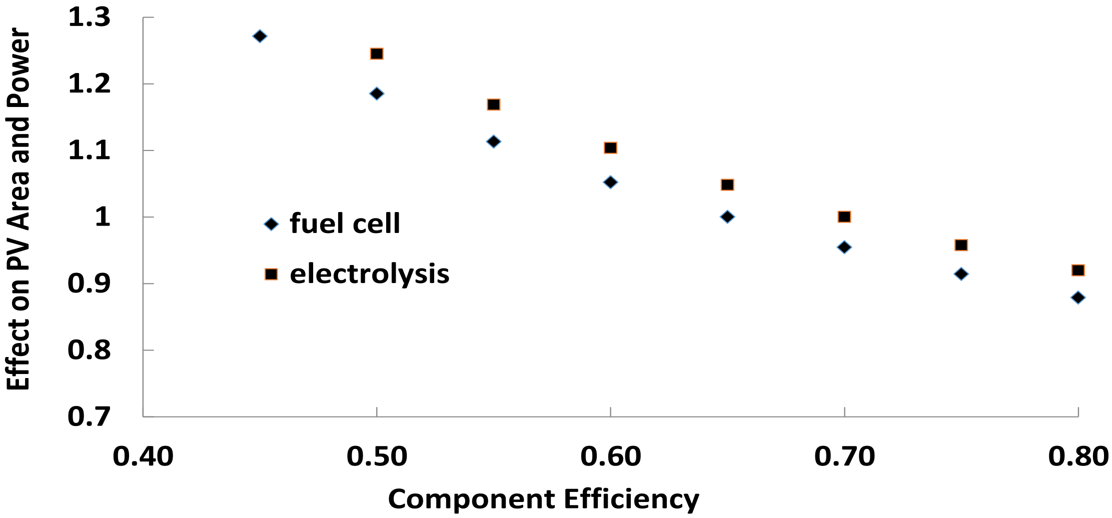

Figure 7. The effect of the electrolysis and fuel cell efficiencies. The area for the base case is 98.75 m^2 and the nominal power of the PV system is 18.3 kW.

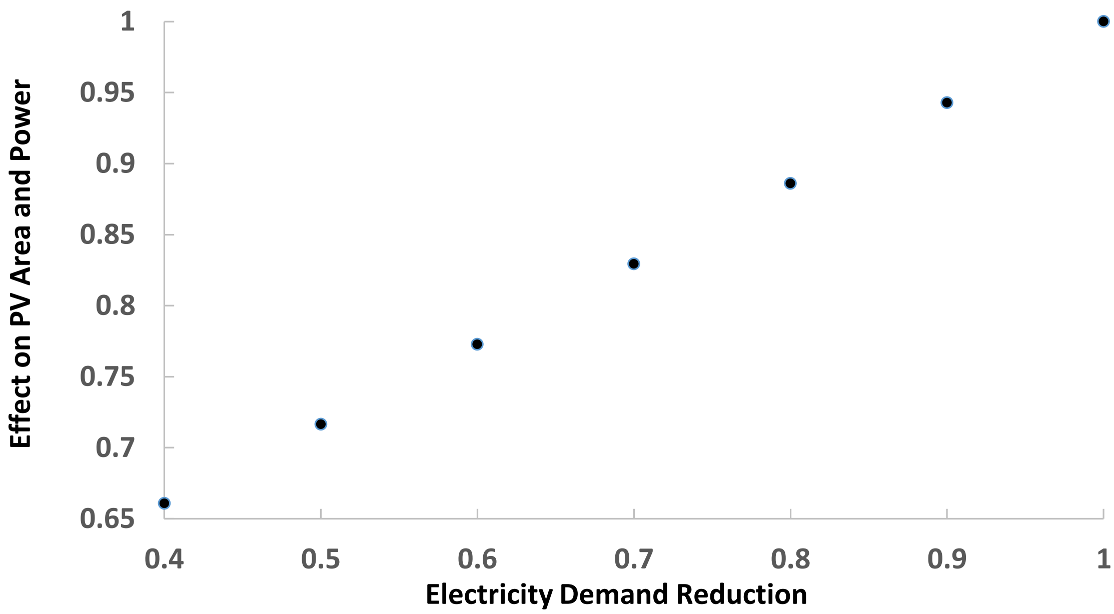

Figure 8. Effect of energy efficiency and conservation measures for the building. The area for the base case is 98.75 m^2 and the nominal power of the PV system is 18.3 kW.

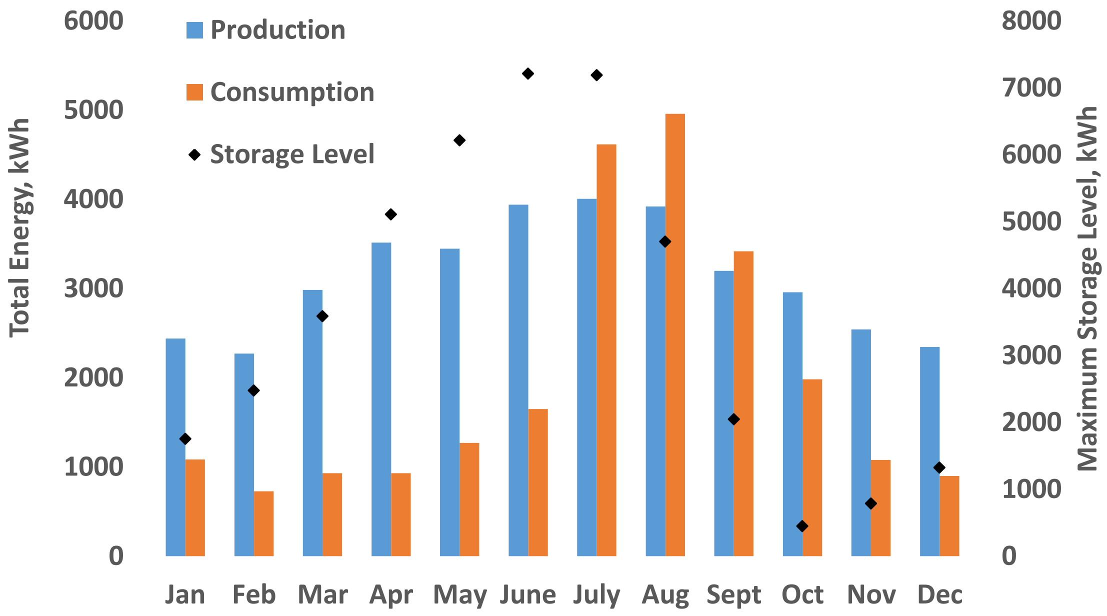

Figure 9. The monthly production, consumption, and storage level of the ZEB-GIB in Fort Worth.

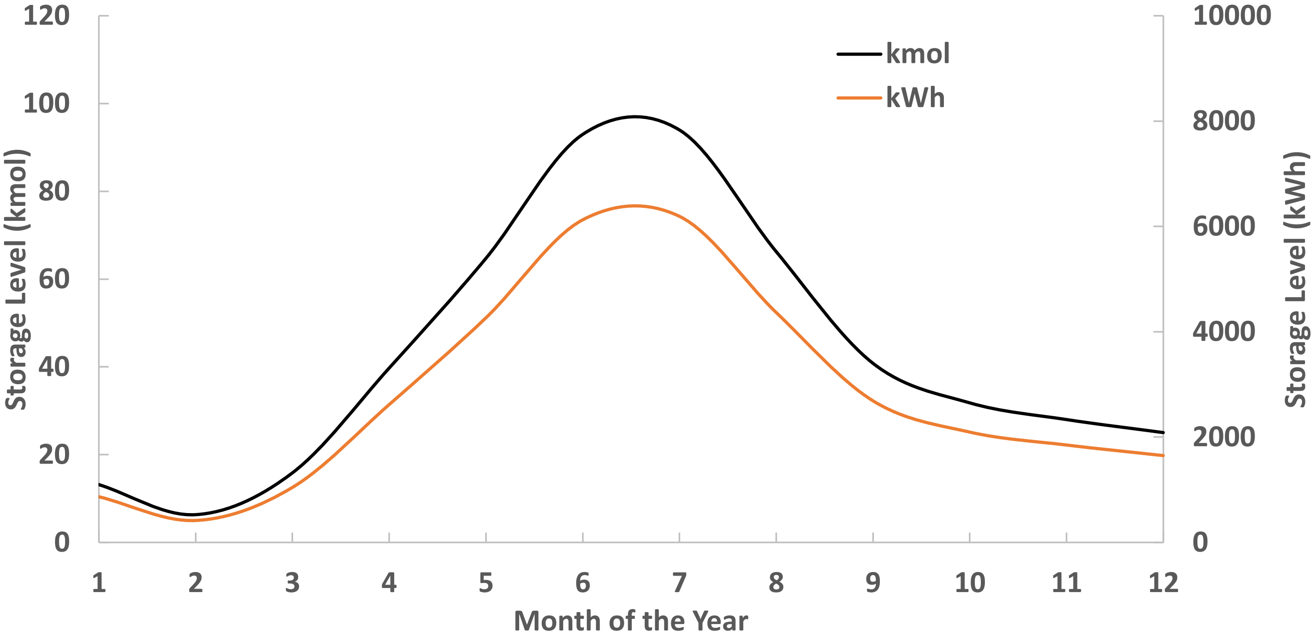

Figure 10. The storage level for the ZEB-GIB system in Fort Worth in kmol of H_2 and kWh.

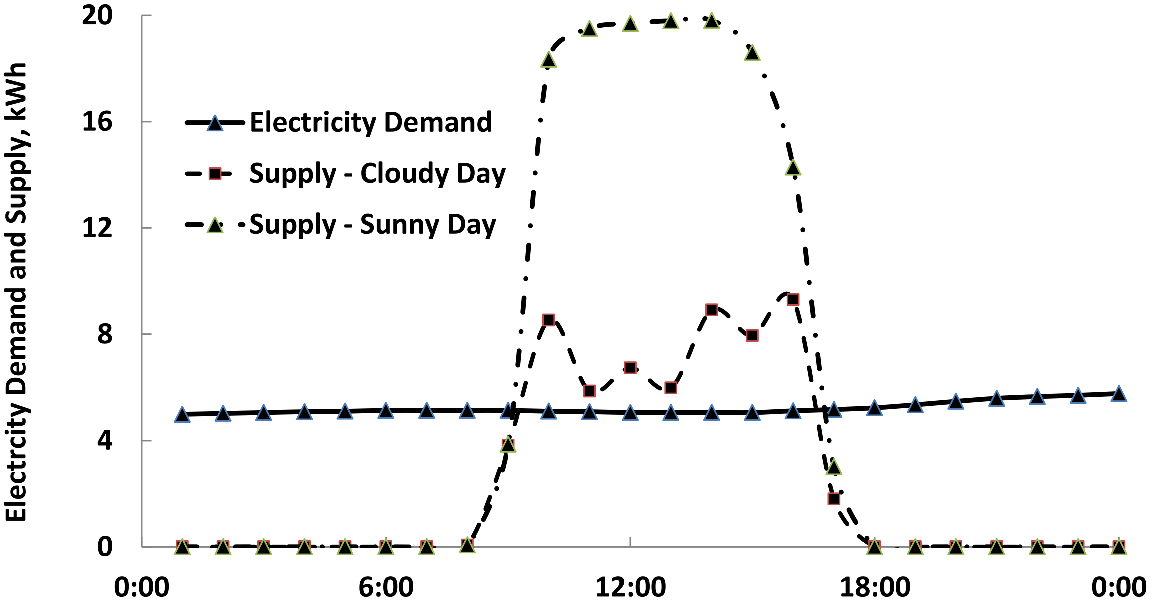

Figure 11. Electric energy demand and supply on two January days for the building in Duluth, MN.

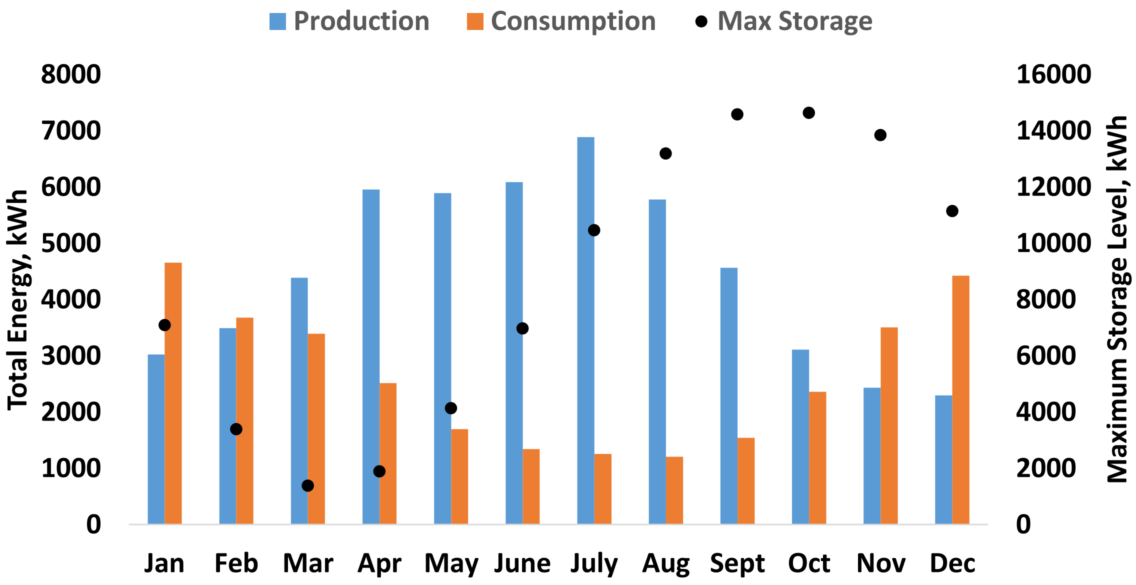

Figure 12. The monthly energy consumption and supply for the Duluth GIB-ZEB as well as the maximum energy storage during the month.

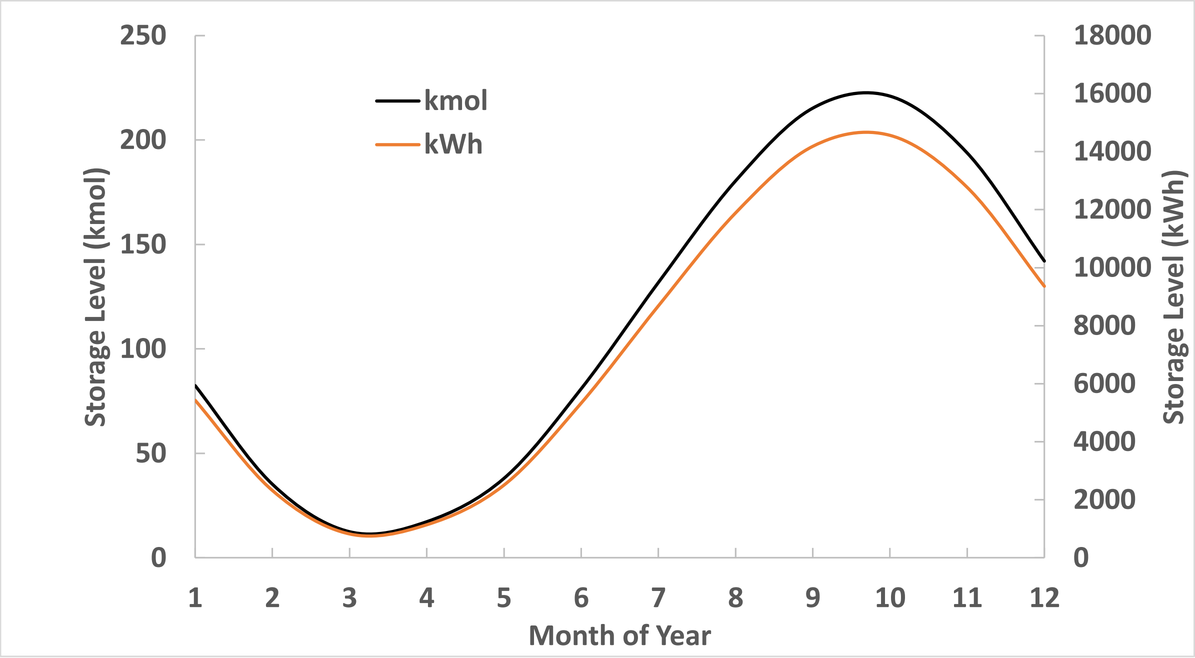

Figure 13. Monthly level of the hydrogen storage system.

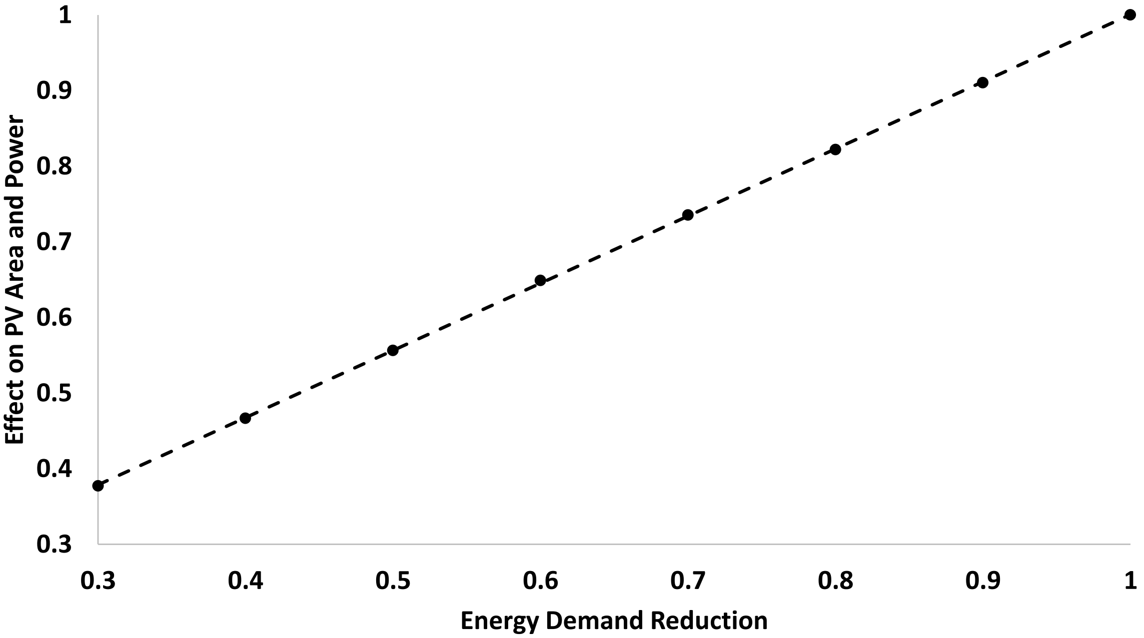

Figure 14. Effect of energy efficiency and conservation measures for the building. The area for the base case is 161 and the nominal power of the PV system is 29.1 kW.