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Performance Analysis of a Zero-Energy Building Using Photovoltaics and Hydrogen Storage

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Abstract: The exploitation of renewable energy sources in the building sector is a challenging aspect of achieving sustainability. The incorporation of a proper storage unit is a vital issue for managing properly renewable electricity production and so to avoid the use of grid electricity. The present investigation examines a zero-energy residential building that uses photovoltaics for covering all its energy needs (heating, cooling, domestic hot water, and appliances-lighting needs). The building uses a reversible heat pump and an electrical heater, so there is not any need for fuel. The novel aspect of the present analysis lies in the utilization of hydrogen as the storage technology in a power-to-hydrogen-to-power design. The residual electricity production from the photovoltaics feeds an electrolyzer for hydrogen production which is stored in the proper tank under high pressure. When there is a need for electricity, and the photovoltaics are not enough, the hydrogen is used in a fuel cell for producing the needed electricity. The present work examines a building of 400 m^2 floor area in Athens with total yearly electrical demand of 23,656 kWh. It was found that the use of 203 m^2 of photovoltaics with a hydrogen storage capacity of 34 m^3 can make the building autonomous for the year period.

Keywords: hydrogen storage; building electrical needs; Power-to-X-to-Power; dynamic analysis; zero-energy building

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1. Introduction

The storage of volatile electricity is a critical issue for achieving sustainability, by extending the exploitation of renewable energies. A lot of research is conducted in this direction because the existence of a significant capacity can increase the stability of the grid [1]. Besides the concept of batteries and hydropower storage, hydrogen is a critical weapon for facing the challenge of energy storage and the hydrogen economy is the challenge of the next years [2]. Moreover, the "Power-to-X" concept, which is usually based on the "Carnot Battery" [3], is an alternative choice to the existing storage technologies with significant economic [4] and environmental benefits [5]. In the case that the "X" in the previous equation is the "hydrogen", then the "Power-to-Hydrogen" concept can be developed, aiming for sustainability with the possibility of long-term storage [6]. The thermal storage in thermal pumping storage units [7], practically Carnot batteries configurations, presents drawbacks such as thermal losses, restricted storage time, and exergy losses during the storage, a problem that does not exist with hydrogen, which can be stored for long-term periods with a high storage volume. Moreover, it is useful to state that the "Power-to-X" concept will reach the capacity of 500 MW in countries such as France and Germany by 2025, so it is characterized as a technology of the future [8].

The hydrogen can be produced by water electrolysis and this is a usual strategy in the Power-to-X configurations [9]. It has been found that the efficiency of the electrolysis conversion and the electrolysis capital cost plays a significant role in the sustainability of these systems [10]. Practically, the production of hydrogen from renewables makes it a green fuel that can be reused in fuel cells for recovering electricity [11]. In addition, there is the possibility to produce any other useful output such as feedstock or fuel in various industries (e.g., steel, food, and chemicals) [12]. So, it is clearly highlighted that hydrogen production gives great flexibility in its further utilization; something that makes it a promising future solution for achieving sustainability. In addition, hydrogen is an important weapon for facing challenges in the domain of transportation [13].

The literature includes different studies which are based on hydrogen production from renewable and alternative energy sources for storage and possible re-utilization. A critical domain in which hydrogen can be an important solution is the building sector, especially nearly zero or zero-energy buildings, as well as buildings that are not connected to the grid. Hydrogen can be also used as a storage solution with high storage density, and it can be produced from the grid or renewable electricity through electrolysis, as a usual choice. So, this domain regards the recent literature trends that are examined by various researchers. Sun et al. [14] examined an off-grid building in the climate conditions of Iran and they emphasized hydrogen storage with a battery. Their work indicated that around 75 m^2 of photovoltaics (PV) can provide the needed electricity for a building of 150 m^2 area. Moreover, they examined the thermal comfort conditions inside the building. Temiz and Dincer [15] investigated the use of PV, building-integrated PV and geothermal energy for a 20-floor building in Canada which also includes hydrogen storage. The studied configuration can cover all the energy needs of the building with an overall energy efficiency of 19% and an overall exergetic efficiency of 11%. Hai et al. [16] studied the use of PV, solar thermal collectors, and geothermal energy in a building for covering all its needs. The studied location was Kuwait and the goal was to achieve a zero-energy building. They found a 33% reduction in CO_2 emissions compared to the design with fossil fuels. The idea of power to hydrogen storage in buildings has also been studied by Guo et al. [17]. The investigated unit included photovoltaics, battery, electrolyzer, hydrogen storage, fuel cell, hot water tank, absorption chiller, and evacuated tube solar thermal collectors. They gave emphasis to the satisfaction of the building's energy needs and an interesting result is that the fuel cell can provide 90% of the hot water demand.

The concept of flexible buildings with photovoltaics and buildings has been studied by Zhou and Zhou [18]. They examined a configuration that includes also charging electric vehicles and the examined location was in China. They found that hydrogen storage can enhance off-peak renewable energy shifting. Another work by Zhang et al. [19] investigated the use of biomass and grid electricity for feeding a polygeneration system for the building sector that includes hydrogen storage. They found 12% primary energy reduction and 87% CO_2 emissions reduction with the followed strategy. The combination of wind energy and solar thermal energy in a multi-generation system has been examined by Nikitin et al. [20]. They used hydrogen and water storage in their configuration, while there are several other devices such as electolyzer, absorption chiller, and reverse osmosis unit. They found that the payback period for this system ranges from 8 to 21 years depending on the examined location. In addition, the use of hydrogen as the storage technology in polygeneration systems for the building sector has been studied by other researchers in the literature [21]. More specifically, in this work [21], there are parabolic trough solar concentrating collectors in combination with an internal combustion engine for producing hydrogen, power, fresh water, and hot water. They found that the system energy efficiency is around 23.9%, while the system exergy efficiency is at 28.2%.

The previous analysis clearly indicates a high interest in energy storage based on hydrogen production. Hydrogen as a storage solution is a promising solution for the building sector, except for the national grid. The present work comes to investigate an off-grid building of 400 m^2 floor area in Greece which uses photovoltaics and hydrogen storage for covering all its energy needs which are for heating, cooling, domestic hot water (DHW), and covering the appliances/lighting. Moreover, the system includes an electrolyzer for converting electricity into hydrogen, a storage tank for the hydrogen, and a fuel cell for converting the hydrogen into electricity when there is demand. The analysis is a dynamic one using results from simulation with TRNSYS software. The analysis is conducted on a yearly basis aiming to determine the PV area and the hydrogen storage capacity that is required for ensuring a safe operation during the year. The result can be used in the future for designing zero-energy buildings and the final conclusions can be used as guidelines in this direction.

2. Material and Methods

Data regarding the building description, the description of the energy system, the basic mathematical modeling, and the following methods are given in the present section.

2.1. Building Description

The present study investigates a building with a 400 m^2 floor area (20 m × 20 m) with a height of 3.1 m. The building is located in Athens, Greece (37.984°, 23.728°) and it is a residential one with six occupants. The present analysis is conducted with the TRNSYS tool [22] which is a dynamic simulation tool and the meteorological data were used from its libraries. The building includes a south wall, a west wall, a north wall, and an east wall. The south wall includes a window of 12 m^2, the east wall includes a window of 6 m^2, and the west wall has a window of 6 m^2, while the north wall has no windows. The windows are placed in the center of the respective walls, and they have a square shape.

The ground slab exchanges heat with the ground, and the external walls and the roof with the external air. More specifically, the roof is a flat one without inclination. The composition of the structural materials and the thermal properties of the respective materials have been taken from Ref. [23]. It is useful to state that the U-values of the ground, roofs external walls, and windows were selected to be 0.304 W/m^{2}K, 0.318 W/m^{2}K, 0.365 W/m^{2}K, and 1.4 W/m^{2}K. The windows have a g-value of 0.59, while the building has no shadings. The aforementioned values for the U-values are acceptable values according to the Greek legislation for Zone B [24].

The thermal comfort limit of the temperature was set at 20 °C for the winter and 26 °C for the summer period. The total infiltration rate and natural ventilation rate were set at 0.8 air changes per hour which is a reasonable value according to Greek legislation [24]. The specific gain for the appliances and the lighting were selected totally at 9 W/m^2 [24] and the daily variation in this load is depicted in Figure 1; which is a typical one according to the literature [25]. The specific thermal load of the occupants was chosen at 100 W per person (ISO-7730 [26]). Table 1 includes the basic data of the studied building.

Table 1. Basic data for the building description.

Parameter	Value
Temperature comfort limit in winter	20 °C
Temperature comfort limit in summer	26 °C
Building's net floor area	400 m^2
Side width (South, West, North, East)	20 m
Height	3.1 m
Area of the south window	12 m^2
Area of the west window	6 m^2
Area of the east window	6 m^2
Infiltration and natural ventilation	0.8 air change per hour
Appliances and lighting specific load	9 W/m^2
Residents	6 occupants in the rest
Specific thermal load per person	100 W/person (ISO 7730)
Ground U-value	0.304 W/m^{2}K
Roof U-value	0.318 W/m^{2}K

Table 1. *Cont.*

Parameter	Value
Wall U-value	0.365 W/m^{2}K
Window U-value	1.4 W/m^{2}K
Windows g-value	0.59

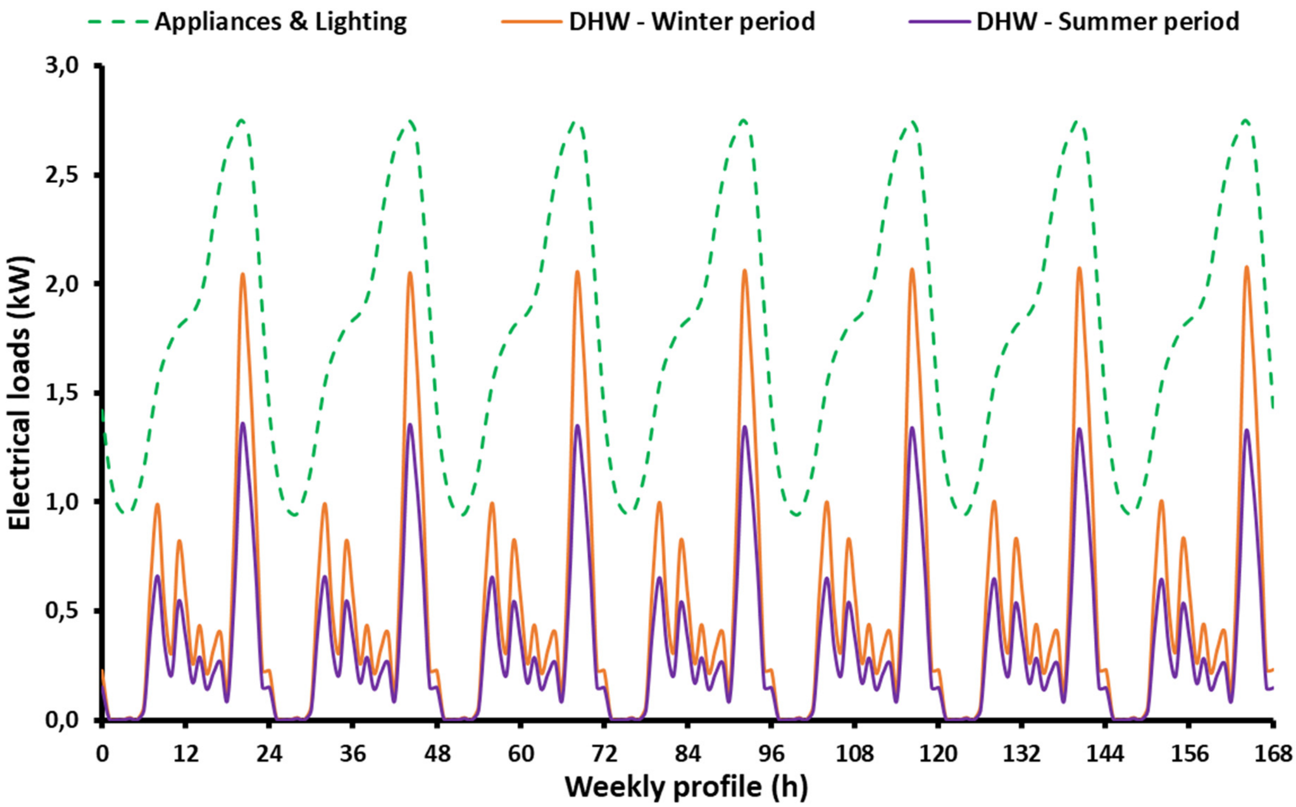

Figure 1. Description of the electrical profile demands for DHW, and appliances—lighting.

2.2. System Description

This study examines a renewable-driven system for the building sector that incorporates photovoltaics and hydrogen storage. This system covers all the needs of the building and it can lead to a zero-energy building (see Figure 2). The building uses a reversible heat pump for covering the heating and cooling loads, while the DHW needs are covered with an electrical heater. The heat pump was selected to have a relatively satisfying performance for examining a well-designed building. So, the seasonal coefficient of performance (SCOP) was selected at 4 and the seasonal energy efficiency ratio (SEER) at 4. The electrical heater for the DHW was selected to have an efficiency of 95% [24]. The DHW was provided at 45 °C [27], while the grid water temperature has been taken from Ref. [28]. It is useful to state that the average grid water temperature is close to 18 °C and every person needs 50 L per day hot water [24]. The daily variation demand profile of DHW has been taken from the literature [29] and the respective electrical demand is depicted in Figure 1. It is obvious that the electrical demand in the winter is higher in comparison to the summer period due to the lower grid water temperature in the winter.

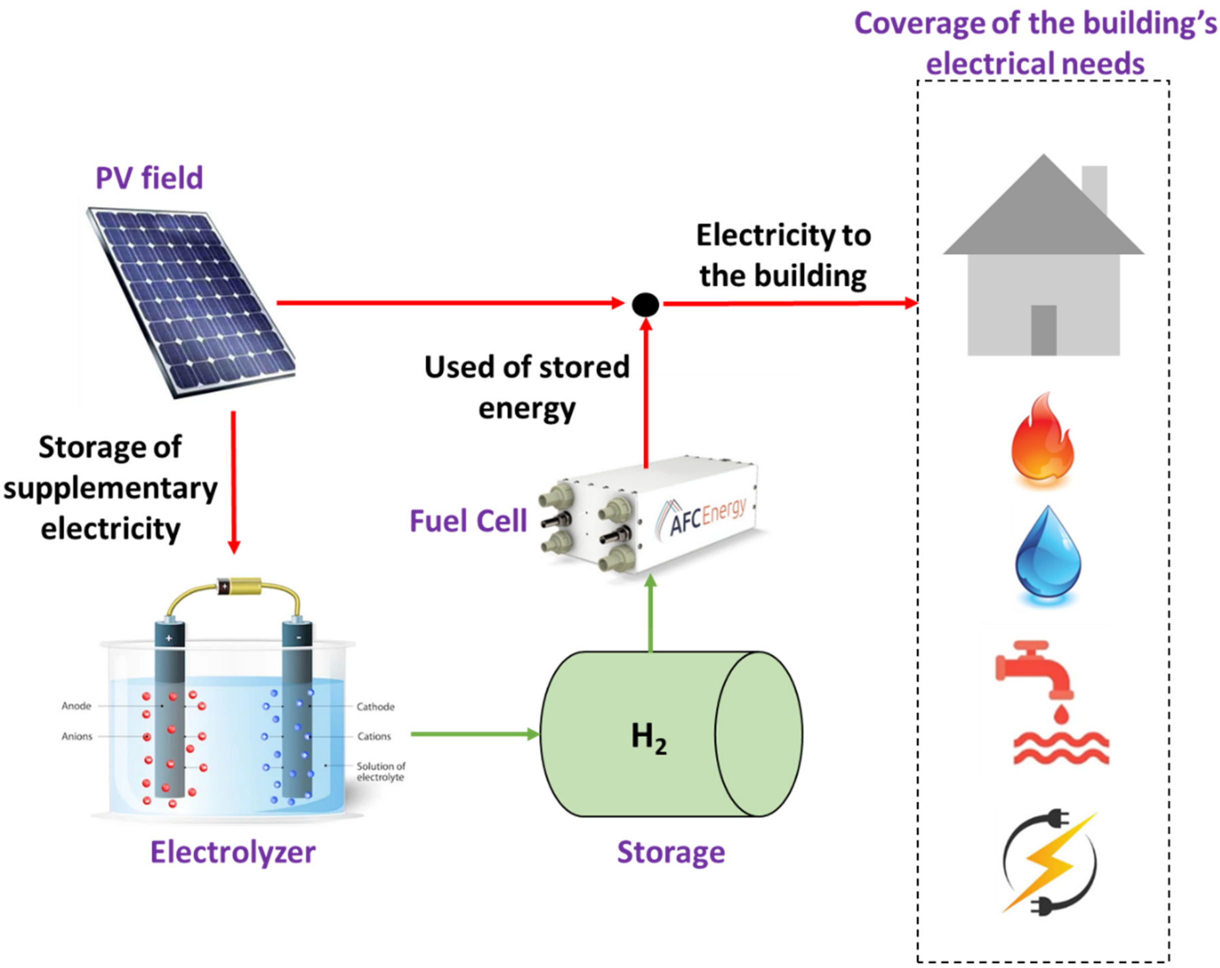

Figure 2. The suggested system for covering all the energy needs of the building.

The electrical needs of the system are covered by photovoltaic panels of high efficiency (X63 Premium PV) which has a nominal efficiency of 19.7% (X63L345 panel) [30]. The slope of the photovoltaics was selected at 30° which is an optimal choice according to the PVGIS tool [31]. In the present work, meteorological data were used by the libraries of the TRNSYS tool [22] and for the slope of 30° in the south direction, the yearly solar potential was found at 1739 kWh/m^2.

The electricity, which is not directly consumed by the building needs, feeds an electrolyzer for hydrogen production. More details regarding the electrolyzer can be found in Refs. [32–34]. More specifically, the electrolyzer is a proton exchange membrane water with a mean conversion efficiency of 60% according to the aforementioned studies. More specifically, the electrolyzer operates at 1 bar, with water at 80 °C and a membrane with 100 µm thickness. The hydrogen is stored under high pressure of 100 bar where its density is around 7.7 kg/m^3, while its lower heating value (LHV) was selected at 120 MJ/kg [35]. When there is a demand for electricity and the photovoltaics cannot produce it, then the stored hydrogen feeds a fuel cell for electricity production. More specifically, the present system includes a proton exchange membrane fuel cell with a mean conversion efficiency of 40% [36]. Table 2 summarizes the main data of the present system.

Table 2. Basic data for the investigated system.

Parameter	Value
SCOP of the heat pump	4.0
SEER of the heat pump	4.0
DHW electrical heater efficiency	95%
DHW daily demand	50 L/person
DHW temperature	45 °C
Water mean grid temperature	18 °C
Electrolyzer mean conversion efficiency	60%
Fuel cell mean conversion efficiency	40%
Density of the stored hydrogen	7.7 kg/m^3
Hydrogen lower heating value	120 MJ/kg
Photovoltaic nominal electrical efficiency	19.7%
Temperature reduction coefficient	-0.004 K^{-1}
Tilt angle of the photovoltaic panels	30°
Azimuth angle of the photovoltaic panels	0°

2.3. Basic Mathematical Part

The electricity consumption of the heat pump in the heating mode ($P_{el,hp,heat}$) is calculated as:

$$P_{el,hp,heat} = \frac{Q_{heat}}{COP} \tag{1}$$

The electricity consumption of the heat pump in the cooling mode ($P_{el,hp,cool}$) is calculated as:

$$P_{el,hp,cool} = \frac{Q_{cool}}{EER} \tag{2}$$

The electricity consumption for the DHW production ($P_{el,DHW}$) is calculated as:

$$P_{el,DHW} = \frac{Q_{DHW}}{\eta_{el,DHW}} \tag{3}$$

The DHW thermal demand (Q_{DHW}) is calculated as:

$$Q_{DHW} = m_{DHW} \cdot c_p \cdot \left(T_{DHW} - T_{grid}\right) \tag{4}$$

The electricity demand for the appliances & lighting ($P_{el,a\text{-}l}$) is calculated utilizing the floor area of the building (A_{floor}), the specific load ($q_{a\text{-}l}$) and the operating fraction according to the time (fr):

$$P_{el,a-l} = A_{floor} \cdot q_{a-l} \cdot fr \tag{5}$$

The total electricity demand ($P_{el,tot}$) is calculated as below:

$$P_{el,tot} = P_{el,hp,heat} + P_{el,hp,cool} + P_{el,DHW} + P_{el,a-l} \tag{6}$$

The photovoltaic electrical efficiency can be calculated by the next equation [37]:

$$\eta_{el} = \eta_{el,ref} \cdot (1 - \beta \cdot (T_{cell} - T_{ref})) \tag{7}$$

where the reference temperature (T_{ref}) was selected at 25 °C in this work.

The cell temperature can be estimated by the next formula [38]:

$$T_{cell} = T_{am} + f \cdot G_T \tag{8}$$

In this work, the cell temperature parameter (f) was selected close to 0.04 m^{2}K/W according to the literature [37,38].

The electricity production of the photovoltaic field is calculated as:

$$P_{el,pv} = \eta_{el} \cdot A_{pv} \cdot G_T \tag{9}$$

When the produced electricity from the photovoltaic field is higher than the demand, the electricity quantity that feeds the electrolyzer is calculated as below:

$$P_{el,elect} = P_{el,pv} - P_{el,tot} > 0 \tag{10}$$

In this case (charging/storage mode), the produced hydrogen ($m_{H2,prod}$) is calculated as below:

$$m_{H2,prod} = \frac{\eta_{elect} \cdot P_{el,elect}}{LHV} \tag{11}$$

When the produced electricity from the PV is lower than the demand, the electricity quantity that has to be produced by the fuel cell is calculated as below:

$$P_{el,fc} = P_{el,tot} - P_{el,pv} > 0 \tag{12}$$

In this case (discharging mode), the hydrogen consumption ($m_{H2,cons}$) is calculated as below:

$$m_{H2,cons} = \frac{P_{el,fc}}{\eta_{fc} \cdot LHV} \tag{13}$$

2.4. Summary of the Followed Methodology

The present study investigates a stand-alone energy system that feeds the total electrical loads of a building. The studied building is placed in Athens, Greece and its thermal loads are calculated using the TRNSYS software [22]. The weather data of the present work have been extracted by the TRNSYS libraries which include weather data from Meteonorm. The typical meteorological year (TMY) is used for the location of Athens. Below, some critical results for the weather conditions of the studied location taken from TRNSYS libraries are given. Figure 3 shows the variation in the environment temperature in the studied location, while Figure 4 shows the solar irradiation on the tilted surface for the same location. Moreover, Figure 4 depicts the respective cumulative solar energy expressed in [kWh/m^2]. It is obvious that Athens has a high solar potential with 1739 kWh/m^2 on a yearly basis.

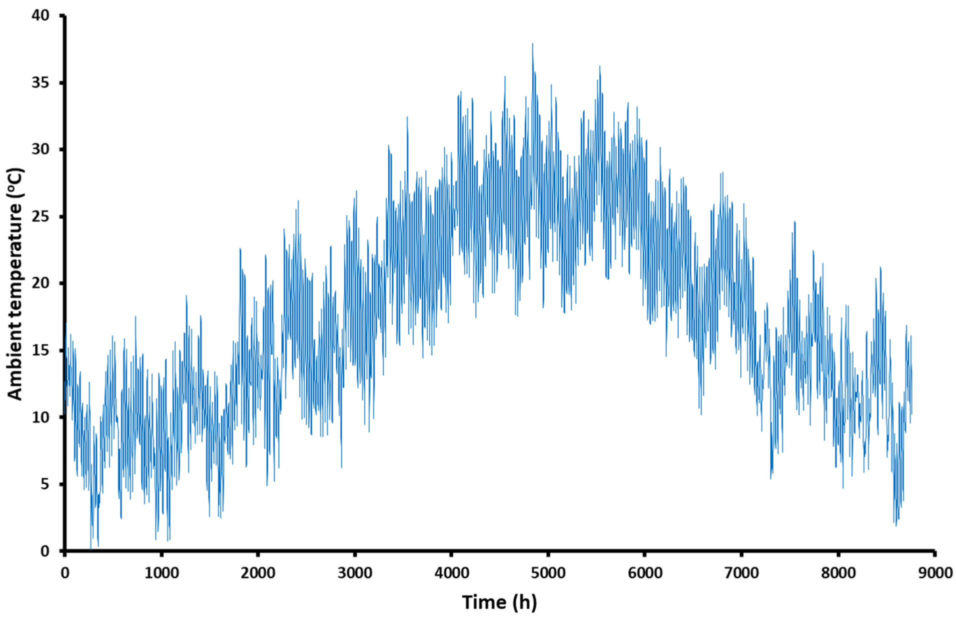

Figure 3. The environment temperature variation for the studied location (Athens, Greece).

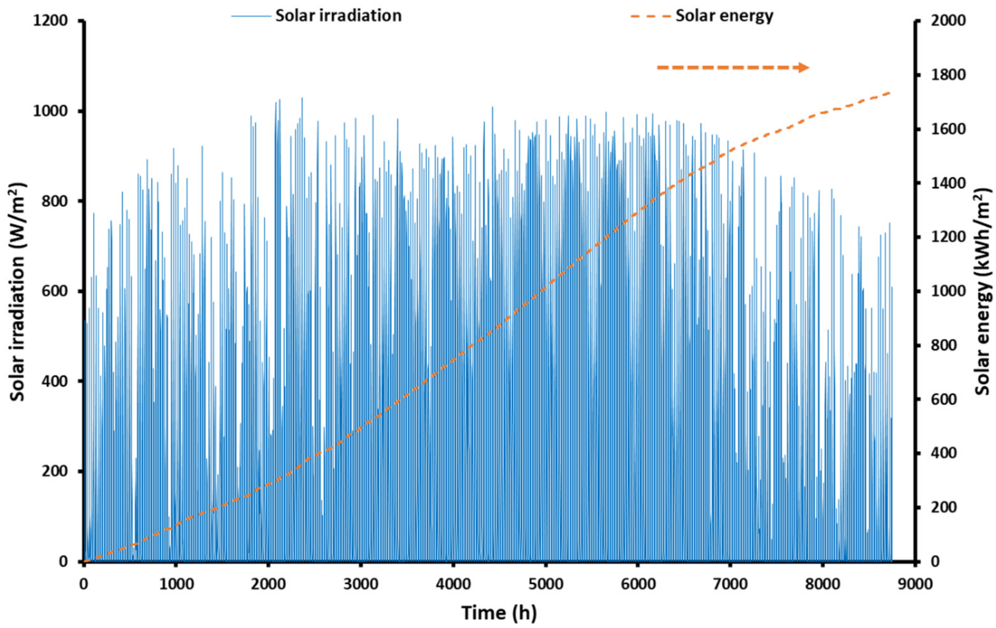

Figure 4. The solar irradiation variation on the tilted surface and the cumulative solar energy quantity per area for the examined location (Athens, Greece).

The calculation methodology of the electricity for covering the DHW, appliance, and lighting has been described in the previous subsections. Photovoltaic collectors are used for covering the electricity needs of the building and there is a hydrogen storage unit based on an electrolyzer and a fuel cell. Practically, the surplus electricity production from the PV is converted into hydrogen by electrolyzing water. The hydrogen is stored under high pressure and when there is a need, then it feeds a fuel cell for producing electricity for covering the building's demands. In the present work, the first step was the calculation of the thermal loads and the total energy needs for electricity with the TRNSYS tool. The second step was the investigation of the overall configuration together by using the provided equations in a homemade code by exploiting the weather data from TRNSYS libraries for the PV production calculations.

It is important to state that a critical parameter is an initially stored quantity in the storage tank of the hydrogen, as well as the estimation of the PV area in order to provide a proper system sizing. These two parameters were calculated internationally by taking into account the following constraints: (i) The hydrogen storage quantity at the start of the year to be the same as at the end of the year, and (ii) The minimum stored quantity to be positive in order to cover the building needs successfully. These constraints ensure a proper operation without oversizing the system.

3. Results and Discussion

This section gives the results of the present analysis separated into subsections. More specifically, Section 3.1 includes the results of the building's energy needs providing loads and cumulative energy demands. Section 3.2 is devoted to presenting and discussing the results concerning the performance of the total configuration with photovoltaics and hydrogen storage.

3.1. Results for the Building Energy Needs

The first step of this work regards the presentation of the building's thermal loads which are depicted in Figure 5. The heating and cooling loads are given in this depiction and it is clear that the studied building has both significant heating and cooling loads. These loads are covered by a heat pump which is a reversible one. In addition, the electrical consumption of the heat pump is given in Figure 6. The maximum heating load was found on 15 January and is 8.38 kW, while the maximum cooling load was found on 19 August and is 8.29 kW. It is useful to state that the heating period starts on the 1 of November and it lasts up to the end of April. On the other hand, the cooling period starts on 25 May and lasts up to the middle of October. So, the heating period lasts for six months and the cooling period for 4 months and 20 days. The reported electrical consumption of the heat pump has significantly lower values than the loads because the used heat pump is an efficient one. So, it is remarkable to refer that the maximum electrical demand of the heat pump is found at 2.1 kW.

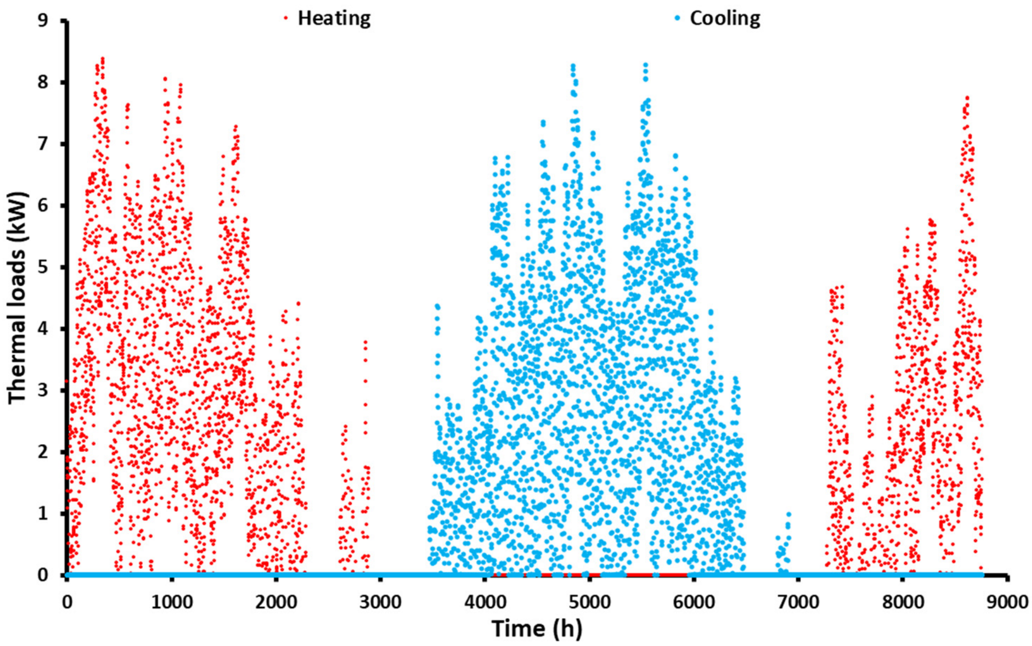

Figure 5. Heating and cooling thermal loads of the studied building.

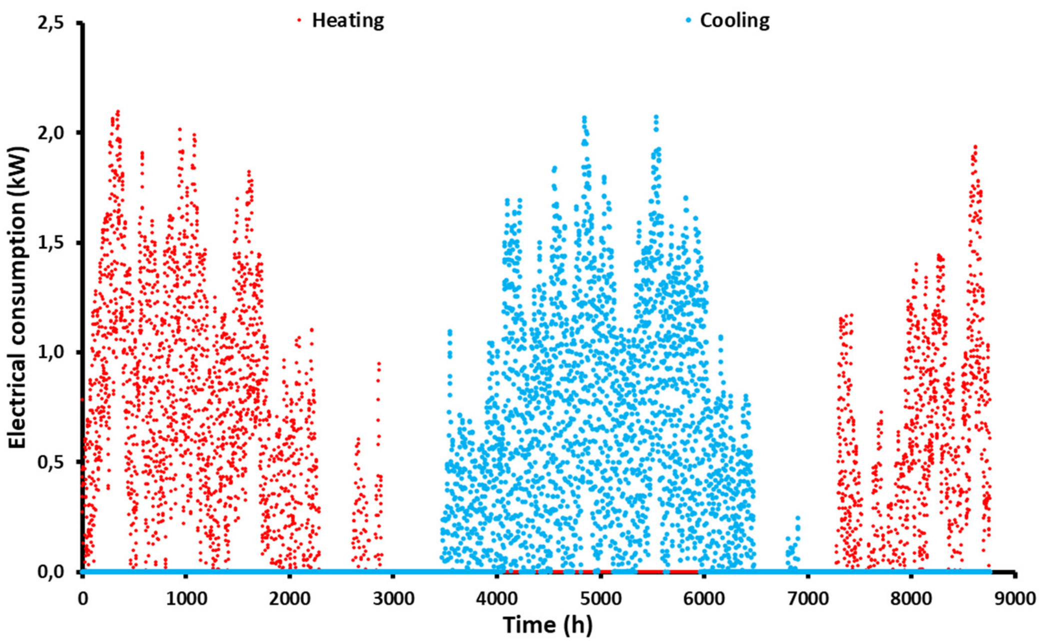

Figure 6. Electricity demand for covering the heating and cooling needs of the studied building.

The cumulative energy demands are depicted in Figure 7 for heating, cooling, and DHW. On a yearly basis, the heating energy demand was found at 9777 kWh and the cooling energy demand at 7237 kWh. The load for DHW demand was found at 3452 kWh.

Figure 8 illustrates the respective electrical energy demand for the year, also including the appliances and lighting demand. More specifically, the yearly electrical consumption for the heat pump for heating was found at 2444 kWh and for cooling at 1809 kWh. The electrical consumption for covering the domestic hot water was found at 3634 kWh, while the consumption for appliances and lighting was found at 15,769 kWh. The cumulative curve for the DHW presents a reduced slope in the summer because the load is lower in this period. More specifically, the grid water is warmer in the summer period and this is the reason for the reduced DHW needs in the summer period. Finally, the sum of the aforementioned electrical consumption is 23,656 kWh which corresponds to a yearly demand of 59.14 kWh/m^2.

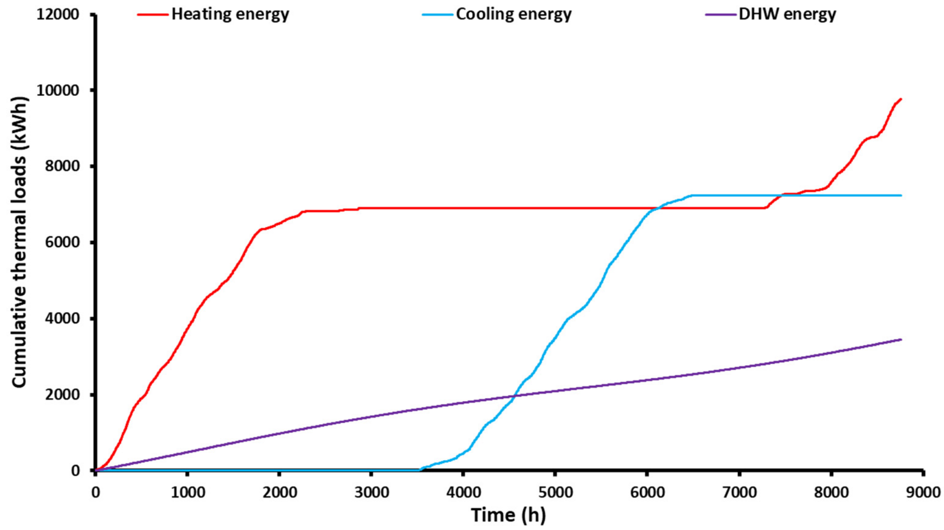

Figure 7. Cumulative thermal loads for heating, cooling, and DHW of the studied building.

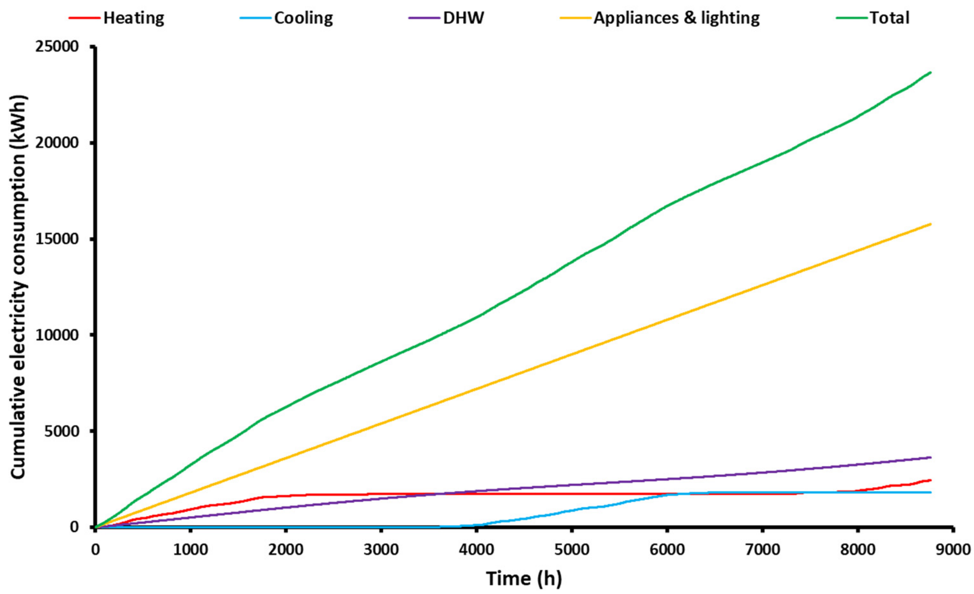

Figure 8. Cumulative electricity demands for covering the different needs of the studied building.

3.2. Performance Analysis of the Total Configuration

This section includes results for the performance of the overall unit including the photovoltaics, the electrolier, and the fuel cell. Figure 9 illustrates the total electricity demand of the building that has to be provided by the energy system. In addition, the cumulative electricity demand is given in this figure. It is interesting to state that the maximum electrical load of the building is 6.42 kW. In addition, it is essential to state that the cumulative curve of electricity has a relatively linear character, something that proves the low variation in the electrical demand during the different seasons. This result is also verified by the existence of similar heating and cooling loads in terms of [kW] and [kWh].

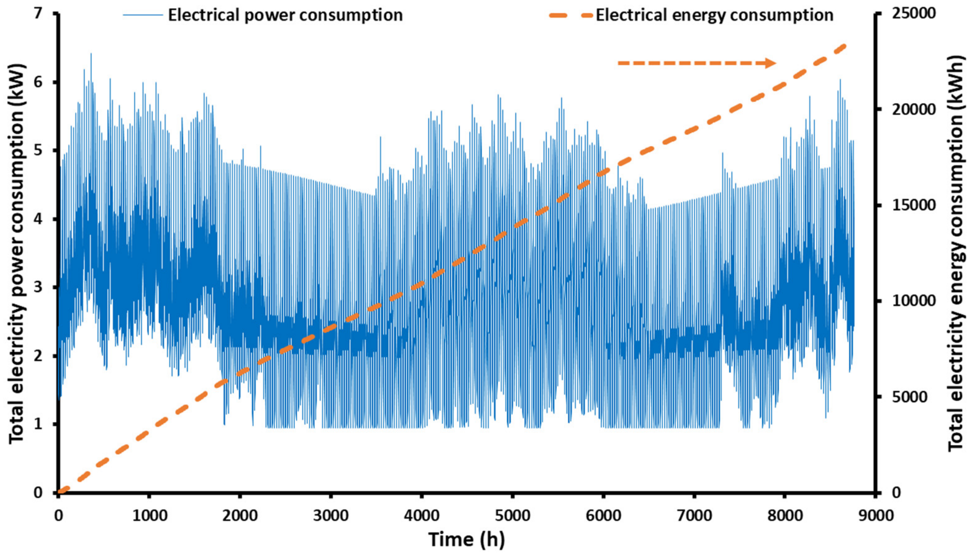

Figure 9. Variation in the total electricity demand in [kW] and the cumulative electricity demand in [kWh] of the studied building.

Figure 10 exhibits the electricity production of the photovoltaics in terms of [kW] and also the cumulative electrical production curve is given in this figure. The cumulative curve has a greater slope in the summer period, a fact that indicates that in this period, there is greater electricity production. The maximum instantaneous electrical production was found at 41.04 kW. The yearly electrical production was found at 63,637 kWh, while the solar potential was at 352,971 kWh. The mean yearly electrical efficiency was found at 18.03% which is a reasonable value considering that the nominal efficiency of the PV cell is at 19.7%. It is obvious that the produced electricity from the photovoltaic field is significantly higher than the electricity demand. However, this is a reasonable fact because there are important conversion losses in the electrolyzer and in the fuel cell, and thus an electrical quantity is lost during the charging/discharging processes.

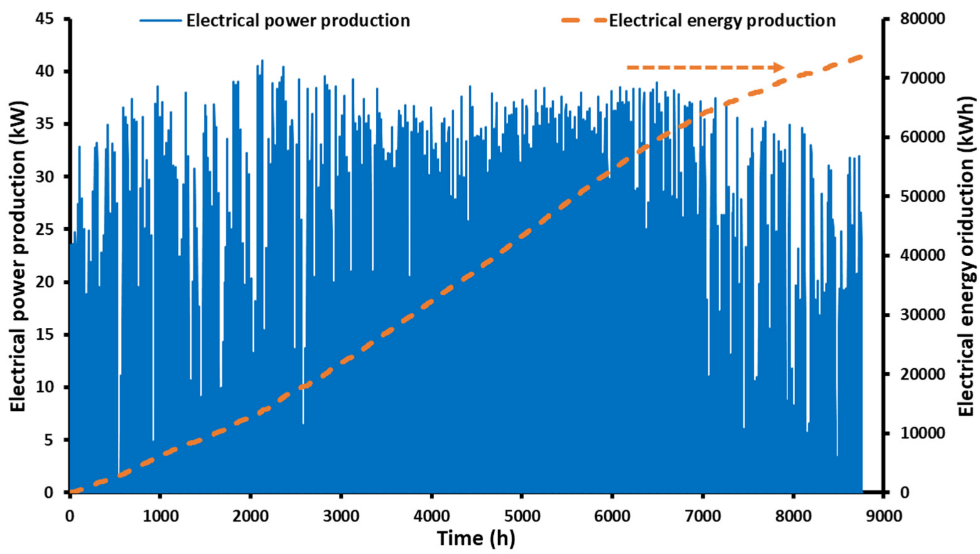

Figure 10. Variation in the produced electricity from the photovoltaics in [kW] and the cumulative electricity production in [kWh].

The next step is the presentation of daily results for the electricity and the hydrogen flows. More specifically, Figure 11 shows results for a typical winter day and Figure 12 for a typical summer day. Similar profiles can be found with the PV production to be maximized around the summer, with the maximum hydrogen demand being later in the afternoon (20:00). However, the production of the PV is higher in the summer (32.5 kW) compare to winter (20.3 kW). These figures practically prove that the present unit is an appropriate choice for the year period, and so is a sustainable one. However, a crucial issue is the selection of a proper storage capacity for hydrogen.

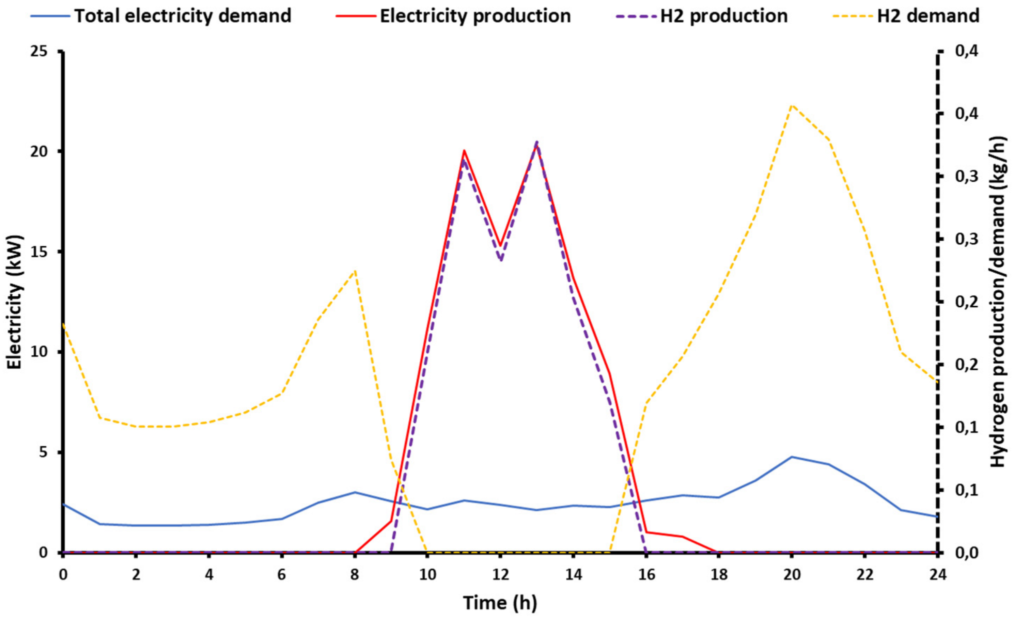

Figure 11. Winter Day: Variation in the electricity demand/production and hydrogen demand/production.

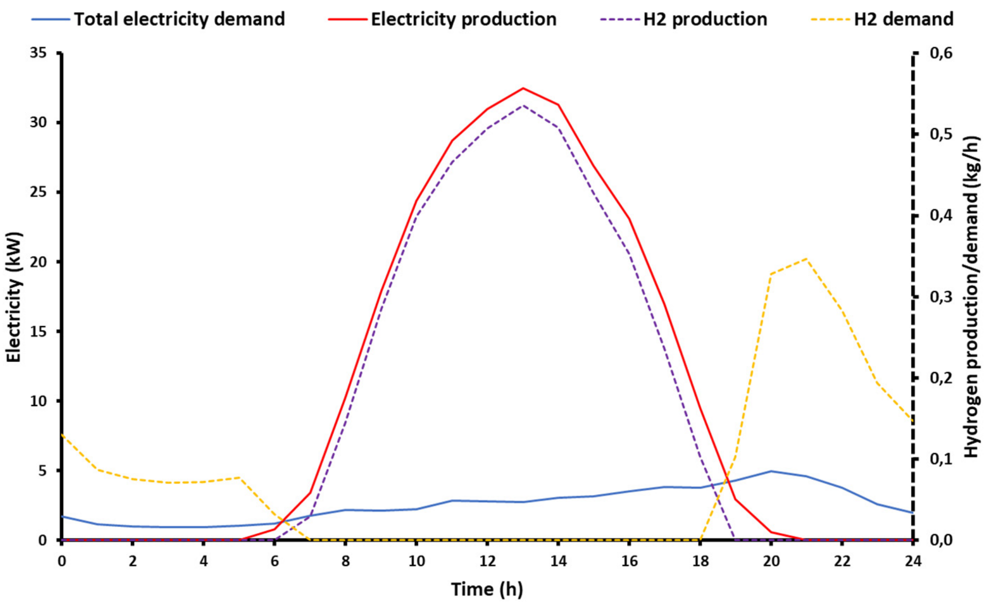

Figure 12. Summer Day: Variation in the electricity demand/production and hydrogen demand/production.

Figure 13 depicts the variation in the hydrogen stored quantity during the year. This figure is the core figure of this analysis because it is directly associated with the sizing of the system. After an iteration process, it was determined that the maximum storage capacity has to be 258 kg of hydrogen which corresponds to a tank of around 34 m^3. The PV field area has to be at 203 m^2 for producing the demanded quantity. More specifically, the nominal power of the photovoltaic field is about 40 kW and in total 116 panels have to be installed. Practically, the PV area was found to be approximately half of the roof area and this is an interesting conclusion that can be used as a preliminary assumption in future studies. The initial charge of the tank is selected at 150 kg of hydrogen which corresponds to a 58% charging percentage. It is important to state that the charging effect at the beginning and at the end of the year is approximately the same; the fact indicates that the final solution is a converged one. The minimum stored quantity is observed on 27 March and it corresponds to 2.6% of the maximum stored quantity. This small percentage creates safety in the system operation, and it is important that it exists. On the other hand, the maximum charge (100%) was found at 21 of October.

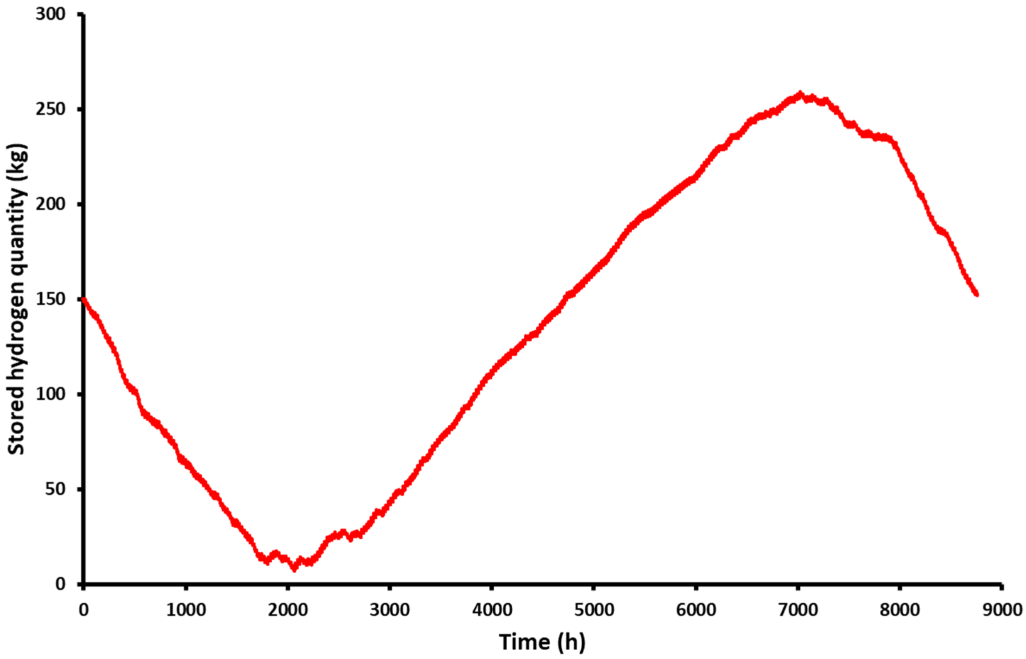

Figure 13. Variation in the stored hydrogen quantity during the year.

In the last part of the present investigation, the summary of the obtained results is included in Table 3. This table includes the load energy quantities, the electrical demands, the electrical production, as well as the electrical energy quantities associated with the electrolyzer and the fuel cell. The specific heating thermal loads of the building per floor area are found at 24.44 kWh/m^2, while for cooling at 18.09 kWh/m^2. The thermal load of the DHW was found at 8.63 kWh/m^2, while the electrical demand for appliances & lighting was at 39.42 kWh/m^2. The global electrical demand for covering all the needs was found at 59.14 kWh/m^2. At this point, it is critical to highlight that the distribution of electrical needs is found at 10.3% for heating, 7.6% for cooling, 15.4% for DHW, and 66.7% for appliances and lighting. It is important to state that the appliances and lighting demand are the major contributors to the total electricity demand of the examined building.

The PV performance is found at 18.03% which is a satisfying value. It is remarkable to state that the PV produces 63,637 kWh and only 11,062 kWh are directly absorbed by the building, which is about 17.4% of the produced energy. The other remaining quantity (82.6%) feeds the electrolyzer. The fuel cell produces 12,594 kWh and practically the global efficiency of the electrolyzer-fuel cell is about 24%, which is a relatively low value. This fact indicates the need to enhance the performance of these devices for creating a system with a higher conversion ratio and lower size. Regarding the building loads, the PV directly covers 46.8% of the building loads, while 53.2% is covered by the fuel cell.

Table 3. Final data of the simulation analysis.

Energy Parameter	Value (kWh)
Heating thermal energy demand	9777
Cooling thermal energy demand	7237
DHW thermal energy demand	3452
Electricity demand for heating	2444
Electricity demand for cooling	1809
Electricity demand for DHW	3634
Electricity demand for appliances and lighting	15,769
Total electricity demand	23,656
Electricity production by the PV	63,637
Available solar energy	352,971
Directly absorbed electricity from the PV	11,062
Electricity input in the electrolyzer	52,575
Electricity production by the fuel cell	12,594

At this point, it is important to make a preliminary economic evaluation of the present system. Assuming typical specific costs for the devices and electricity cost at 0.3 €/kWh [33], the simple payback period is close to 20 years which is a relatively high value. More specifically, this value has been calculated by assuming a specific cost for PV at 1000 €/kW [39], for electrolyzer at 1500 €/kW [39], for fuel cell at 2000 €/kW [39], and for hydrogen storage at 250 €/kg (mean value of recent trends) [40,41]. These costs will be reduced in the future and a lot of research is being conducted for reducing the costs of electrolyzers, fuel cells, and storage tanks. In addition, there is the possibility of storing the hydrogen in alternative ways (e.g., cavern, if it is possible) and in this case significantly reducing the cost, especially in great-scale applications. Moreover, the increasing trend of the electricity will lead to reduced payback periods and an optimistic scenario with a 20% reduction in the cost and an increase in the electricity price at 0.4 €/kWh would lead to a simple payback period of around 12 years.

Moreover, it is useful to compare the present system with hydrogen storage with the alternative choice of using batteries. Hydrogen presents some advantages as high energy storage density and the lack of energy loss during the long storage period. Moreover, the batteries present degradation issues and they need replacement after some years. So, there are advantages to the suggested storage technology with hydrogen. In the future, it would be very interesting to investigate a system with both hydrogen and battery storage with proper economic optimization for minimizing the overall system cost. In addition, the present system can be examined in buildings of different uses (e.g., commercial buildings), and this configuration can be examined in different climate conditions.

4. Conclusions

Hydrogen storage is an alternative and promising method for storing significant electricity quantities and helping the development of stand-alone buildings without grid connection. The present work investigates a building of 400 m^2 with photovoltaics, electrolyzer, hydrogen storage, and fuel cell in Athens, Greece. The most critical conclusions of this analysis are the following:

- The specific heating thermal loads of the building per floor area are found at 24.44 kWh/m^2, while for cooling at 18.09 kWh/m^2. The thermal load of the domestic hot water was found at 8.63 kWh/m^2, while the electrical demand for appliances & lighting was at 39.42 kWh/m^2.
- The global electrical demand for satisfying all the building's needs was estimated at 59.14 kWh/m^2. This quantity is separated into 10.3% for heating, 7.6% for cooling, 15.4% for DHW, and 66.7% for appliances and lighting. So, it was found that the appliances and lighting demand are the major contributors to the total electricity demand.

- The PV area was determined at 203 m^2 which is about half of the roof area. The storage capacity for the hydrogen was determined at 258 kg which means a tank of about 34 m^3. Regarding the building loads, the PV covers directly 46.8% of the building loads, while 53.2% is covered by the fuel cell.
- The PV performance is found at 18.03% and it corresponds to a produced electricity of 63,637 kWh or 313.5 kWh_{el}/m^2 of the PV field. From the produced quantity, only the 11,062 kWh are directly absorbed by the building, which is about 17.4% of the produced energy, while the remaining quantity feeds the electrolyzer device.
- The minimum stored quantity was observed on 27 March and it corresponds to 2.6% of the maximum stored quantity, while the maximum charge (100%) was found on 21 October.

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Nomenclature

A	Area, m^2
COP	Coefficient of performance
cp	Specific heat capacity, kJ/kgK
EER	Energy efficiency ratio
f	Cell temperature coefficient, Km^2/W
fr	Fraction of the operation, %
GT	Global solar irradiation on the tilted surface, W/m^2
LHV	Lower heating value, MJ/kg
SCOP	Seasonal coefficient of performance
SEER	Seasonal energy efficiency ratio
Pel	Electricity rate, kW
Q	Heat rate, kW
qa-l	Specific load for appliances and lighting, W/m^2
T	Temperature, °C
U	Structural element thermal transmittance, W/m^2K
Greek Symbols	
β	Temperature reduction coefficient of the photovoltaic cell, K^{-1}
η_{el}	Electrical efficiency of the PV
$\eta_{el,ref}$	Reference electrical efficiency of the PV
η_{elect}	Electrolyzer conversion efficiency
η_{fc}	Fuel cell conversion efficiency
Subscripts and Superscripts	
am	Ambient
cell	Photovoltaic cell
cool	Cooling
DHW	Domestic hot water
floor	Building floor
el, a-l	Electricity for appliances & lighting
el, DHW	Electricity for domestic hot water
el, elect	Electricity in the electrolyzer
el, fc	Electricity in the fuel cell
el, tot	Electricity total

grid	Grid
heat	Heating
hp, cool	Heat pump, cooling
hp, heat	Heat pump heating
H2,cons	Hydrogen consumption
H2,prod	Hydrogen production100
PV	Photovoltaic
ref	Reference
Abbreviations	
DHW	Domestic Hot Water
PV	Photovoltaics
TMY	Typical Meteorological Year

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