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# Dynamic analysis and multi-objective optimization of an integrated solar energy system for Zero-Energy residential complexes

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ABSTRACT

This study introduces and evaluates a novel, integrated solar energy system for achieving sustainable and zero-energy residential buildings. The proposed system integrates photovoltaic-thermal (PVT) solar panels, heat pumps, electrolyzers, fuel cells, reverse osmosis desalination units, and thermal storage tanks to simultaneously supply electricity, heating, cooling, and potable water. A primary challenge in solar energy systems—the intermittency of energy production—is addressed using energy storage solutions, including hydrogen-based electrolysis and fuel cell systems, which stabilize the supply across day-night cycles. The energy system is designed to meet the energy demands of a 160-unit residential complex in San Diego, each unit covering 110 m$^2$. A dynamic simulation over an entire year is performed using TRNSYS software. System optimization is conducted via Response Surface Methodology (RSM), targeting three objective functions: total power capacity, life cycle cost (LCC), and thermal comfort represented by the predicted percentage dissatisfied (PPD) index. Optimization system is based on five key decision variables: solar PVT area, fuel cell capacity, electrolyzer capacity, heat pump capacity, and hydrogen tank size. Results demonstrate that, under optimized configurations, the system achieves an annual electricity output of 29,145.8 kWh/year, an LCC of $894,228, and a PPD index of 6.8 %, fully meeting the residential complex's electricity demand of 200 MWh/year. The results validate the effectiveness of the hybrid system in enhancing efficiency, ensuring system reliability, and mitigating environmental impacts, thus offering a scalable solution for zero-energy building applications.

## 1. Introduction

Buildings play a significant role in the global energy landscape across residential, commercial, and service sectors, accounting for over 40 % of global energy demand and nearly 30 % of CO2 emissions[1]. The primary energy requirements of buildings encompass heating (including space heating and domestic hot water), electricity, and cooling, with drinking water supply also significantly contributing to energy consumption in various regions. Notably, heating and cooling together account for almost 50 % of total energy needs, with their relative demands varying by climate—cooling needs are predominant in warmer regions, while heating is more critical in colder climates [2].

As fossil fuel resources become increasingly limited and costly, there is a marked shift towards renewable energy sources. The concept of net-zero energy buildings has gained traction among researchers and practitioners, presenting a viable solution to mitigate pollutants and greenhouse gas emissions [3]. With the rising costs of fossil fuels and their detrimental environmental impacts, the adoption of zero energy principles has become both practical and widespread.

Electricity constitutes another major energy requirement for buildings, supporting equipment, lighting, and electronics, and accounts for over 35 % of total energy demand [4]. The level of energy consumption is directly correlated with emissions across all sectors, including

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## Nomenclature

| | |
|---|---|
| A | area ($m^2$) |
| $C_P$ | WT's power coefficient |
| $E_{PV/T}$ | generated electricity by PV/T collectors (kJ/h) |
| T | temperature (°C) |
| h | Enthalpy (kJ/kg) |
| c | specific heat capacity (J/kg.K) |
| $G_T$ | total solar radiation incident upon the collector surface (kJ/hr.$m^2$) |
| $U$ | voltage (V) |
| $\dot{V}_{H_2}$ | total hydrogen consumption |
| $x$ | factor |
| $y$ | response |
| $\dot{m}$ | mass flow rate (kg/h) |
| LCC | life cycle cost ($) |
| IAM | incidence angle modifier |
| L | length (m) |
| $i$ | inflation rate |
| I | current (A) |
| $Q_{gen}$ | total heat produced by fuel cell |
| $\dot{q}_{sens}$ | sensible cooling performed by the heat pump (kJ/h) |
| T | Temperature ($^0$C) |
| P | Pressure (kPa) |
| N | Number |
| $C_P$ | Specific heat of air and water at constant pressure [kJ/kg.K] |
| K | The ratio of specific heats |
| $N_{tubes}$ | number of tubes in PV/T collector |
| $Q_{gen}$ | total heat produced by fuel cell |
| $\dot{q}_{sens}$ | sensible cooling performed by the heat pump (kJ/h) |
| $\dot{q}_{tot}$ | total cooling performed by the heat pump (kJ/h) |
| $n_{c,\ ser}$ | number of cells in series |

*Abbreviations*

| | |
|---|---|
| RSM | Response surface method |
| ASHRAE | American society of heating, refrigerating, and air-conditioning engineers |
| HP | heat pump |
| EPV/T | generated electricity by PV/T collectors (kJ/h) |
| hairIn | enthalpy of air entering the heat pump (kJ/kg) |
| hairOut | enthalpy of air exiting the heat pump (kJ/kg) |
| PV | photovoltaic |
| PV/T | photovoltaic/thermal |
| RSM | response surface methodology |
| TPC | Total power capacity (kWh/year) |
| PMV | predicted mean vote |
| PWF | present worth factor |
| PPD | Predicted percentage dissatisfied index |

*Scripts*

| | |
|---|---|
| in | inlet |
| out | outlet |

*Greek symbols*

| | |
|---|---|
| $\varepsilon_m$ | an emissivity of the top surface of the collector |
| $\theta$ | angle of incidence () |
| $\eta$ | efficiency |
| $\rho$ | density (kg/m3) |
| $\rho_a$ | Air density (kg/m3) |
| $\theta$ | angle of incidence () |
| $\tau\alpha$ | transmittance-absorptance product for PV/T collector |

buildings, which are responsible for nearly a third of global environmental issues [5]. Consequently, there is an urgent need to identify solutions that reduce energy consumption through both passive and active techniques, advanced materials, and innovative energy management approaches. Concepts such as smart buildings, net-zero energy buildings, net-zero emission buildings, and positive energy buildings have emerged from these efforts [6].

Given the finite and highly polluting nature of fossil fuels, a renewed focus on renewable energy sources is essential. Renewable energy is clean, sustainable, and can be replenished naturally within a short time frame. This study investigates the thermodynamic, economic, optimization, and regional aspects of a comprehensive energy system designed to produce electricity, hydrogen, oxygen, cooling, heating, and drinking water. The system integrates various components, including solar panels, fuel cells, proton exchange membrane electrolyzers, heat pumps, and reverse osmosis technology.

By optimizing the performance of solar-based systems, this research aims to enhance efficiency and reduce costs, making the system applicable across different geographical regions considering short-term power forecasting [7]. Recent literature highlights various advancements in this field, including innovative simulation models and hybrid systems that effectively utilize solar energy for building applications. For instance, studies have demonstrated the effectiveness of solar thermal hybrid systems, the integration of heat pumps with renewable sources, and the optimization of energy systems using advanced software tools[8].

Table 1 provides a summary of research related to and close to the topic of this study.

In 2022, Almojil et al. proposed a solar system to supply energy to residential buildings and to reduce emissions. Walls with phase change materials were used in the investigated building. The results showed that using larger blades led to an increase in wall temperature at night and longer wall performance, and the use of the Trombe wall reduced $CO_2$ production [29].

In 2022, Chen et al. worked on using solar energy for building energy. This study investigated the performance of a solar ground source heat pump. The results showed that the proposed system can meet the heating, cooling, and domestic hot water needs of the building [30].

Yan et al. in L 2024 contributed to the process integration and thermodynamic analysis of a novel system involving solar-assisted biomass gasification and ammonia production by chemical loop. This paper proposes the use of a solar-assisted biomass gasifier instead of fossil fuels to provide the required energy. In addition, it uses a solid oxide fuel cell to eliminate the need for an air separation unit in the nitrogen supply process. The proposed approach involves a multi-generation system that combines biomass gasification with solar thermal assistance to produce electricity, heat, cooling, and ammonia. The results show that in the cooling mode, the system with solar input has energy and exergy efficiencies of 53.61 and 31.41 %, respectively, and without solar input, they have energy and exergy efficiencies of 53.98 and 34.68 %, respectively [31].

Bao et al. (2024) investigated the probabilistic characteristics and extreme values of wind pressure of tiltable solar photovoltaic system panels under omnidirectional wind. This study emphasizes the necessity of incorporating non-Gaussian characteristics and omnidirectional wind considerations into the structural design of photovoltaic systems to avoid under- or over-design, especially in sensitive areas. These findings contribute valuable insights to enhance the accuracy and safety of structural design in renewable energy applications [32].

Yang et al. (2024) studied the optimal placement of wind hybrid systems. With the increasing integration of wind power into the grid, its inherent variability and uncertainty pose challenges to the stability of

**Table 1**
Summary of literature for the present study.

| Author(s) | Year | Summary of Topic | Key Results |
|---|---|---|---|
| Wang et al. | 2022 | Developed a simulation model using TRNSYS for a ground source heat pump and solar energy. | Achieved a maximum performance factor of 4.54, 23.8 % higher than the original system[9]. |
| Aldhabi et al. | 2022 | Combined PV panels and solar thermal collectors in a hybrid system (PVT). | The efficiency correlation coefficient was 0.98 and 0.978 for the integrated system[10]. |
| Rashad et al. | 2022 | Focused on software simulation accuracy for building energy analysis. | Improved feedback for investors and builders; emphasized the importance of accurate energy source selection [11]. |
| Bisengimana et al. | 2023 | Studied a heat pump using renewable solar energy and PVT panels for electricity supply. | Provided clean energy for building cooling and heating needs[12]. |
| Liang et al. | 2023 | Conducted multi-purpose simulation and analysis on PVT and heat pump requirements for buildings. | Heating system performance suitable for all studied areas; return period for Dalian was 6.53 years[13]. |
| Khanmohammadi et al. | 2022 | Analyzed a combined PVT system for electricity and heating supply using real meteorological data. | Investigated systems in Stockholm, Doha, and Tehran for effective energy production[14]. |
| Mansir et al. | 2022 | Studied transient behavior of an energy system for residential buildings using TRNSYS. | Hydrogen system outperformed battery systems under high load conditions[15]. |
| Açıkkalp et al. | 2022 | Analyzed a solar desiccant air cooling system for buildings using exergy analysis. | Results indicated new systems could reduce electricity consumption or produce renewable energy [16]. |
| Esmaeilzadeh et al. | 2023 | Developed methods to minimize the environmental footprint of HVAC systems in large buildings. | Retrofitting hybrid systems reduced CO2 emissions by 90 % compared to original systems[17]. |
| Ebrahimi-Moghadam et al. | 2023 | Proposed a sustainable three-generation system powered by a gas turbine cycle with biomass fuel. | Achieved optimal performance producing 541 kW electricity, 2052 kW heat, and 2650 kW cold[18]. |
| Cao et al. | 2023 | Investigated mechanisms to enhance heat pump performance in buildings. | Provided recommendations for further research based on detailed performance descriptions[19]. |
| Acar et al. | 2023 | Developed a solar hydrogen energy system for zero-energy buildings. | Ensured reliable electricity supply throughout the year using solar data[20]. |
| Bosu et al. | 2023 | Investigated solar energy-saving techniques, including solar chimneys and photovoltaics. | Demonstrated energy savings in zero net energy buildings through solar technologies[21]. |
| Fadnes et al. | 2023 | Studied a smart city thermal energy plant with wastewater heat pumps and solar heating. | Identified advanced methods for achieving energy efficiency in power plant operations[22]. |
| Souayfane et al. | 2023 | Investigated renewable energy systems for buildings in three cities, focusing on climate variability. | Found that climate changes increase investment costs for fully renewable energy systems [23]. |
| Xu et al. | 2023 | Addressed probabilistic forecasting of renewable energy production and building load. | Analyzed strengths and limitations of statistical and machine learning-based forecasting methods [24]. |
| Abu-Hamdeh et al. | 2022 | Investigated the efficiency of flat plate solar collectors using phase change materials. | Found improved thermal conductivity and performance with graphene-based materials [25]. |
| Luo et al. | 2024 | Evaluated the techno-economic performance of PV-building-EV integrated energy systems. | Measured technical–economic performance and battery degradation in an integrated system[26]. |
| Mansouri et al. | 2024 | Investigated adaptive control strategies for wind farm integration using VSC-HVDC systems. | Designed a nonlinear controller to enhance energy extraction and grid stability[27]. |
| Mansouri et al. | 2023 | Reviewed wind energy conversion topologies and maximum power point tracking. | Provided insights into challenges and future directions for efficient energy conversion[28]. |

real-time power system operations. Accurate wind power prediction (WPP) is crucial for ensuring grid reliability, this paper proposes a dual NWP wind speed correction method based on trend fusion and fluctuation clustering, aiming to enhance prediction accuracy and improve the stability of power system operations [33].

In the realm of zero-energy buildings, the primary objective is to minimize energy consumption while generating energy through renewable sources to meet the building's energy needs. Given the constraints posed by limited energy resources, pollution stemming from fossil fuel consumption, and various other factors, it is imperative to focus on optimizing energy use and harnessing natural energies such as solar and wind across different sectors. The building sector accounts for a significant portion of global energy consumption; thus, the design and implementation of zero-energy building solutions can play a crucial role in reducing overall energy demand. In numerous countries, the energy consumption attributed to buildings constitutes a substantial share of total energy use.

Due to the escalating costs associated with energy supply and the scarcity of resources, coupled with the principles of sustainable development, architects and builders in the construction industry are increasingly inclined towards creating structures that prioritize optimal energy consumption. Consequently, advancing research on the utilization of renewable and clean energy, as well as the development of zero-energy and green buildings, emerges as a critical area warranting further attention.

In line with ongoing research efforts in sustainable building energy systems, this study introduces an innovative solar-based multi-output energy system. The aim is to establish an energy system for buildings that achieves at least net-zero energy and emissions, and ideally, operates as a positive energy unit. This research encompasses a thermodynamic evaluation and regional analysis of a multi-energy production system tailored to the energy demands of residential buildings, which include electricity, hot water, fresh water, cooling, and heating energy.

The proposed hybrid solar power system integrates solar photovoltaic thermal (PVT) panels with a water-to-water heat pump, an electrolyzer connected to a hydrogen fuel cell, a reverse osmosis unit, and storage tanks. This configuration enables the system to provide electricity, heating, cooling, and potable water for the buildings. Within this framework, a solar unit captures solar thermal energy via a thermal photovoltaic panel, while the fuel cell generates electricity and supplies thermal energy to the system. A heat pump is employed to meet the cooling and heating requirements during varying seasonal conditions, and a reverse osmosis desalination unit is utilized for fresh water production. Additionally, a water heater unit generates hot water, and a proton exchange membrane electrolyzer produces hydrogen to supply the fuel needed by the compressor.

Considering the scale of components involved, it can be argued that the proposed energy system is primarily designed for large buildings, such as social housing complexes, commercial structures, and service facilities like hospitals, particularly in regions where potable water is scarce, such as arid countries. To ground the design and analyses in realistic parameters, a case study involving a building block with 160 residential units in San Diego, USA, has been conducted. All relevant data from this region have been utilized to calculate demand profiles throughout the year. The system has been dynamically simulated in TRNSYS with an hourly resolution over an entire year.

In summary, the objectives of this research include:

- Harnessing the maximum potential of globally available renewable energy sources, particularly solar energy, for system operation.
- Introducing a novel system that combines fuel cell units, photovoltaic thermal panels, proton exchange membrane electrolyzers, heat pumps, and water heaters to maximize the production of electricity, hydrogen, cooling, heating, and hot water without adverse environmental effects.
- Utilizing the fuel cell power generation unit to fulfill electrical needs during peak consumption periods and when renewable energy is unavailable.
- Employing a combination of TRNSYS and Design Expert software for transient simulation and multi-objective optimization.
- Implementing a reverse osmosis desalination unit for water purification and drinking water production.
- Conducting multi-objective optimization of the system to maximize production and minimize costs through response surface methodology.
- Evaluating the technical and economic performance of the system in the selected case study city.
- Analyzing system performance to meet the energy consumption needs of residential buildings.
- Designing and optimizing a new energy system for buildings.

In conclusion, the advantages of the proposed system can be summarized as follows:

- Clean energy production through solar energy absorption by photovoltaic panels.
- Stability in energy production facilitated by the integration of a fuel cell and thermal storage solutions.
- Generation of diverse outputs, including refrigeration, heating, electricity, fresh water, and hot water, suitable for residential, commercial, and healthcare facilities.
- Hydrogen production as a clean fuel alternative.
- The synergistic combination of photovoltaic panels and fuel cells to enhance energy generation efficiency.

## 2. Building energy system

This section presents the modeling and description of a solar energy-based building energy system, which integrates a fuel cell, heat pump, and reverse osmosis unit. The system has been simulated using TRNSYS software, and this section outlines the main implementation, communication, and operational dynamics of each subsystem.

### 2.1. System description

Fig. 1 illustrates the design of the proposed building energy system, which harnesses solar energy through photovoltaic-thermal (PVT) panels and incorporates a combination of fuel cells, an electrolyzer, and a heat pump. The primary outputs of this innovative system include clean electricity, hydrogen, fresh water, heating, and cooling. Key components of the system consist of solar PVTs, heat pumps, a proton exchange membrane electrolyzer, a fuel cell, a reverse osmosis desalination unit, a hydrogen storage tank, a hot water storage tank, and a compressor.

During daylight hours, the solar PVTs generate both electricity and hot water. The hot water produced is routed to the heat pump and the hot water storage tank. Given that the output temperature of the solar PVTs varies throughout the day and across seasons, a heat pump is employed to ensure that the water temperature meets consumer requirements. The heat pump's role is crucial, as it raises the temperature of incoming water to desired levels and transfers the heated water to the storage tank, maintaining a consistent outlet temperature as needed.

The heat pump serves as the heart of the system, addressing both cooling and heating demands to enhance the comfort of residents. It draws energy from the electricity generated by the system to provide cooling in warm seasons and heating during colder months. Notably, during hot periods when the output temperature from the solar PVTs satisfies consumer needs, the heat pump intelligently refrains from producing additional hot water.

The proton exchange membrane electrolyzer is responsible for hydrogen production, utilizing electricity generated by the solar PVTs. The more electricity allocated to the electrolyzer, the greater the hydrogen output, which is stored in the hydrogen storage tank for subsequent use in the fuel cell. This process not only increases the efficiency of the system but also enhances overall energy production capabilities.

The fuel cell plays a pivotal role in the system, stabilizing energy production by supplying necessary electricity and heat. Its importance is particularly pronounced during periods when solar energy is unavailable. The reverse osmosis unit ensures the production of potable water, utilizing the electricity generated by the entire system to meet its energy requirements. This integrated system is designed to meet the energy demands of 160 residential units located in a coastal area, close to the sea or ocean.

### 2.2. Modeling of the building energy system

- **Solar PVT Panels**

The panel used in this system is type 560, which is to generate electricity from the solar PVTs and provide heat to the fluid flow passing through the pipes connected to the absorbent plate located under the panels. The heat lost to the fluid flow is useful for two reasons:

1- It cools the cells (PVTs) and allows higher power conversion efficiency.
2- It provides a heat source for many possible low-temperature applications.

This model relies on linear factors relating cell efficiency (PVTs) to cell temperature and incident solar radiation.The amount of electricity produced and the fluid outlet temperature is calculated from equations (1) and (2) [34]:

$$E_{PV/T} = (\tau\alpha)_n \cdot IAM \cdot G_T \cdot A \cdot \eta_{PV/T} \quad (1)$$

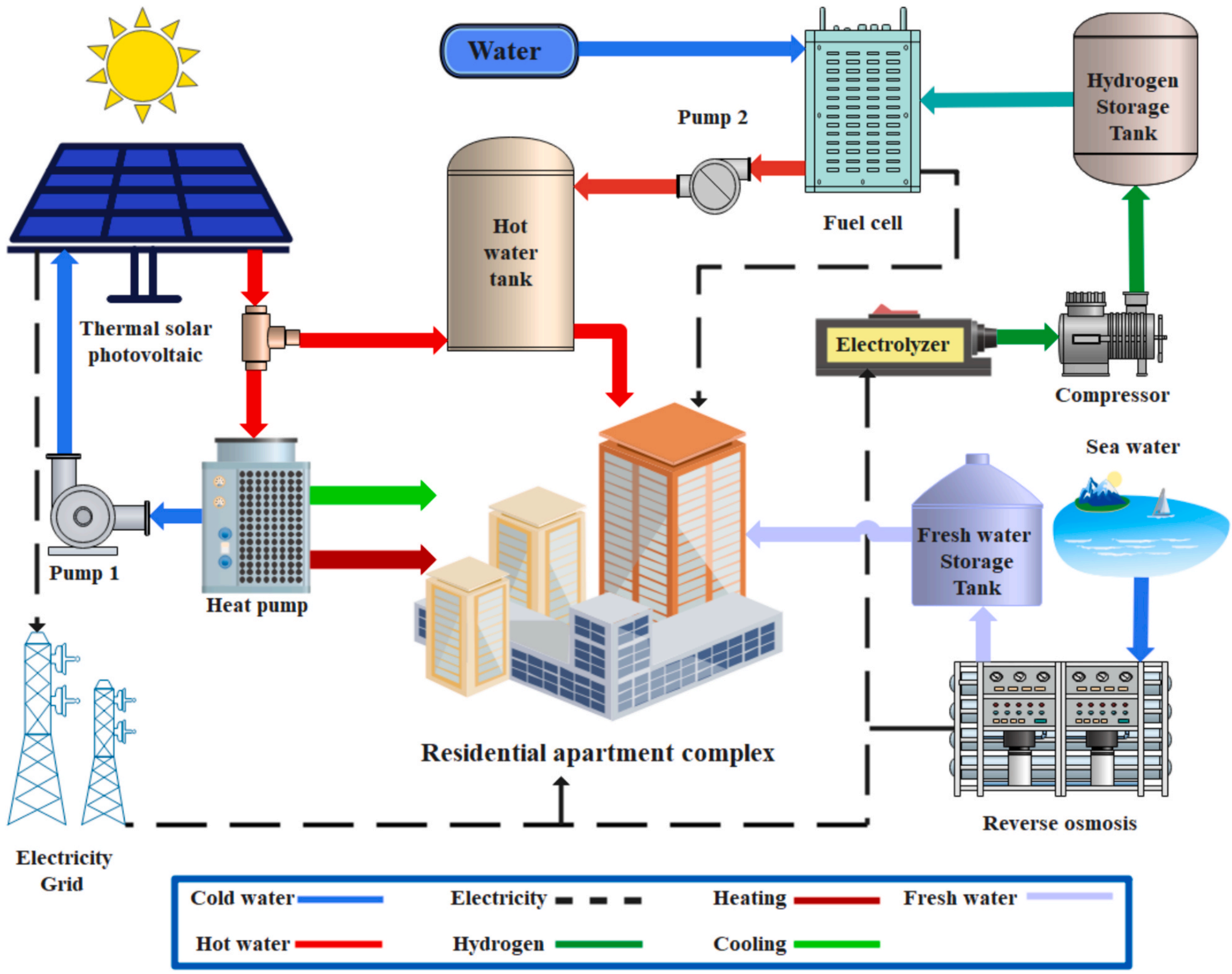


**Fig. 1.** Design of the new proposed system.

$$T_{f,out} = \left(T_{f,in} + \frac{\varepsilon_m}{k}\right)\exp\left(\frac{N_{tubes}}{\dot{m}_f c_f}\frac{\kappa}{\theta}L\right) - \frac{\varepsilon_m}{k} \quad (2)$$

In these relationships,$\tau\alpha$ absorption coefficient, IAM panel angle modifier, $G_T$ amount of solar radiation, a solar panel area,$\eta$ solar panel efficiency,$\varepsilon_m$ radiation emission, L Panel length and $\theta$ is the angle of radiation. K represents the ratio of specific heat and $N_{tubes}$ is the number of tubes in PV/T collector.

- **Fuel Cell**

The fuel cell used in this system is type 173, a simple mathematical model for an alkaline fuel cell. The heat generated by the AFC stack is accounted for, but no detailed dynamic thermal model is included. This example from Type173 assumes that air (as opposed to pure oxygen) is present on the cathode side.

The cell voltage is calculated using equation (3) [34]:

$$U_{cell} = \frac{U_{mod}}{n_{c,ser}} \quad (3)$$

U represents the voltage. $n_{c,ser}$ represents the number of cells in Series.

Fuel cell output power, hydrogen consumption, and total heat produced are calculated using the following relationships.

$$E_{stack} = U_{stack} I_{stack} \quad (4)$$

$$\dot{V}_{H_2} = \frac{n_{c,ser} n_{m,ser} I_{FC}}{zF\rho_{gas}} S_{H_2}\eta_F \quad (5)$$

$$Q_{gen} = E_{stack}\left(\frac{1-\eta_E}{\eta_E}\right) \quad (6)$$

$Q_{gen}$ represents the total heat produced by fuel cell. $\dot{V}_{H_2}$ represents the total hydrogen consumption[34].

- **Heat Pump**

A heat pump is a device that transfers energy from a low-temperature source to a higher-temperature sink. It differs from a pure refrigeration cycle in that the result of the application can be heated or cooled depending on the direction in which the refrigerant is currently flowing in the system. In Type917, the air side is the source, and the heat pump heats or cools the liquid stream. These devices are sometimes known as heat pump water heaters. This part models a single-stage air source heat pump. A heat pump conditions a water flow by discharging energy to (cooling mode) or absorbing energy from (heating mode) the airflow:

The total amount of capacity for heating the secondary liquid flow used by DHW and also the DHW outlet temperature is obtained as follows [34]:

$$\dot{q}_{dhw} = UA_{desper,h}\ (T_{desper} - T_{dhw,in}) \quad (7)$$

$$T_{dhw,out} = T_{dhw,in} + \frac{\dot{q}_{dhw}}{\dot{m}_{dhw} Cp_{dhw}} \tag{8}$$

The read power, which is the power absorbed by the compressor, can be calculated from the data file minus the blower and controller power (entered as model parameters).

Assuming that the humidity of the outside air does not change, the output enthalpy will be calculated as follows:

$$h_{air,out} = h_{air,in} + \frac{\dot{q}_{evap}}{\dot{m}_{air}} \tag{9}$$

h represents the enthalpy.

TRNSYS psychrometric fully characterizes the exhaust air condition. If the return state of relative humidity is more than 90 %, the air will be assumed to be saturated and dense. Finally, fan energy is added to the airflow. A new outlet air enthalpy is calculated as follows:

$$h_{air,out} = h_{air,out} + \frac{\dot{P}_{blower}}{\dot{m}_{air}} \tag{10}$$

To calculate the total energy transfer, we will use the following relations:

$$\dot{q}_{total,air} = \dot{m}_{air}(h_{air,out} - h_{air,in}) \tag{11}$$

$$\dot{q}_{sens,air} = \dot{m}_{air} Cp_{air}(T_{air,out} - T_{air,in}) \tag{12}$$

$$\dot{q}_{lat,air} = \dot{q}_{total,air} - \dot{q}_{sens,air} \tag{13}$$

$$\dot{q}_{Liq} = \dot{q}_{condens} \tag{14}$$

If the auxiliary heater control signal is ON (its input is set to 1), the entire capacity of the auxiliary heater is applied to the primary liquid flow. Whether the auxiliary heater is on or not, the following equation calculates the outlet temperature of the primary liquid stream:

$$T_{Liq,out} = T_{Liq,in} + \frac{\dot{q}_{Liq} + \dot{q}_{aux}}{\dot{m}_{Liq} Cp_{Liq}} \tag{15}$$

- **Electrolyzer**

Type160 TRNSYS is used for high-pressure tinned water electrolyzer. This model is designed with a combination of thermodynamic relations, heat transfer, and experimental relations. For this reason, the hydrogen produced in the electrolyzer unit is calculated based on the following equation [35].

$$\dot{n}_{H_2} = \eta_f N_{cells} \frac{I_{ely}}{nF} \tag{16}$$

- **Reverse Osmosis Desalination Unit**

Reverse osmosis is a membrane separation process that separates water by creating an osmotic pressure greater than that of seawater. For desalination, seawater must be pressurized, which requires high energy; because the pressure created must be greater than the osmotic pressure of seawater, and also the higher the salinity of the water, the higher the pressure and, consequently, the higher the energy consumption. The pressure applied in the reverse osmosis process for seawater purification is about 54–80 bar. Since the brine created in the reverse osmosis process is very concentrated, the water recovery rate in this process is low, about 40 %. Much of the energy waste in the reverse osmosis process is due to the release of the high-pressure brine; For this reason, today, large industrial seawater purification systems and units using the RO method are equipped with devices to recover mechanical compression energy from the brine flow, which can increase the efficiency of these systems by up to 95 %. The energy required to desalinate seawater is approximately 9 kJ per kilogram of water produced.

The reverse osmosis pump output power is calculated from the following equation [36,37]:

$$Pumppower = \dot{W}_{RO} * 1.79 \tag{17}$$

W represents power.

The rate of fresh water is obtained from the following relationship:

$$FreshWaterRate = \frac{((Q1 \times PumpPower^2) + (Q2 \times PumpPower) + Q3)}{(PumpPower + Q1)} \tag{18}$$

The unit of freshwater production rate in this research is cubic meters per hour. The coefficients related to the freshwater rate equation are written in Table 2.

The life cycle cost of the reverse osmosis unit is calculated as follows [38,39]:

$$LCC_{RO} = S\frac{1-(1+i)^{-n}}{i} \tag{19}$$

In this regard, S is the cost in dollars, i is the interest rate in percent and n is the project life in years. $LCC_{RO}$ calculates the value of an amount of money in the present compared to the same amount received at a future date, given that the value of money increases over time based on interest rates.

- **Building**

The main goal of this research is to meet the needs of 160 residential buildings. To accurately model and achieve real results of Radiative, Convective, Electric power fraction, Abs. The relative humidity of the residents inside each building unit, the level of lighting, and electrical equipment are given in Table 3.

### 2.3. Case study

San Diego is a stunning coastal city located in southern California and the southwestern region of the United States [40]. As of 2014, the city's population is estimated to be approximately 1,255,540 residents, making it the second-largest city in California and the eighth-largest in the entire country. Its geographical location can be seen on the map in Fig. 2.

San Diego shares a land border with Tijuana, Mexico, and is home to the largest naval base in the United States, along with numerous related industries, including General Atomics. One of the city's highlights is La Jolla Beach, which stretches for 1.6 miles and is renowned for its calm waves during the summer months, making it an ideal spot for beach-goers. The beach also boasts excellent access to freshwater sources.

In addition to its well-developed infrastructure, San Diego benefits from favorable weather conditions and abundant sunshine, which are significant factors in its selection as the focus of this case study. The combination of its vibrant community, economic significance, and natural beauty makes San Diego an exemplary location for research and analysis.

For this study, 8 buildings with a total of 160 residential apartments are considered as the end-users of the energy system products. The area of each apartment unit is 110 m$^2$. Information about each apartment is shown in Table 4 [41].

Fig. 3 provides significant insight into the annual temperature and

**Table 2**
Freshwater rate relationship coefficients.

| Coefficients | $Q_1$ | $Q_2$ | $Q_3$ | $q_1$ |
|---|---|---|---|---|
| Value | 0.06739 | 183.2 | 130.2 | 867.3 |

**Table 3**
Specifications of loads inside the building.

| Gain | Radiative | Convective | Electric power fraction | Abs. humidity |
|---|---|---|---|---|
| People | 156.6 | 113.4 | 0 | 0.081 |
| Electrical equipment | 5.04 | 20.16 | 1 | 0 |
| Lights | 6.804 | 2.916 | 1 | 0 |

humidity patterns in San Diego. Throughout the year, ambient temperatures show clear fluctuations, with the highest recorded temperature reaching around 30 °C (86 °F) during the summer months, while the lowest temperature in the winter is around 5 °C (41 °F). This temperature range is indicative of a temperate climate that is characteristic of the Mediterranean climate prevalent in the region.

Also, according to the solar radiation data graph, San Diego benefits from abundant sunshine throughout the year. Maximum levels of solar radiation typically occur during the summer months, with peak values reaching around 8 kWh/m2/day, while minimum values are recorded during the winter months, averaging approximately 3 kWh/m2/day.

In summary, San Diego's climate is characterized by hot summers and mild winters, with significant variations in temperature and humidity. The region's high levels of solar radiation, especially in the summer, increase its suitability for energy-efficient building designs and renewable energy applications.

Reference articles have been used to accurately solve the specifications of each apartment in the selected apartment [42]. Fig. 4 presents information about the hourly electricity demands of all the buildings.

Fig. 5 presents the cooling and heating loads for each apartment throughout the year.

Table 5 presents further specifications and data used for doing the simulations for the case study.

## 3. Optimization method

The optimization methodology employed in this research is designed to comprehensively evaluate the key factors influencing the performance of building energy systems. This method allows for a detailed analysis of how each parameter affects system design and enables the assessment of the implications of adjusting these parameters on both cost and energy generation.

The research follows a systematic approach, which includes the following steps:

**Table 4**
Specifications of each apartment unit.

| Item | Unit | Value (unit) | Reference |
|---|---|---|---|
| The ceiling height of each unit | m | 3 | [42] |
| Windows in each unit | – | 3 | [42] |
| Heat transfer of the entire walls in each unit | $W.m^{-2}.K^{-1}$ | 0.525 | [43] |
| Ability to absorb solar energy in walls | – | 0.61 | [44] |
| The amount of heat transfer coefficient in the roofs | $W.m^{-2}.K^{-1}$ | 0.319 | [43] |
| The amount of solar absorption in the roof | – | 0.59 | [44] |
| The amount of heat transfer coefficient in the floor | $W.m^{-2}.K^{-1}$ | 0.321 | [43] |
| The amount of heat transfer coefficient in windows | $W.m^{-2}.K^{-1}$ | 2.91 | [43] |
| Area per unit | $m^2$ | 110 | [45] |
| Number of residents per unit | people | 5 | [46] |


**Fig. 2.** San Diego is on the map.

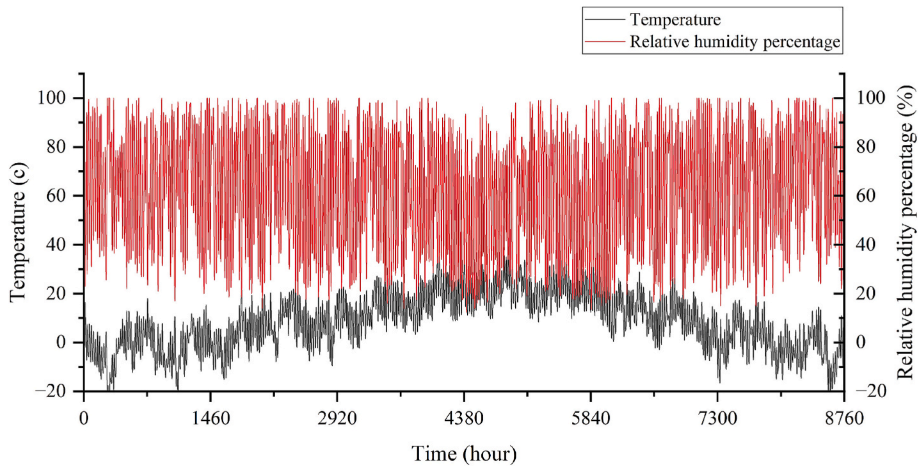


**Fig. 3.** Ambient temperature and relative humidity percentage.

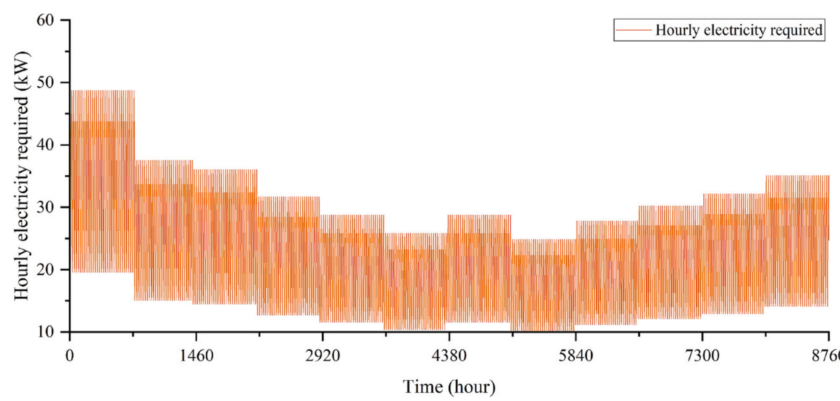


**Fig. 4.** Electricity required for apartment residential units.

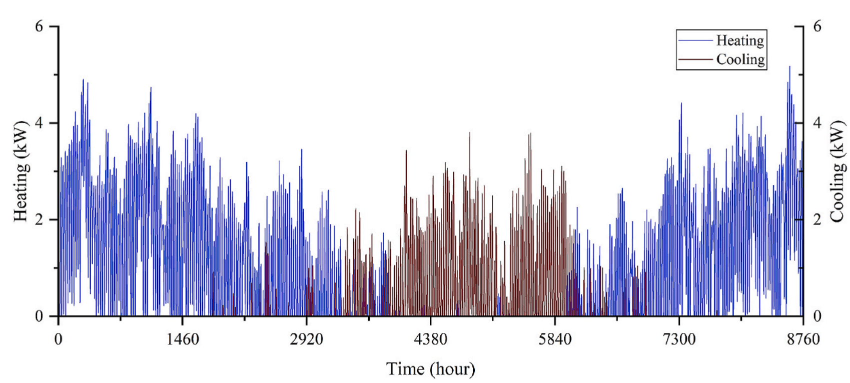


**Fig. 5.** Cooling and heating loads for each apartment.

- Modeling: The initial phase involves creating a detailed model using TRNSYS software to simulate the energy system's performance under various conditions.
- Validation: To enhance the accuracy of problem-solving, the performance of photovoltaic panels is validated, ensuring that the model reflects real-world conditions.
- Data Extraction: Weather data specific to the study area is sourced from Meteonorm software, providing essential information on local climatic conditions.
- Optimization: The optimization process aims to enhance system performance while minimizing costs. This is achieved through the Response Surface Methodology (RSM) and Design Expert software, which facilitate the identification of optimal configurations.
- Performance Evaluation: Finally, the optimized system's capability to supply energy to a residential complex consisting of 160 units is assessed, ensuring that the solution is practical and applicable.

The RSM employed in this study is particularly effective in determining the most optimal configurations by creating a comprehensive set of input variables. This methodology examines the impact of these variables on various responses, allowing for a more holistic understanding of the system's dynamics. A significant advantage of RSM is its ability to reduce the complexity of simulations compared to traditional

**Table 5**
The data used in the simulation.

| Input data | Value | Unit | Ref. |
|---|---|---|---|
| Fuel cell electrode | 100 | $cm^2$ | [47] |
| The number of fuel cell modules | 65 | – | [47] |
| Electrolyzer electrode | 0.26 | $m^2$ | [47] |
| Number of electrolyzer cells | 70 | – | [47] |
| Number of stacks (electrolyzer) | 4 | – | [47] |
| Thermal resistance (electrolyzer) | | K/W | [47] |
| Solar PVT area | 1.657 × 0.9921 | m | [48] |
| Thermal conductivity solar PVTs | 46 | $Wm^{-1}K^{-1}$ | [48] |
| The tilt angle of the solar PVTs | 28 | ° | [48] |
| The volume of hot water tank | 17.5 | $m^3$ | [48] |
| Hydrogen storage tank pressure | 200 | bar | [48] |
| Heat pump bypass deficit | 0.12 | – | [49] |
| Heat pump heating energy ratio | 0.242 | – | [49] |
| System lifespan | 30 | years | [50] |

methods, thereby streamlining the process of identifying optimal solutions.

The initial design of RSM is expressed according to equation (20) [51].

$$y = r_0 + \sum_{i=1}^{n_f} r_i x_i + \sum_{i=1}^{n_f} r_{ii} x_i^2 + \sum_{i<j=2}\sum^{n_f} r_{ij} x_i x_j \quad (20)$$

The economic interaction of the studied LCC system is obtained from equation (21) [52].

$$LCC = I_C + PWF \times AOC - R_I$$

$$PWF = \begin{cases} \dfrac{1}{d-i}\left[1-\left(\dfrac{i+1}{d+1}\right)^{n_L}\right] & if\ i^1 d \\ \dfrac{n_L}{i+1} & if\quad i = d \end{cases} \quad (21)$$

The PPD is a statistical index related to PMV, but it can be presented and investigated as a separate index. PPD shows the percentage of people's dissatisfaction with environmental conditions. The worse the comfort situation, the higher the PPD of people, usually 10 %, and less than that is a suitable number for this index [52]. The answers obtained from the performance of the performed optimization strategy include total electricity consumption and LCC as economic indicators of system performance, and the difference between the total electricity consumed building energy system and produced by the system, which TPC expresses in Eq. **(22)** is shown.

$$TPC = \frac{\sum_{i=1}^{n_t}\left(E_{Load} + E_{HP} + E_{Elctrolyzer} + E_{Pumps} + E_{Compressor} - E_{TPP} - E_{FuelCell}\right)}{3600 \times \frac{1}{\Delta t}} \quad (22)$$

Table 6 summarizes the goal of the optimization strategy created for the proposed system, considering the required energy and selected economic topics.

## 4. Results and Discussions

### 4.1. Validation

The first step in any new study and simulation is to validate the work. Since this system is designed for the first time and has no exact equivalent, it must be validated. Although the system simulation was done with TRNSYS software and all the components of this software, have already been validated. Still, in order to determine the correctness of the solution carried out in this study, the subsystem of thermal solar panels was validated with the research of Kanyarusoke and his Gryzagoridis in (2016). The validation results in Fig. 6 can be seen [53].

The solar system of the present work is new and innovative and for this reason, it has not been investigated before and it is one of the strengths of this research. For this reason, in addition to the photovoltaic panel, the validation of the reverse osmosis desalination unit has also been done with the research of Nafey et al [54] and the results are presented in Table 7. The results show that the modeling has good accuracy and the calculation error is close to zero.

**Table 6**
Optimization objective functions.

| Indicator/response | Objective | Unit |
|---|---|---|
| Total production capacity (TPC) | maximum | kWh/year |
| predicted percentage of dissatisfied (PPD) | target = 10 | % |
| Life cycle cost (LCC) | minimum | $ |

## 5. Results

### 5.1. Simulation influencing parameters

To have a correct understanding of the system components and their performance, a parametric study was conducted. This parametric study aims to know the exact impact of each parameter separately on the performance of the whole system. In Fig. 7, the increase in the capacity of the fuel cell and electrolyzer and their effect on the system's TPC, LCC, and expected PPD can be seen. As the black line shows, with increasing (FC) from 30 (kWh) to 80 (kWh), the production power of the system is on the rise and is increasing. When the capacity of the fuel cell is 30 kWh, the system is still unable to provide all the electricity needs, and the number shown in the graph tells us that the system still lacks 60,000 (kWh/year) of electricity production. But when the capacity reaches 80 (kWh), in addition to not having a shortage of electricity production against the needs of the applicants, the system has an excess of 20,000 electricity production. However, the LCC is increasing in the same proportion according to the purple line in the diagram, and the cost of the system increases to $880,000. In addition to these two important parameters, the PPD has little changes.

Fig. 8 shows the increase in heat pump capacity and their impact on TPC, LCC, and PPD. The heat pump is the heart of the system and provides heating, cooling and a significant part of the hot water required by the system. As the black dashed line shows, increasing the heat pump's capacity reduces the TPC by 10,000 kWh/year. This issue is completely normal because as the heat pump's power increases, its electricity consumption increases and this issue cause the power of the entire system to decrease. On the other hand, due to the increase in capacity, the cost of the system increases, and as the red line in the diagram shows, the cost of the system increases from $870,000 to $930,000 in

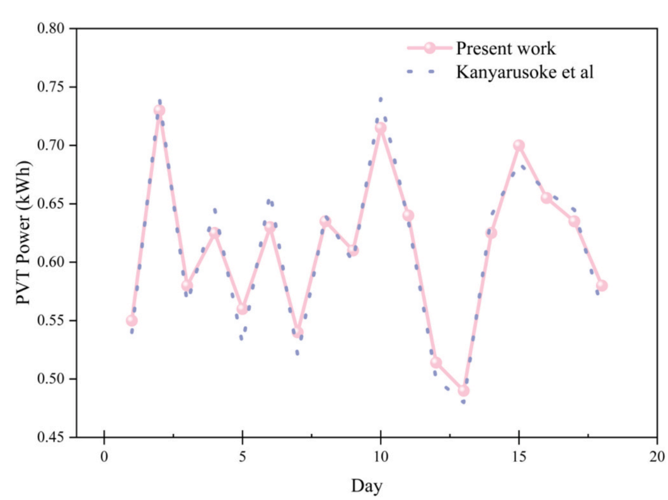


**Fig. 6.** Validation of the present study with the research of Kanyarusoke et al. in (2016).

**Table 7**
Validation of desalination.

| Variable | Unit | Present Study | Nafey et al [54] | Difference (%) |
|---|---|---|---|---|
| $\dot{W}_{pump/RO}$ | kW | 1122 | 1131 | 0.796 |
| $\mathbf{M_f}$ | $m^3/h$ | 485.9 | 485.9 | 0 |
| **SR** | – | 0.99 | 0.99 | 0 |
| $\mathbf{X_b}$ | ppm | 64,180 | 64,180 | 0 |
| $\mathbf{X_d}$ | ppm | 252 | 250 | 0.8 |
| **ΔP** | kPa | 6856 | 6850 | 0.08 |

proportion to the capacity of 20 to 60 (kWh). Because the heat pump is directly related to the provision of cooling and heating required for residential buildings, and as the blue dashed line shows, increasing the heat pump's capacity has a positive effect on the predicted PPD and is 7.2 % to 6.2 % decreases.

Fig. 9 shows the increase in the volume of the hydrogen storage tank and its effect on the TPC, LCC, and the expected PPD. As the black dashed line shows, with the increase in volume from 60 cubic meters to 200 cubic meters, the production power of the system decreases from 36,500 kWh/year to 34,000 kWh/year. This can only be considered as a result of the increase in the volume of the tank regardless of the change in its internal pressure and the lack of change in the capacity of the compressor, which is considered to increase the work of the compressor and consume more electricity and affect the overall production capacity of the system. On the other hand, the red dashed line indicates that increasing the volume of the hydrogen storage tank increases the cost. Finally, the effect of this parameter on the PPD is low and reaches 7.2 % to 7.45 %.

### 5.2. Optimization results

The development of a suitable and practical method to examine the main influencing factors on performance building energy systems. With this method, we can see the effect of each parameter on the system design and determine the effects of increasing and decreasing each parameter on the cost and power generation of the system. The statistical approach can implement the desired result in the current research by controlling various factors.

Fig. 10, which shows the modeling path of this research, clearly shows the place of optimization and its place in this modeling path.

In short, the working method of this research is as follows:

- In the first step, modeling is done with Transit software.
- Then, to increase problem solving accuracy, the photovoltaic panel is validated.
- Weather information of the study city is extracted from Meteonorm software.
- Optimizing the system to increase performance and reduce cost is done with the response level optimization method and Design Expert software.
- Finally, the system's performance for supplying energy to a residential complex of 160 units is checked.

This research, 5 variables are defined as input and 3 objective functions. The input variables are solar PVT area, fuel cell capacity (FC), electrolyzer capacity (EC), heat pump capacity (HC), and hydrogen tank volume. Also, the objective functions that have been selected to increase the system's efficiency and reduce the cost and comfort of the residents

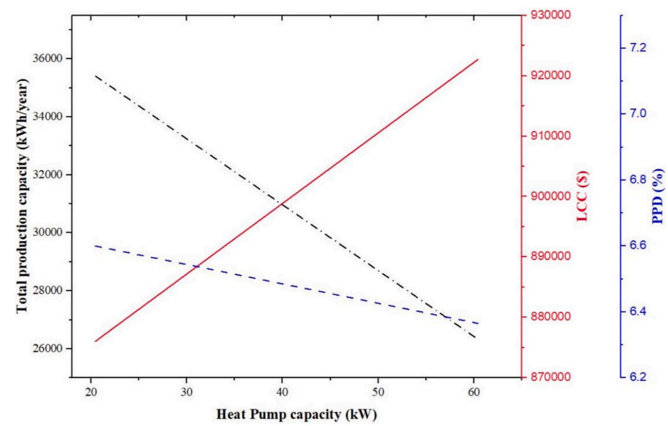


**Fig. 8.** The effect of increasing the heat pump capacity of the building energy system.

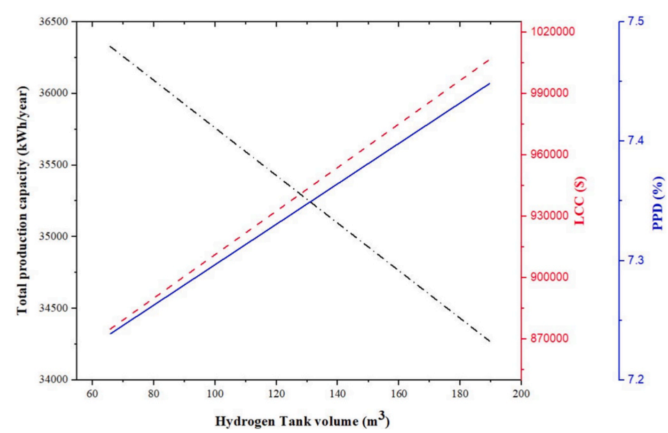


**Fig. 9.** The effect of increasing the volume of the hydrogen storage tank.

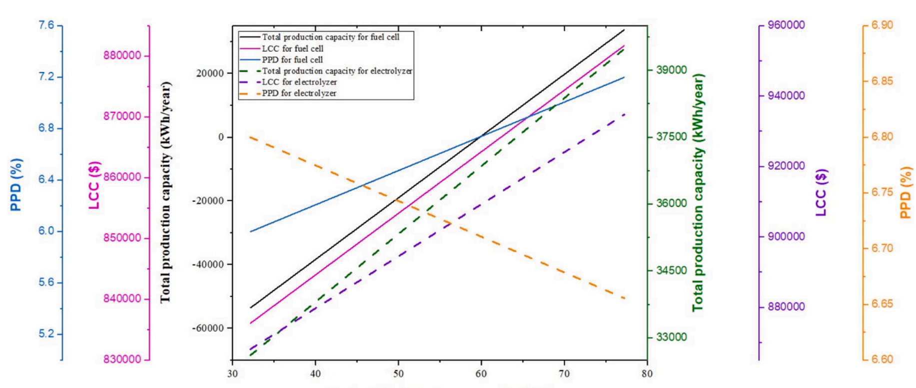


**Fig. 7.** The effect of increasing the capacity of the fuel cell and electrolyzer.

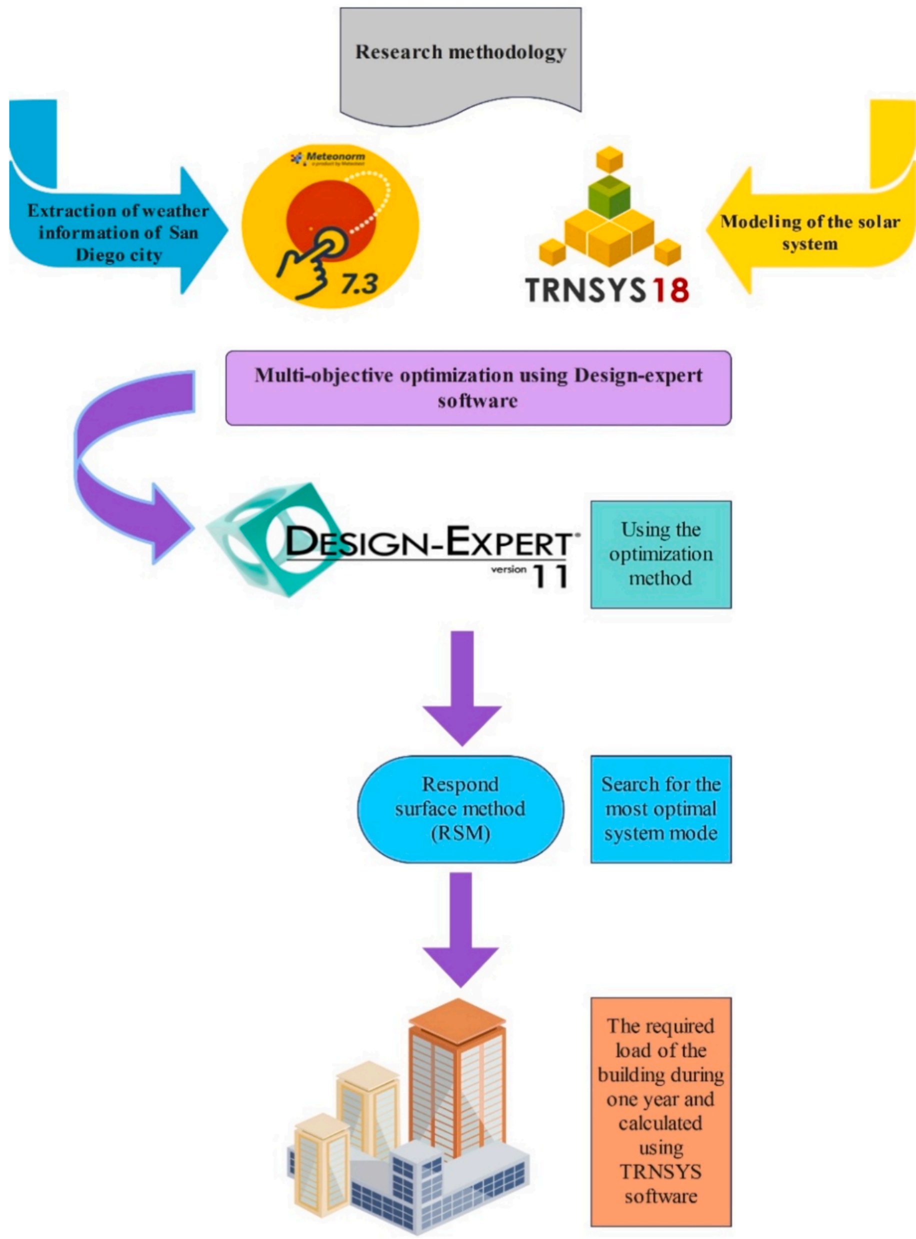


**Fig. 10.** Modeling process.

of residential buildings are the TPC, the LCC, and the PPD. The productivity should be towards the maximum and the life cycle of the system should be towards the minimum. In Table 8, the range of variables is given. It should be noted that the desired optimization points were specified by Design Expert software. Then the specified points were applied in TRNSYS simulation software, and the answers were extracted and compared with each one. Optimization results were calculated based on 32 different runs using RSM.

In Table 9, after optimizing and analyzing the system, the results of the optimal points can be seen in the Design Expert software. For further study, the error percentage of the simulation with the real mode was also checked. In Table 10, the simulation error percentage in Design Expert software can be seen with the actual results in TRNSYS software. As it is clear from the results, the designed system can provide all the annual electricity needs of 160 residential units; in addition, this system can produce 29145.8 (kWh/year) of additional power, which can be sold to the network. Meanwhile, the cost of the system is $894,228.

Fig. 11a shows the behavior of the solar PVTs' area change and the fuel cell's capacity on the production power of the whole system. Increasing both parameters together increases the production capacity

**Table 8**
Range of optimization variables.

| A | PVTs | 500 | 2000 | −1 ↔ 507.50 | +1 ↔ 1502.50 | 1005.00 | 437.74 |
|---|---|---|---|---|---|---|---|
| B | FC | 30 | 100 | −1 ↔ 32.50 | +1 ↔ 77.50 | 55.00 | 19.80 |
| C | EC | 30 | 1 | −1 ↔ 32.50 | +1 ↔ 77.50 | 55.00 | 19.80 |
| D | HC | 20 | 80 | −1 ↔ 20.75 | +1 ↔ 60.25 | 40.50 | 17.38 |
| E | Tank volume | 50 | 250 | −1 ↔ 66.25 | +1 ↔ 188.75 | 127.50 | 53.89 |

**Table 9**
Optimal results for each objective function.

| TTP area ($m^2$) | FC (kW) | EC (kW) | HC (kW) | Tank volume($m^3$) | TPC (kWh/year) | LCC ($) | PPD (%) |
|---|---|---|---|---|---|---|---|
| 925.502 | 77.49 | 38.02 | 20.75 | 66.25 | 29145.8 | 894,228 | 6.8 |

**Table 10**
Simulation error percentage.

| Title | TPC (kWh/year) | LCC ($) | PPD (%) |
|---|---|---|---|
| *The results obtained in Design Expert* | 34817.4 | 894,228 | 6.8 |
| *The results obtained in TRNSYS* | 31671.9 | 887,686 | 7.05 |
| *percentage error* | 6.1 | 0.74 | 3.5 |

of the entire system. When the area of the solar PVTs reaches 1000 square meters, and the capacity of the fuel cell reaches 80 (Kw) per hour, we have the maximum production capacity of 34,817 (kWh/year). In Fig. 11b, the behavior of the electrolyzer and fuel cell can be seen simultaneously in the production power of the entire system. As it is known, the production power of the whole system increases with the increase of electrolysis capacity (EC). Increasing the capacity of the fuel cell and electrolyzer has a direct and linear relationship with the production power of the entire system. Fig. 11c shows the increase in the volume of the hydrogen storage tank and the fuel cell's capacity on the system's total power. As the graph shows, increasing the tank volume has a very small and insignificant effect on the production power of the entire system. Of course, the fuel cell capacity (FC) still positively increases the system's electricity production. In Fig. 11d, the increase in the heat pump and electrolysis capacity and its effect on the production power of the entire system is intended. Increasing the heat pump capacity alone has little effect on the total production capacity.

In Fig. 12a, the increase in solar PVT area and the capacity of the fuel cell and their behavior on LCC can be seen. As it is known, the increase of both parameters increases LCC in the whole proposed system when the area of solar PVTs is 1000 square meters and the capacity of the fuel cell is 80 (kW), the cost reaches the highest value. In Fig. 12b, the increase in the electrolyzer and fuel cell capacity and its behavior on LCC can be seen. As the results show, the effect of these two parameters on LCC is low. Also, in Fig. 12c and 12d, respectively, the increase in the capacity of the electrolyzer and heat pump and the increase in the volume of the hydrogen storage tank and fuel cell and their behavior on LCC can be seen. The results show that increasing the capacity of electrolysis and heat pump has a small effect on LCC, but increasing the volume of the hydrogen storage tank in LCC and its increase have a positive effect, and this issue can be seen.

### 5.3. Transient analysis of the building energy system

After optimizing and finding the optimal points and checking the performance of the system, the optimal points should be applied in the TRNSYS simulation software. The final results of the simulation, which include the production power of the entire system, the amount of hot water produced, the amount of freshwater produced, and other system behavior is to be expressed In Fig. 13, the amount of electricity produced

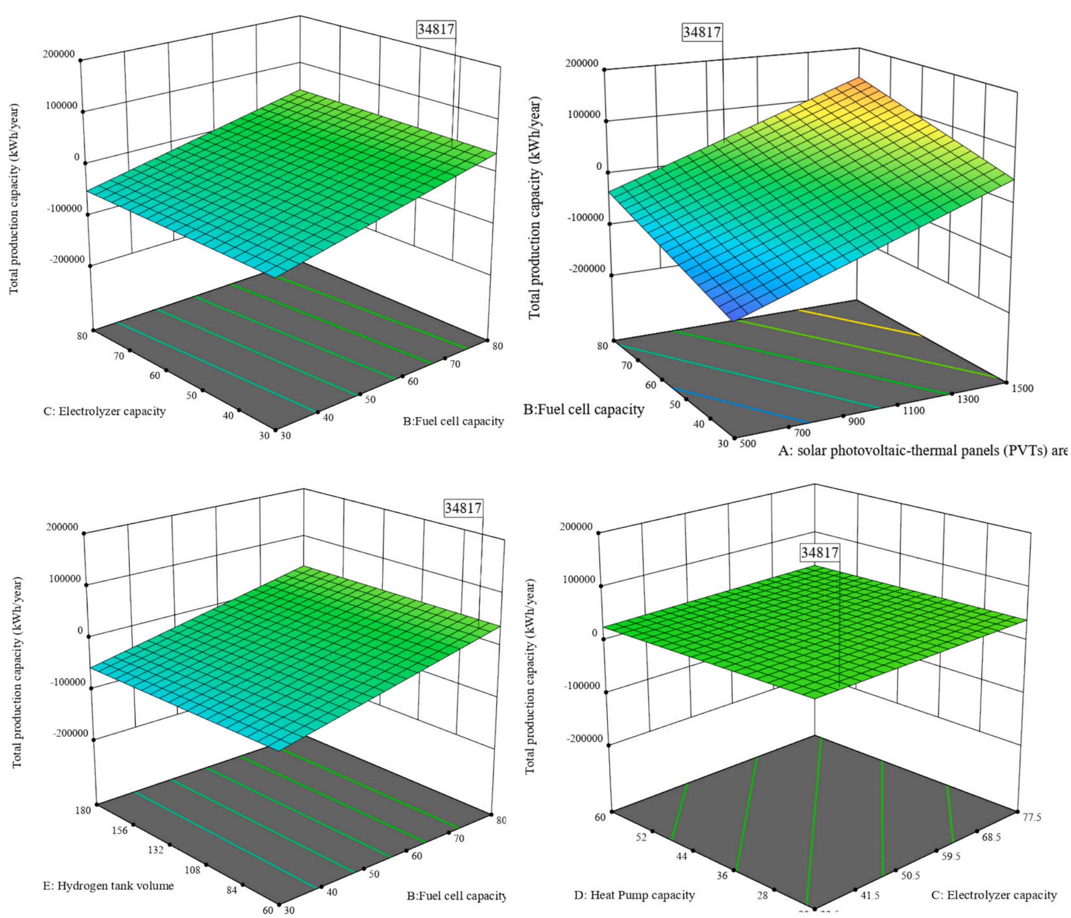


**Fig. 11.** The effect of design parameters on the production capacity of the whole system.

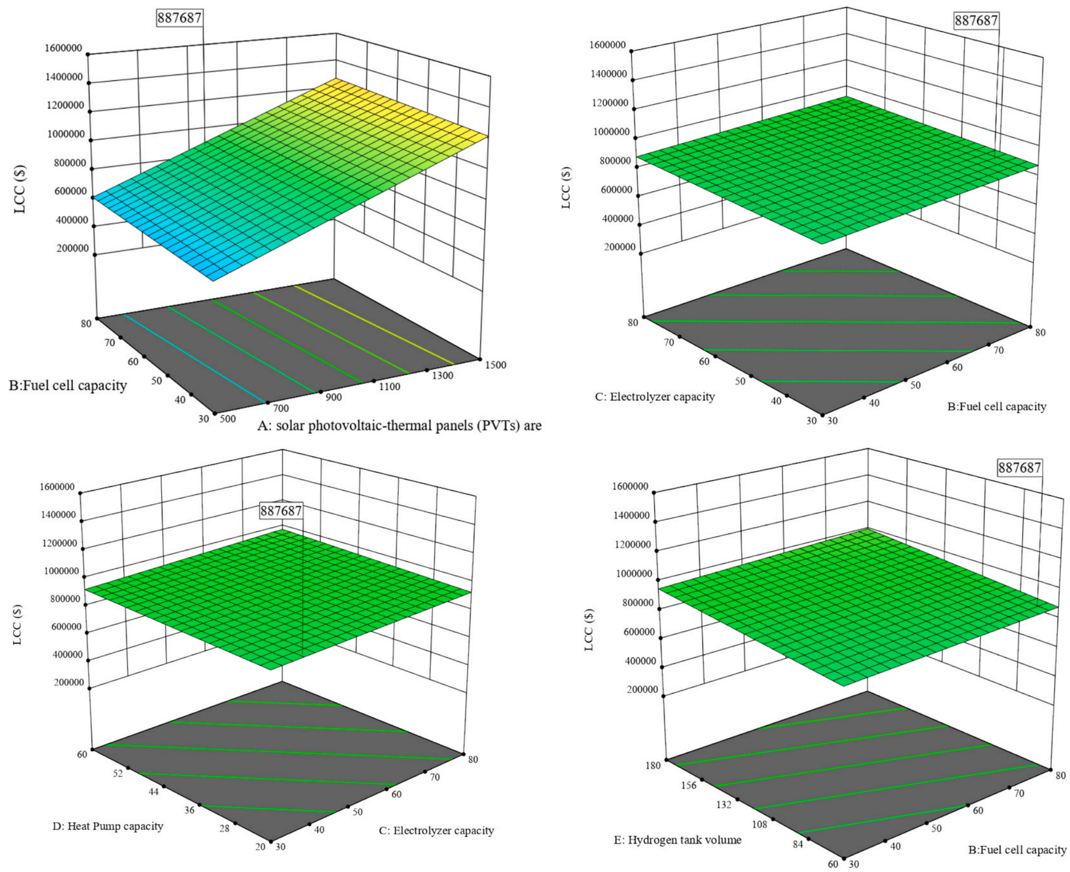


**Fig. 12.** Effect of design parameters on LCC.

by the system can be seen. The red lines show the electricity produced by the solar PVTs for 8760 h, equivalent to 365 days of the year, and the blue line shows the production power of the fuel cell for one year in an hourly manner. The TPC of the system, which is the result of PVTs and fuel cells and is equal to 230761.55 (kWh/year), is purple. The highest amount of production is related to the summer months, and the lowest is related to the winter months.

In Fig. 14, the amount of fresh water produced by the reverse osmosis desalination unit can be seen hourly for one year. Reverse osmosis has allocated 0.04 of the production power of the entire system for the production of freshwater needed by the residents of residential houses.

Fig. 15 shows a comparison with PMV to prove the PPD. PMV is the criterion used to measure thermal comfort, and based on the ASHRAE-55 standard [55], PMV is within the recommended range of −0.5 to 0.5. Fig. 15 proves that the PPD less than 10 % is well-checked and the reason is the PMV number in the margin of the standard proposal.

## 6. Comparison

In this part, the technical and economic performance of the system has been compared with related research, and results such as the amount of energy production of the system and the cost of the system have been presented. The result of comparing the results extracted in this research with the work of others is presented in Table 11.

## 7. Alternative energy storage solutions

Energy storage in solar power plants is one of the key challenges and opportunities in the optimal use of renewable energies. With the increasing share of solar power plants in energy supply, the need to use efficient storage methods to deal with production fluctuations and ensure a stable energy supply has become more important than ever.

Energy storage not only improves the ability of solar power plants to provide base loads; it also plays a significant role in reducing dependence on fossil resources and reducing greenhouse gas emissions. Therefore, understanding new methods of energy storage in solar power plants, such as battery storage, thermal storage and hybrid technologies, is a fundamental step in advancing sustainable energy policies.

Energy storage in solar power plants is a fundamental solution to overcome production fluctuations and increase the reliability of the electricity grid. These technologies can store excess energy produced during peak hours of sunlight and use it during peak hours or hours without sunlight. In addition, energy storage systems in solar power plants help balance electricity supply and demand, paving the way for the development of large-scale renewable energy.

The following is a review of the main methods of energy storage:

- **Energy storage using batteries**

Energy storage with batteries is one of the most widely used methods in solar power plants. This technology is considered a suitable option for various power plants due to its high flexibility and fast implementation.

- These types of batteries are among the most advanced technologies available in energy storage.
- High energy density: Lithium-ion batteries are able to store more energy in a smaller volume.
- Long life: The high charge and discharge cycles of these batteries make them have a long useful life.
- **Lead-acid battery**

Lead-acid batteries are one of the oldest and most reliable energy storage technologies in solar power plants.

Lower cost: The production and maintenance of these batteries is

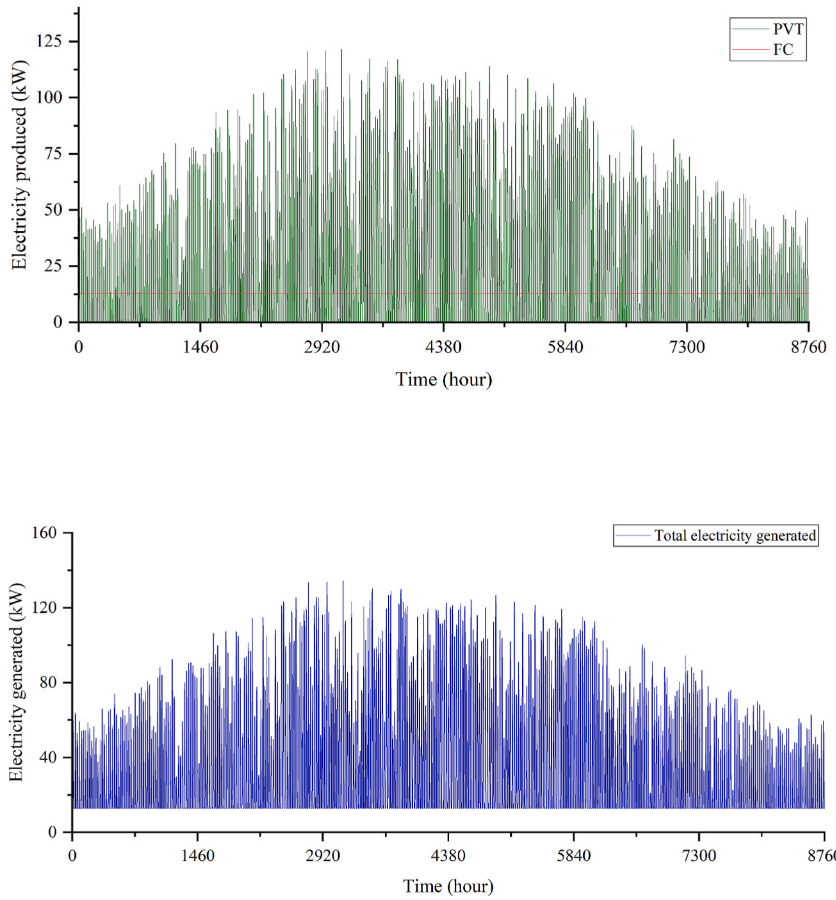


**Fig. 13.** Production power of the whole system.

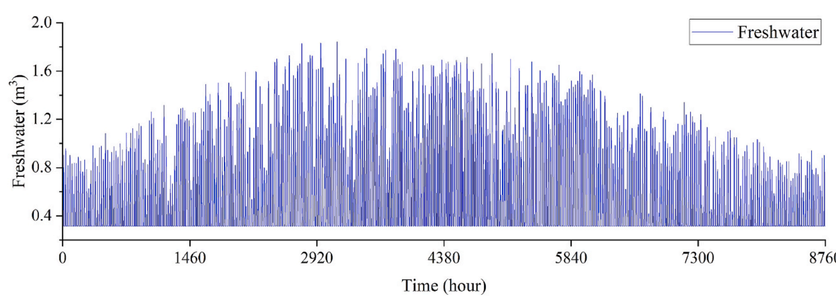


**Fig. 14.** Produced fresh water.

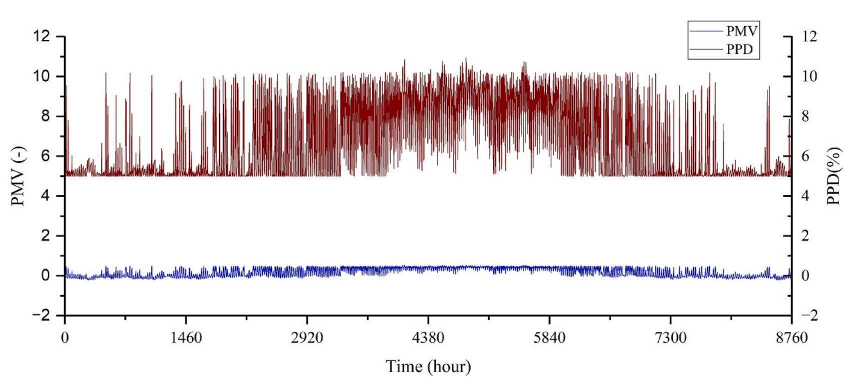


**Fig. 15.** Checking the number of PMV with PPD in one of the apartment units.

**Table 11**
Comparison with the results of the conducted researches.

| Research | Renewable energy | System products | Production capacity | Economic | Recommendation |
|---|---|---|---|---|---|
| **Present work** | Solar energy | Cooling, heating, electricity, fresh water, hot water and hydrogen | 29145.8 kWh/year | 894,228 $ | This system can produce 6 energy simultaneously using solar energy and fuel cells, which help to stabilize the system's production, especially at night and on rainy days. |
| [35] | Solar-wind energy | Hydrogen, desalination, electricity, heating, cooling | 225694.8 kWh/year | 674278.4 $ | The simultaneous use of two high-potential renewable energies has been used to produce 5 energies. However, wind energy cannot be a good complement to the stability of the system at night or on rainy days. |
| [55] | Geothermal Energy | Electricity, heating, cooling | 237364.6 kWh/Year | – | Geothermal energy has been used to produce three types of energy. Given the sustainability of the system, it can also be used to produce fresh water. |
| [56] | Solar energy | Electricity, heating, cooling | 210,000 kWh/Year | 46.6 $/hour | Solar energy has been used to generate three energy consumptions of buildings, but by designing a hybrid renewable system, it is possible to help the system to be stable during the nights and days when the sun is available. Energy storage units can also be used to stabilize the system. |
| [57] | Solar energy | Electricity, cooling, heating and freshwater production | 166,164 kWh/Year | 46 $/h | Energy storage units should be used to stabilize the system. It is also possible to combine two or more renewable energies to stabilize the system when solar energy is not available. |

more economical.

Old technology: These types of batteries are proven and reliable for use in solar power systems.

- **Flow batteries**

Flow batteries are among the newer technologies in energy storage in solar power plants that have significant performance.

High scalability: This type of battery has the ability to increase storage capacity by increasing electrolyte tanks.

Long lifespan: The useful life of flow batteries is much longer than other types.

- **Hydrogen energy storage**

One of the long-term solutions for energy storage in solar power plants is the use of hydrogen as an energy carrier.

Hydrogen production through electrolysis using solar energy

In this method, excess solar energy is used to produce hydrogen from water through the electrolysis process. This technology not only helps in energy storage; but also paves the way for other applications of hydrogen, including fuel for vehicles and industries.

Hydrogen storage and its use in fuel cells

The produced hydrogen is stored in special tanks and, when needed, is used to generate electricity through fuel cells. This process allows for high-efficiency energy recovery.

- **Compressed air energy storage**

Energy storage in the form of compressed air is another new technology used in solar power plants. In this method, the excess energy produced during peak hours of sunlight is used to compress air. The air is stored in large tanks and released when needed to produce energy.

Air storage in underground tanks and energy recovery when needed Compressed air is usually stored in underground tanks or high-pressure tanks and, when discharged, a turbine is used to generate electricity.

- Suitable for large-scale energy storage
- Reducing dependence on the electricity grid
- **Thermal energy storage**

Thermal storage is one of the most efficient and productive methods in solar thermal power plants.

In this method, solar energy is used to heat special salts and the generated heat is stored in insulated tanks.

The stored heat is used to produce steam and drive the power plant's turbines. This method is especially suitable for concentrated solar power plants (CSP(.

Common methods include lithium-ion batteries, thermal storage systems, and compressed air energy storage.

Lithium-ion batteries are one of the most widely used methods, enabling small- to medium-scale energy storage. With their high efficiency and long life, these batteries are a suitable option for energy storage. However, their high initial cost and the need for advanced infrastructure are their main challenges.

In contrast, thermal storage systems, which are used especially in concentrated solar power (CSP) plants, store energy in the form of heat. This method performs better in sunny, warm conditions and is less expensive than batteries, but offers less flexibility.

Compressed air energy storage is a relatively new method. In this system, air is compressed and stored in tanks to release energy when needed. This method is considered an innovative solution due to its high stability and good efficiency at large scales. However, the high cost of infrastructure is one of its main challenges.

## 8. Conclusion

In recent years, due to global warming and climate change, the use of renewable energy is increasing, and many studies have been conducted on renewable energy integration in various sectors, especially in the building sector. With the ambition of contributing to the recent research efforts on sustainable energy building systems, this study proposes a hybrid solar-based multi-generation energy system that can supply almost all the energy/potable water demand of large buildings in arid areas at low cost and high overall efficiency. In particular, the study pursued the three main objectives of:

- reducing the cost of renewable-based energy systems in a building, which has been a deterrent factor for the broad implementation of such systems, via optimized system design and operation strategy as well as two-way connection to the electricity grid for occasional profits,
- stability in the production of the system (electricity, hot water, cooling, and heating) around the clock, which is a major challenge of solar energy systems via storage tanks and the electrolyzer/fuel cell setup,
- self-sufficiency of the system for all the energy needs of the building for the sake of decentralizing goals and possible contribution to the local grid frequency control during the peak consumption periods.

The goal of this study is that the energy system of the building is at least one unit of net zero energy/emissions and even, if possible, one unit of positive energy. Considering the scale of the components used here, it can be argued that the proposed energy system was mainly designed for large buildings (at least a few hundred units/apartments such as social apartment blocks, commercial buildings, service buildings such as hospitals, etc.). It is suitable for areas where access to drinking water is difficult.

For making the analyses and assessments meaningful, a large building complex consisting of 160 apartments in San Diego City, the USA was selected as the case study. All the real data for a whole year was used for the simulations and analyses. For this case and with the main objectives stated above, scenario assessments resulted in a system consisting of solar PVTs coupled with a heat pump, an electrolyzer/fuel cell setup, a reverse osmosis unit, and storage tanks as the winning solution. A multi-objective optimization algorithm was used to ensure the system was designed, sized, and operated optimally. TPC, LCC, and PPD of the building residents are considered as the objective functions, with the five decision variables of area of solar PVTs, fuel cell capacity, electrolysis capacity, heat pump capacity, and hydrogen tank volume. RSM is the method used to find the most optimal points on the multi-dimensional Pareto. The results showed that the designed system could provide all the electricity demand of the 160-unit case study, i.e., 200 MWh/year, and produce 29145.8 kWh/year of additional power for grind contribution and added profit. Also, the system can provide all the heating and cooling needs of the studied buildings, domestic hot water, and drinking water. This way the system results in an LCC of $894,228 and a PPD of 6.8 %. The standard recommended range of the predicted percentage dissatisfaction index (PPD) is between −50 % and + 50 %, and this parameter's ideal value is 0. So, the closer the percentage of PPD is to 0, the more favorable it is for the building.

Other results are as follows:

- Changing the area of solar PVTs and the capacity of the fuel cell increases the production capacity of the entire system.
- Increasing the volume of the tank has a very small and insignificant effect on the production capacity of the entire system.
- The capacity of the fuel cell positively increases the power generation of the system.
- Increasing the heat pump capacity alone has little effect on the total production capacity.
- Increasing the capacity of electrolysis and heat pumps has little effect on LCC.
- Increasing the volume of the hydrogen storage tank in LCC and increasing it has a positive effect.
- The analysis of this system showed that to reach the maximum production, the area of solar PVTs should reach 1000 square meters and the fuel cell capacity should reach 80 kWh per hour to reach the maximum production capacity of 34,817 kWh/year.

**The following method can be used to improve system performance:**

A hybrid renewable energy system is a combination of a set of renewable energy technologies and sources that are used simultaneously or intermittently to produce and supply energy. In this type of system, various types of renewable energy sources, such as solar, wind, geothermal, etc., are combined together and no non-renewable or fossil resources are used.

Hybrid solar energy systems usually include a combination of solar energy and other sources, such as wind, bioenergy, or geothermal energy. This combination helps increase the reliability of the system and allows for energy supply at times when one source alone is not sufficient. In general, using multiple energy sources instead of relying on one type of energy increases the energy security of communities.

By using hybrid systems, maximum efficiency of energy sources can be achieved. For example, on sunny days, using photovoltaic systems, solar electricity is generated, and on nights or cloudy days, using other sources helps to stabilize the electricity and energy needed.

As one of the most advanced and efficient methods of generating renewable energy, the solar-wind hybrid system offers a combination of two clean and sustainable energy sources: solar energy and wind energy. These systems are known as an effective solution to meet energy needs in different regions due to their unique characteristics.

In fact, this hybrid energy system refers to the integration of solar panels and wind turbines that are used simultaneously or alternately to generate electricity. Given that these two sources are active at different times, this combination can help to provide a stable energy supply. These systems are designed to exploit the strengths of both sources, thereby increasing the reliability and efficiency of energy production.

## 9. Suggestions

In this section, suggestions are given to the researchers to complete the present project, because renewable science is a new science, and various research is needed to complete its information.

- The renewable sources of wind and sun are the main sources of energy that have the potential to supply power on a large scale. However, when these sources are used independently, their reliability is low due to the unpredictable nature of climate change. Due to the evolutionary nature of these two energy sources, when they are combined, not only does the reliability of the system increase but also the economic cost decreases.
- The use of multi-objective optimization algorithms such as particle swarm algorithm, genetic algorithm, and combination with neural network can also increase the accuracy of the optimization solution.
- It is possible to use abandoned oil wells as geothermal power plants and combine them with the proposed system. In this method, some of the initial costs are solved and the problems related to blocking oil wells are eliminated.
- The main challenge of solar energy is its absence at night. Different methods have been proposed for solar energy storage, each of which has its advantages and disadvantages. Among them, we can mention sensible heat transfer, latent heat, and the chemical method, which has the highest energy storage capacity.
- This system can be used for installation in solar and high-availability areas.
- By combining the system with energy storage units such as CAES, the system reliability can be helped.
- The simultaneous combination of solar and ocean thermal energy is an attractive idea for coastal areas, which can help increase regional income in addition to increasing the stability of solar systems.
- By using an absorption chiller, it can help increase cooling production for hot areas.

**AI-Assisted Technologies in the Writing Process:**

In the course of preparing this manuscript, the authors employed ChatGPT to enhance the readability of certain sections and to improve the grammatical accuracy of select sentences. Following the use of ChatGPT, the authors meticulously reviewed and edited the content as necessary, thereby assuming full responsibility for the final published article. It is important to emphasize that ChatGPT's role was strictly to assist in the refinement of the text and language, rather than to supplant any essential tasks performed by the authors.

## CRediT authorship contribution statement

**Saleh Mobayen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ehsanolah Assareh:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Ali Dezhdar:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Siamak Hoseinzadeh:** Writing – review &

editing, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Davide Astiaso Garcia:** Writing – review & editing, Visualization, Supervision, Methodology.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## References


[1] International Energy Agency (IEA). (2020). "Global Energy Review 2020.".
[2] United Nations Environment Programme (UNEP). (2018). "Global Status Report: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector.".
[3] Yi X, Lu T, Li Y, Ai Q, Hao R. Collaborative planning of multi-energy systems integrating complete hydrogen energy chain. Renew Sustain Energy Rev 2025;210:115147.
[4] U.S. Energy Information Administration (EIA). (2021). "Annual Energy Outlook 2021.".
[5] World Resources Institute. (2019). "Building a Sustainable Future: The Role of Buildings in Climate Change.".
[6] GhaffarianHoseini A, et al. Sustainable energy strategies for buildings: A review. Renew Sustain Energy Rev 2017;68:153–64.
[7] Li N, Dong J, Liu L, Li H, Yan J. A novel EMD and causal convolutional network integrated with Transformer for ultra short-term wind power forecasting. Int J Electr Power Energy Syst 2023;154:109470.
[8] Bhandari K, et al. Advancements in solar energy systems for building applications: a review. Sol Energy 2020;207:180–97.
[9] Wang Q, et al. Optimization of solar-assisted GWHP system based on the Trnsys model in cold regions. Renew Energy 2022;196:1406–17.
[10] Alshibil AM, Farkas I, Víg P. Multi-aspect approach of electrical and thermal performance evaluation for hybrid photovoltaic/thermal solar collector using TRNSYS tool. International Journal of Thermofluids 2022;16:100222.
[11] Rashad M, et al. Analysis of energy demand in a residential building using TRNSYS. Energy 2022;254:124357.
[12] Bisengimana E, et al. Numerical investigation of PVT coverage on an integrated building-solar-heat pump system: technical and economic study. Sol Energy 2023;249:507–20.
[13] Liang R, et al. Performance modeling and analysis of a PVT-HP system with the roll-bond plate as the evaporator during winter conditions. Appl Therm Eng 2023;224:120102.
[14] Khanmohammdi S, Musharavati F, Sheykhmohammadi M. Energy and exergy examinations of a PVT based hybrid system for power, heating and potable water production: transient modeling. Renew Energy 2022;195:540–53.
[15] Mansir IB, et al. Comparative transient simulation of a renewable energy system with hydrogen and battery energy storage for residential applications. Int J Hydrogen Energy 2022;47(62):26198–208.
[16] Açıkkalp E, et al. Extended exergy analysis of a photovoltaic-thermal (PVT) module based desiccant air cooling system for buildings. Appl Energy 2022;323:119581.
[17] Esmaeilzadeh A, et al. How combination of control methods and renewable energies leads a large commercial building to a zero-emission zone–A case study in US. Energy 2023;263:125944.
[18] Ebrahimi-Moghadam A, Farzaneh-Gord M. A sustainable optimal biomass waste-driven CCHP system to boost the nearly zero energy building concept. Energ Conver Manage 2023;277:116669.
[19] Cao J, et al. Advances in coupled use of renewable energy sources for performance enhancement of vapour compression heat pump: A systematic review of applications to buildings. Appl Energy 2023;332:120571.
[20] Acar C, et al. Performance analysis of a stand-alone integrated solar hydrogen energy system for zero energy buildings. Int J Hydrogen Energy 2023;48(5):1664–84.
[21] Bosu I, et al. Applied single and hybrid solar energy techniques for building energy consumption and thermal comfort: a comprehensive review. Sol Energy 2023;259:188–228.
[22] Fadnes FS, Olsen E, Assadi M. Holistic management of a smart city thermal energy plant with sewage heat pumps, solar heating, and grey water recycling. Front Energy Res 2023;11:1078603. https://doi.org/10.3389/fenrg.2023.1078603.
[23] Souayfane F, et al. On the behavior of renewable energy systems in buildings of three Saudi cities: Winter variabilities and extremes are critical; 2023.
[24] Xu C, et al. Quantile regression based probabilistic forecasting of renewable energy generation and building electrical load: a state of the art review. Journal of Building Engineering 2023;79:107772.
[25] Abu-Hamdeh NH, et al. Study of the flat plate solar collector's efficiency for sustainable and renewable energy management in a building by a phase change material: containing paraffin-wax/Graphene and Paraffin-wax/graphene oxide carbon-based fluids. Journal of Building Engineering 2022;57:104804.
[26] Luo J, et al. Comprehensive techno-economic performance assessment of PV-building-EV integrated energy system concerning V2B impacts on both building energy consumers and EV owners. Journal of Building Engineering 2024;87:109075.
[27] Mansouri A, et al. Novel adaptive observer for HVDC transmission line: A new power management approach for renewable energy sources involving Vienna rectifier. IFAC J Syst Control 2024;27:100255.
[28] Mansouri A, et al. "Wind energy based conversion topologies and maximum power point tracking: A comprehensive review and analysis." e-Prime - Advances in Electrical Engineering. Electronics and Energy 2023;6:100351.
[29] Almojil SF, et al. Using solar energy and phase change materials to supply energy to a building to reduce environmental pollution. Journal of Building Engineering 2022;61:105180.
[30] Chen P, et al. Performance of a solar ground source heat pump used for energy supply of a separated building. Geothermics 2022;105:102524.
[31] Yan R, et al. Process integration and thermodynamic analysis of a multi-generation system including solar-assisted biomass gasification and chemical looping ammonia generation. Energ Conver Manage 2024;306:118263.
[32] Bao T, et al. Research on probabilistic characteristics and wind pressure extreme values of adjustable-tilt solar photovoltaic systems panels under full-direction wind. J Wind Eng Ind Aerodyn 2024;254:105913.
[33] Yang M, Che R, Yu X, Su X. Dual NWP wind speed correction based on trend fusion and fluctuation clustering and its application in short-term wind power prediction. Energy 2024;302:131802.
[34] Dezhdar A, et al. Transient optimization of a new solar-wind multi-generation system for hydrogen production, desalination, clean electricity, heating, cooling, and energy storage using TRNSYS. Renewable Energy 2023;208:512–37.
[35] Sommerfeldt, N. and P. Ollas. Reverse engineering prototype solar PV/thermal collector properties from empirical data for use in TRNSYS type 560. in ISES Solar World Congress and IEA Solar Heating and Cooling Conference 2017, Abu Dhabi, UAE, October 29-November 2, 2017. 2017.
[36] Klein, S., et al., TRNSYS Reference Manual: Mathematical Reference. 2006.
[37] Hoseinzadeh S, Yargholi R, Hamed Kariman P, Heyns S. Exergoeconomic analysis and optimization of reverse osmosis desalination integrated with geothermal energy. Environ Prog Sustain Energy 2020;39(5):e13405.
[38] Rashidi H, Khorshidi J. Exergoeconomic analysis and optimization of a solar based multigeneration system using multiobjective differential evolution algorithm. J Clean Prod 2018;170:978–90.
[39] Naseri A, et al. Exergy analysis of a hydrogen and water production process by a solar-driven transcritical CO2 power cycle with Stirling engine. J Clean Prod 2017;158:165–81.
[40] Smythe, W.E., History of San Diego, 1542-1908. 1908: Jazzybee Verlag.
[41] Park S-H, Jang Y-S, Kim E-J. Multi-objective optimization for sizing multi-source renewable energy systems in the community center of a residential apartment complex. Energ Conver Manage 2021;244:114446.
[42] Rayegan S, et al. Dynamic simulation and multi-objective optimization of a solar-assisted desiccant cooling system integrated with ground source renewable energy. Appl Therm Eng 2020;173:115210.
[43] Saedpanah E, Pasdarshahri H. Performance assessment of hybrid desiccant air conditioning systems: a dynamic approach towards achieving optimum 3E solution across the lifespan. Energy 2021;234:121151.
[44] Heidari A, Roshandel R, Vakiloroaya V. An innovative solar assisted desiccant-based evaporative cooling system for co-production of water and cooling in hot and humid climates. Energ Conver Manage 2019;185:396–409.
[45] Fong K, Lee C. Solar desiccant cooling system for hot and humid region–A new perspective and investigation. Sol Energy 2020;195:677–84.
[46] Sohani A, Sayyaadi H. Thermal comfort based resources consumption and economic analysis of a two-stage direct-indirect evaporative cooler with diverse water to electricity tariff conditions. Energ Conver Manage 2018;172:248–64.
[47] Saleem MS, et al. Design and optimization of hybrid solar-hydrogen generation system using TRNSYS. Int J Hydrogen Energy 2020;45(32):15814–30.
[48] Sommerfeldt Nelson, Hatef Madani. In-depth techno-economic analysis of PV/Thermal plus ground source heat pump systems for multi-family houses in a heating dominated climate. Solar Energy 2019;190:44–62.
[49] Saedpanah, E., et al., Life cycle comparison of potential scenarios to achieve the foremost performance for an off-grid photovoltaic electrification system. Journal of Cleaner Production.
[50] Dongellini M, Morini GL. On-off cycling losses of reversible air-to-water heat pump systems as a function of the unit power modulation capacity. Energ Conver Manage 2019;196:966–78.
[51] Gelis K, Akyurek EF. Entropy generation of different panel radiator types: Design of experiments using response surface methodology (RSM). Journal of Building Engineering 2021;41:102369.
[52] Kazemian M, Nassab SG, Javaran EJ. Comparative techno-economic investigation of CCHP combined by GSHP based on response surface methodology. Therm Sci Eng Prog 2022;34:101386.
[53] Kanyarusoke K, Gryzagoridis J, Oliver G. Validation of TRNSYS modelling for a fixed slope photovoltaic panel. Turk J Electr Eng Comput Sci 2016;24(6):4763–72.
[54] Nafey AS, Sharaf MA. Combined solar organic Rankine cycle with reverse osmosis desalination process: energy, exergy, and cost evaluations. Renew Energy 2010;35:2571–80.
[55] Assareh E, Keykhah A, Hoseinzadeh S, Astiaso Garcia D. Application of PCM in a zero-energy building and using a CCHP system based on geothermal energy in

canada and the UAE. Buildings 2024;14:477. https://doi.org/10.3390/buildings14020477.
[56] Assareh E, et al. A proposal on a co-generation system accompanied with phase change material to supply energy demand of a hospital to make it a zero energy building (ZEB). Energ Buildings 2024;318:114478.
[57] Assareh E, et al. Zero energy building optimization for a residential complex with a new optimized cogeneration system for electricity, cooling, heating and freshwater production. Appl Therm Eng 2024;244:122527.