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Solar-Powered Smart Buildings: Integrated Energy Management Solution for IoT-Enabled Sustainability

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Abstract: The increasing demand for energy-efficient and sustainable solutions in the building sector has driven the need for innovative approaches that integrate renewable energy sources and advanced control systems. This paper presents an integrated energy management solution for solar-powered smart buildings, combining a multifaceted physical system with advanced IoT- and cloud-based control systems. The physical system includes a heat pump, photovoltaics, solar thermal panels, and an innovative low-enthalpy radiant wall and ceiling, providing self-sufficient heating and cooling. The control system makes use of advanced IoT and communication engineering technologies, using Modbus, HTTP, and MQTT protocols for seamless interconnectivity, monitoring, and remote management. The successful implementation of this solution in an average-sized model house in Paris and a deep energy retrofit of a semidetached single-family house in Oviedo, northern Spain, demonstrates increased energy efficiency, improved thermal comfort, and reduced environmental impact compared with conventional alternatives. This study illustrates the potential of integrating solar energy, IoT, and communication technologies into smart buildings, contributing to the global effort to reduce the environmental impact of the building sector.

Keywords: integrated energy control; IoT-enabled energy management; real-time monitoring and remote management; positive energy buildings; smart buildings; home energy management systems (HEMS)

1. Introduction

The global climate change crisis has precipitated the urgent need for innovative, sustainable solutions to reduce the environmental impact of heating and cooling in buildings. The building sector is a significant contributor to greenhouse gas emissions, and the development of systems that harness renewable energy sources for these functions has the potential to considerably mitigate this impact [1].

Smart buildings, enabled by the Internet of Things (IoT), have revolutionized energy management strategies. The integration of IoT technologies in smart buildings enables the real-time monitoring, control, and optimization of energy consumption and generation. Recent advances and research in energy management through IoT in smart buildings focus on the following aspects:

- Real-Time Energy Monitoring and Analytics: IoT-based energy monitoring systems collect and analyze energy consumption data in real time. Smart meters and sensors installed in various building systems provide granular data on energy consumption. Advanced analytics techniques, such as machine learning and data mining, process these data to identify patterns, anomalies, and opportunities for energy optimization [2–4].

- Solar Energy Generation: While crystalline silicon panels have been the mainstay, emerging photovoltaic technologies like perovskites and organic materials are gaining prominence for their adaptability and efficiency. Recent advancements include benzothiophene-based nonfullerene acceptors for improved indoor OPV efficiency and all-polymer solar cells with enhanced efficiency and stability for outdoor use [5,6]. Complementing these are hybrid systems that combine photovoltaic panels with solar thermal panels, offering a robust solution that maximizes energy capture and efficiency. These hybrid panels not only generate electricity but also harness solar thermal energy, making them particularly effective in comprehensive energy solutions. Additionally, IoT enables real-time monitoring, data collection, and analytics in solar power systems. This connectivity allows for the efficient tracking of solar panel performance, enabling proactive maintenance and optimization. Moreover, IoT facilitates smart grid integration, enabling seamless communication between solar installations and the broader energy infrastructure [7,8].
- Demand Response and Load Management: IoT enables demand response strategies and load management techniques in smart buildings. Real-time energy monitoring systems, combined with bidirectional communication, allow buildings to adjust their energy consumption based on demand signals and pricing fluctuations. This enables the peak load management, load shifting, and integration of renewable energy sources [9–11].
- Occupancy-Based Energy Optimization: IoT-based occupancy sensing technologies play a critical role in energy optimization. Occupancy sensors, motion detectors, and location-based services track the presence and movement of occupants within the building. These data are used to dynamically control lighting, heating, ventilation, and air conditioning (HVAC) systems, ensuring that energy is only used when and where it is needed [12,13] .
- Intelligent Lighting and HVAC Systems: IoT enables intelligent lighting and HVAC systems that adapt to user preferences and environmental conditions. Connected lighting systems utilize occupancy sensors, daylight harvesting, and personalized controls to optimize lighting levels and reduce energy waste. Smart HVAC systems integrate occupancy data, weather forecasts, and user preferences to dynamically adjust temperature, ventilation, and airflow, improving energy efficiency and occupant comfort [14–16].
- Energy Management Platforms and Integration: IoT-based energy management platforms provide centralized control and monitoring of energy systems in smart buildings. These platforms integrate data from various sensors and devices, allowing building managers to visualize energy consumption, set energy-saving targets, and remotely control equipment. Integration with utility systems enables demand-side management and energy optimization at a broader scale [17–20].

This paper introduces an integrated energy management solution that seamlessly combines a physical system, consisting of a heat pump, photovoltaics, solar thermal panels, and an innovative low-enthalpy radiant wall and ceiling, with a state-of-the-art IoT and cloud-based control system.

IoT-based energy monitoring systems play a crucial role in capturing real-time energy consumption data in single-family homes. Smart meters, coupled with IoT connectivity, enable homeowners to monitor their energy usage remotely and gain insights into consumption patterns. Advanced analytics tools can process these data to provide personalized recommendations for energy conservation.

Microgeneration systems combined with energy storage solutions enable homeowners to generate and store their energy, reducing dependence on the grid and promoting self-sufficiency. The physical system constituting the integrated energy management solution is multifaceted. A heat pump serves as the core component, responsible for transferring heat from the ambient environment into the building during heating mode and extracting heat from the building to the environment during cooling mode. Supplementing the heat pump are photovoltaics, which convert solar radiation into electricity, and solar thermal panels, which capture solar radiation for water heating applications. Additionally, an innovative low-enthalpy radiant wall and ceiling system is incorporated to provide a more uniform and comfortable temperature distribution within the building, optimizing thermal comfort.

The control system, a crucial aspect of the integrated energy management solution, employs advanced IoT and cloud technologies to facilitate the real-time monitoring and management of the system's various elements. Leveraging cutting-edge communication engineering, the system utilizes Modbus and HTTP protocols for intercomponent communication, while the MQTT protocol is employed for efficient communication with the cloud. A database hosted on Amazon Web Services (AWS) enables data storage, web visualization, and remote control of the system, empowering users to monitor and manage the system from any location. The integration of IoT and communication engineering technologies not only enhances the overall functionality of the system but also contributes significantly to the optimization of energy consumption and management.

The effectiveness of the integrated energy management solution is demonstrated through its successful implementation in an average-sized house model in Paris, France, and a deep energy retrofit of a semidetached single-family house in Oviedo, northern Spain. The system has demonstrated its ability to be self-sufficient, providing all required heating and cooling using only the solar energy harnessed by the system's components. Furthermore, the solution has proven to be more efficient than traditional alternative energy solutions, offering improved thermal comfort through stable and constant temperature control. The successful deployment of this system in real-world residential settings illustrates the potential for widespread adoption of solar-powered smart buildings as a key component in the global effort to mitigate the environmental impact of the building sector.

As climate change continues to pose significant challenges, the need for innovative and sustainable energy management systems in buildings becomes increasingly crucial. The integrated energy management solution presented in this paper represents a significant advancement in the pursuit of IoT-enabled sustainability, utilizing solar energy to provide self-sufficient heating and cooling in buildings. The seamless combination of a physical system with state-of-the-art IoT- and cloud-based control systems, supported by advanced communication engineering, enables real-time monitoring and management, ultimately leading to enhanced energy efficiency and improved thermal comfort. The successful implementation of this system in diverse residential settings illustrates the potential for widespread adoption of solar-powered smart buildings as a key component in the global effort to mitigate the environmental impact of the building sector.

2. Materials and Methods

2.1. Physical System

This study focuses on an integrated energy management solution that synergistically employs various technologies to address the energy needs of a building, encompassing heating, cooling, domestic hot water (DHW), and electricity. The system's design maximizes energy efficiency and sustainability by harnessing solar energy and effectively managing, storing, and distributing the captured energy based on demand. The solution's effectiveness relies on the seamless interaction between the five main components shown in Figure 1, each fulfilling a specific function within the system:

- Hybrid Solar Panels: These panels are crucial for harnessing solar energy and converting it into two usable forms—electricity and heat [21]. The hybrid solar panels comprise a photovoltaic (PV) layer for generating electricity and a thermal layer for capturing heat. The PV layer absorbs sunlight and converts it into electricity, which can be used directly or stored in the electrical battery system. Meanwhile, the thermal layer absorbs residual heat from sunlight not utilized by the PV layer, which is then employed for heating and DHW production through the water–water heat pump.
- Water–Water Heat Pump: This heat pump plays a vital role in providing heating, cooling, and DHW for a building [22]. It is designed to leverage the thermal energy

captured by the hybrid solar panels when solar radiation is available or to utilize an external air–water heat exchanger unit when solar radiation is insufficient or during cooling operations. The heat pump's dual function allows it to transfer heat between two water circuits, optimizing its energy efficiency and minimizing the consumption of external energy sources.

- Heat Tank: The heat tank serves as a storage unit for DHW and thermal energy, enabling the system to balance energy supply and demand more effectively. It stores DHW and the excess thermal energy produced by the hybrid solar panels when demand is low, which can be released later to provide heating during periods of limited electrical capacity, such as nighttime or overcast days. This storage capability enhances the system's overall efficiency and resilience, ensuring that heating and DHW needs are consistently met despite fluctuating energy availability.
- Electrical Battery System with Inverters: The electrical battery system functions as an energy storage and management hub for the electricity generated by the hybrid solar panels. The battery stores excess electricity produced by the PV layer, which can be utilized during periods of higher demand or when solar radiation is limited. The system includes a photovoltaic inverter responsible for converting the direct current (DC) electricity generated by the PV layer into alternating current (AC) electricity suitable for use within the building. Additionally, the system incorporates a battery inverter to manage the charging and discharging processes of the battery and to convert the stored DC electricity back into AC electricity when needed.
- Additional Sensors for Data Acquisition: The system incorporates a range of sensors to collect key data for optimizing efficiency and comfort. These include internal sensors in inverters and heat pumps that provide critical information on energy generation, consumption, and operating parameters, such as temperatures and pressures for correct system management. In addition, the system uses a range of Modbus and KNX protocol sensors, including temperature sensors to monitor water temperatures across the different circuits, and indoor and outdoor temperature and humidity sensors to ensure optimal environmental comfort.

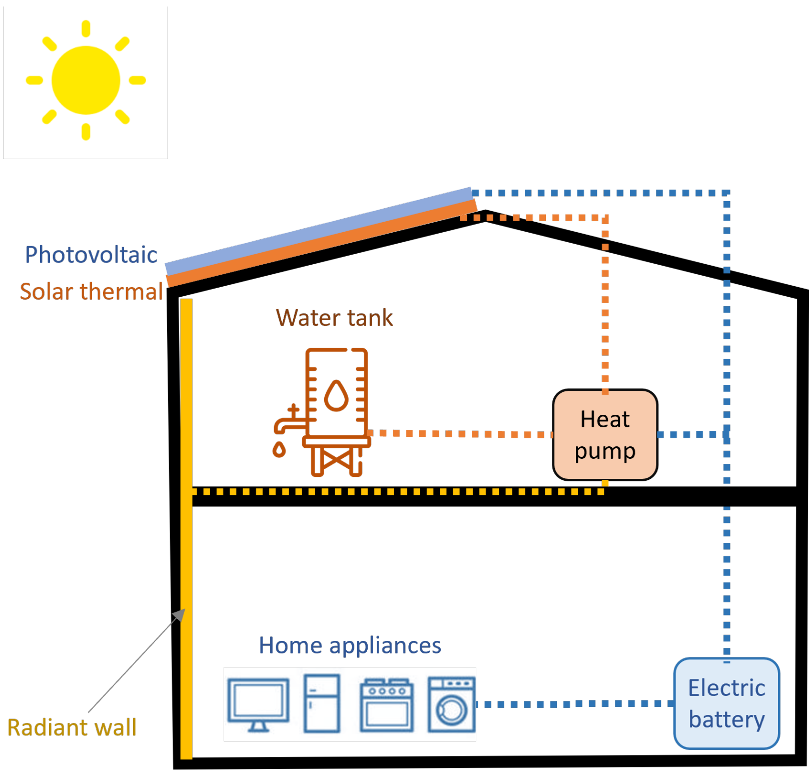

Figure 1. Self-sufficient energy system.

2.2. Control Devices and Communications

The devices involved in the physical system (power generation, heating, etc.), must allow some type of communication, in some cases only transmitting data relevant to the installation, and in others, allowing the reception of control variables. The problem is that there is no de facto standard for this task but, on the contrary, there are different communication technologies available on the market that are adopted at the discretion of the manufacturers. Typical communication technologies found in these apparatuses are listed as follows:

- Modbus (RTU or TCP);
- Ethernet/Wi-Fi;
- KNX.

2.2.1. Modbus

Modbus is a communication protocol widely used in industrial automation and control systems to establish communication between electronic devices such as programmable logic controllers (PLCs), human–machine interfaces (HMIs), and other devices. The protocol was developed by Modicon (now Schneider Electric) in 1979, and it has become the de facto standard in the industry due to its simplicity, versatility, and robustness.

Modbus is a client–server protocol where a master device initiates communication with one or more slave devices to read or write data. It uses a request/response mechanism where the master sends a message to a slave requesting data, and the slave responds with the requested information. The protocol supports different data formats, including integer, floating-point, and character, and it can operate over different communication media such as serial, Ethernet, or other industrial networks.

There are two main types of Modbus protocols: Modbus RTU and Modbus TCP. Modbus RTU is a serial protocol that uses binary encoding to transmit data over RS-232 or RS-485 communication lines. It supports a maximum of 247 devices on a single network and has a maximum data rate of 115.2 kbps. Modbus TCP is an Ethernet-based protocol that uses a client–server architecture and supports a maximum of 254 devices on a network. It uses the same Modbus function codes as Modbus RTU and can transmit data at a maximum rate of 100 Mbps.

Modbus protocol is widely used in various industrial applications, including manufacturing, energy management, building automation, and transportation. It is a well-documented and widely supported protocol that can be easily implemented in new devices or integrated with existing systems.

2.2.2. Ethernet/Wi-Fi

Ethernet is a family of computer networking technologies commonly used in local area networks (LANs). It was first developed in the 1970s by Robert Metcalfe at Xerox Corporation. Today, Ethernet is the most widely used LAN technology, and it has evolved to support data rates from 10 Mbps to 100 Gbps.

Wi-Fi is a wireless networking technology that allows electronic devices to connect to the Internet or exchange data wirelessly using radio waves. Wi-Fi is an abbreviation for Wireless Fidelity and is based on the IEEE 802.11 standard [23].

Wi-Fi networks operate on different frequency bands, including 2.4 GHz and 5 GHz, and use different security protocols, such as WEP, WPA, and WPA2, to protect data transmitted over the network. Wi-Fi technology has evolved over the years, and newer versions of Wi-Fi, such as 802.11ac and 802.11ax, offer faster speeds and greater range than older versions.

Wi-Fi is now a ubiquitous technology and is found in homes, offices, public spaces, and even on airplanes. It has revolutionized the way people access the Internet and communicate with each other.

2.2.3. KNX

KNX (Konnex) is a standardized communication protocol for home and building automation. It is an open protocol that allows devices from different manufacturers to communicate with each other. KNX was first introduced in 1990 and is managed by the KNX Association, which is a nonprofit organization.

The KNX protocol is designed to be reliable and secure, and it can be used for a wide range of applications, including lighting control, heating and cooling control, security systems, and audio–visual systems. KNX supports both wired and wireless communication, and it is designed to be scalable, allowing systems to be easily expanded as needed.

KNX devices communicate using a common language, which is based on the ISO/IEC 14543-3 standard [24]. This language defines a set of data types and communication protocols that allow devices to exchange information with each other. KNX devices can also be programmed using a variety of software tools, which allows installers and users to customize the system to meet their specific needs.

One of the key benefits of KNX is its interoperability. Since KNX is an open standard, devices from different manufacturers can communicate with each other, which allows users to choose the best products for their needs without being locked into a single vendor. Additionally, KNX is designed to be future-proof, which means that new devices can be added to the system as technology advances without requiring a complete overhaul of the existing system.

One of the great advantages of KNX is that it is reliable, flexible, and completely standardized so that all compatible devices have to communicate using the data types defined in the protocol. This is radically opposed to what happens with Modbus-compatible devices, as in this case there is no standardization to ensure that all devices communicate using standard data types. At this point, it should be added that the installations shown in Section 3 do not incorporate devices with this technology, but in projects that are currently in the implementation phase, they are actively being used.

2.3. Control System Integration

A fundamental aspect common to the control systems of these types of installations is the satisfactory integration of the different agents involved in this control. This setup could be seen as a typical home automation system, in which different technologies coexist to achieve the desired objective (air conditioning, lighting, blinds, multimedia, etc.). In this case, it is a matter of integrating devices of different natures in order to obtain the desired comfort and energy efficiency, with the subsequent energy savings and reduction in emissions.

Consequently, a way to successfully combine heterogeneous devices that use different communication technologies is required. As opposed to the case of a typical home automation system in which standard cabling and protocols are used (KNX, Zigbee, Matter, etc.), the equipment involved in photovoltaic generation, heating, and/or A/C might use a standard protocol; otherwise, an additional interface is required.

To overcome this problem, a powerful and cost-effective flexible solution is to use an SoC (System-On-Chip) device, such as the widely known Raspberry Pi 4 or its industrial counterpart. This type of solution allows us, through a bespoke integration using a general-purpose programming language, to implement the different communication protocols required, becoming the nerve center of the installation [25]. Additionally, and with the help of a cloud computing service provider, it is possible to establish a two-way interaction with the system, effectively allowing us to retrieve and store the different control variables exposed by the devices involved in the installation (photovoltaic production, battery management, ambient temperature, etc.), in addition to the sending of control commands to define the values of some of those variables (setpoint temperatures, presence mode, etc.).

In Listings 1 and 2, examples of the data interchange are shown. When the SoC queries the devices found in the installation, the read variables are arranged to create a nested dictionary that will be represented as a JSON text string. At the top level, the keys describe the UUIDs (Universally Unique Identifiers) of the devices. The internal dictionary associated as the value of each UUID has a single key that represents the timestamp of the read event, and as value, another dictionary with pairs of ***address***: *values*, where all the variables read from the device are listed. This structure was chosen to optimize the performance of the AWS DynamoDB database and make the queries simpler and more efficient. In the provided example (Listing 1), the first key in the dictionary represents the UUID of a Modbus-enabled sensor that provides humidity and temperature readings. The value "1682670718708", which constitutes the key of the internal dictionary, is the timestamp of the reading, while in the third-level dictionary linked to this timestamp, we find the read values for the humidity (address: 102; value: 56.4%) and temperature (address: 103; value: 23.5 °C). Finally, the second UUID found in the top-level dictionary collects the readings from a second device, namely a heat pump, also available in the installation where the JSON was taken from.

Listing 1. Example of values read from two devices.


```
{
    "e612ecd9-2644-4b98-9c49-10582bcb7de5": {
        "1682670718708": {
            "102": 56.4,
            "103": 23.5
        }
    },
    "21b4f8c8-1099-4fc9-972c-bd59298acfef": {
        "1682670719287": {
            "1": 23.1,
            "2": 23.6,
            "3": 29,
            "4": 28.1,
            "8": 50.4,
            "11": 18.2,
            "13": 1.7,
            "14": 1.4,
            "30": 0,
            "50": 1,
            "53": 1,
            "128": 0,
            "133": 0,
            "134": 50,
            "135": 20,
            "139": 25,
            "2001": 0,
            "5002": 0,
            "5082": 0,
            "5221": 2,
            "5222": 1,
            "5224": 0,
            "7003": 0
        }
    }
}
```


Listing 2. JSON command example.


```
{
    "uuid":"b38189f9-6915-4268-81d9-3c2bebaa6687",
    "deviceInternalAddress":"200_9",
    "value":1
}
```


To send commands from the cloud and modify the internal parameters of the installation, another JSON is used. As shown in Listing 2, the dictionary is composed of three keys that describe the UUID of the target device, along with the address of the variable and the new value to set. It is relevant to mention at this moment that in this and in the previous case, AWS topics are involved to successfully transmit information to and from the cloud. They are an integral part of the IoT Core feature in AWS and a very easy way to implement the required functionality. The choice of this technology for our system is not trivial, as we have to take into account the fact that nowadays it is very common to be behind a CG-NAT (Carrier Grade Network Address Translation) connection. This fact poses a great challenge, as it prevents the installation from being directly accessible from the outside (port forwarding), thus forcing us to rely on some elaborate mechanism to bypass it. With AWS and IoT Core, this problem is already solved, and no additional setup is required.

Another fundamental advantage derived from the use of an SoC is the implementation of automatic control processes locally, which allows the system to work regardless of the status of the Internet connection. Additionally, the on-site execution of these processes allows us to dramatically reduce the expenses billed by the cloud services provider, as no or little computation power will be needed.

Figure 2 shows an example of such an integration. In this figure, we represent the energy production and storage devices (solar panel, inverter, and battery), the heat pump, and the Raspberry Pi. It is interesting to point out the fact that the inverter and the heat pump communicate using the same protocol but using a different physical media. In this case, the Raspberry Pi is able to send and receive commands to/from the devices, while keeping a channel open with AWS (Amazon Web Services). In this case, we relied on the use of the IoT Core functionality of the cloud provider; therefore, MQTT is the required protocol to interact with the platform. Once inside the AWS, data are received and stored using a DynamoDB database, and through the implementation of a set of web services and a frontend, a final user and an administrator can monitor and modify the internal state of the installation with a standard web browser.

Table 1 provides an overview of the data collected from each component involved in our control system integration. This information is crucial for understanding the comprehensive data management and functionality of the system.

Table 1. Overview of the collected data.

Device	Collected Data
Heat Pump	Water temperatures in thermal collection and generation circuits Water pressures and flows Electrical consumption Operating modes Operating parameter values
Inverter	Photovoltaic power generation Electrical power consumption Electrical power obtained or delivered by the electrical grid Battery charge state Electrical power consumed or being charged by the battery
Sensors	Interior and exterior temperature and humidity Water tank temperatures Indoor radiant panels surface temperature Solar thermal panels temperature
Actuators	Valves (partially or totally open/closed) Hydraulic pumps (on/off, operation mode and flow setpoint)
Raspberry Pi	Temperature, humidity, and operation mode settings from web user interface

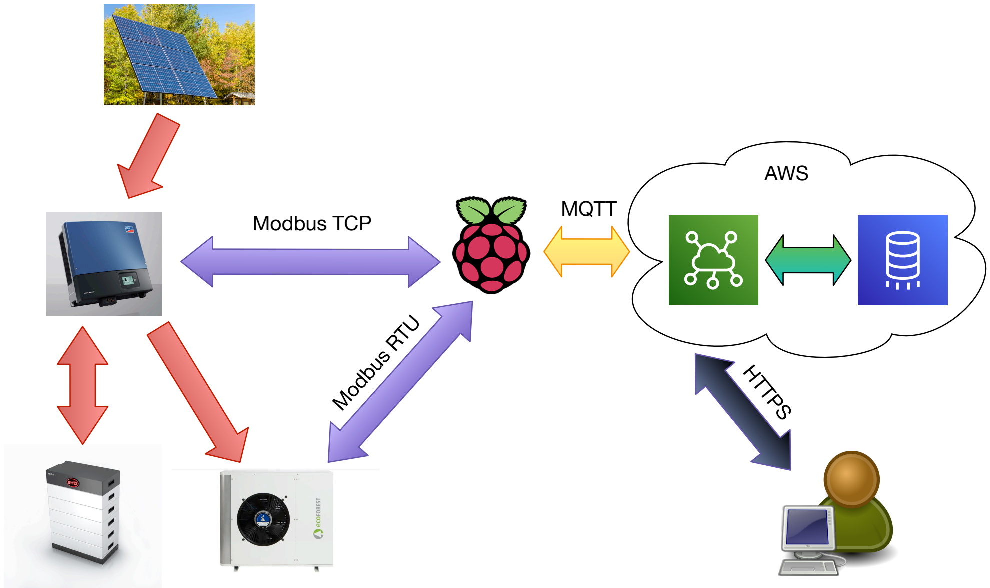

Figure 2. System diagram.

2.4. Automatic Control

A key challenge found in these systems is how to maximize the use of clean energy in cases when a house is connected to the grid or how to avoid the depletion of batteries when the installation is totally disconnected and cannot rely on the grid as a backup energy source.

With this problem in mind, some decisions need to be made depending on the battery charge status, the energy production, and the demand from the different appliances, A/C, and heat pumps running in the house. These relevant decisions must be carried out by means of a set of control rules that are deployed and run in the Raspberry Pi. This approach, as mentioned before, has the advantage of using the processing power provided by the device, while ensuring an off-line operation in situations when the Internet connection is temporarily unavailable. Another important advantage stems from not having to use cloud-based computational resources, which contribute greatly to the total operation cost of the system.

The control strategy of our algorithms is designed to optimize the utilization of photovoltaic energy and environmental conditions, enhancing energy efficiency and comfort. It efficiently recharges the electrical battery during high photovoltaic generation periods. Concurrently, it charges thermal storage systems, including a water tank, capitalizing on the thermal inertia of building structures. This thermal charging is strategically aligned with periods of higher ambient temperatures to augment heat pump efficiency. The stored energy is then utilized during low photovoltaic generation phases or suboptimal external temperatures. Additionally, the algorithm schedules heating and cooling activities to coincide with the most favorable times for energy generation and storage utilization. This ensures that energy demands are met efficiently, even under conditions of low generation or diminished heat pump efficiency. This approach not only maximizes renewable energy usage but also sustains consistent environmental comfort within the building.

In Figure 3, an example of an algorithm used in one of our tests is shown. It was designed according to the specific control variables of a given installation:

1. Photovoltaic power generation and battery charge.
2. Hot water temperature.
3. Ambient temperature and thresholds.
4. Presence (yes/no).

In order to fully understand some of the labels that appear in the diagram, the values between parentheses represent a value in minutes, i.e., the amount of time a certain action (heating, hot water generation) takes to complete. Additionally, temperature values expressed as constants are expressed in degrees Celsius.

With these parameters in mind, the automatic control algorithm has to be carefully chosen to maximize comfort and avoid a power shortage (when the house is off-grid) and/or the use of energy provided by an electricity company.

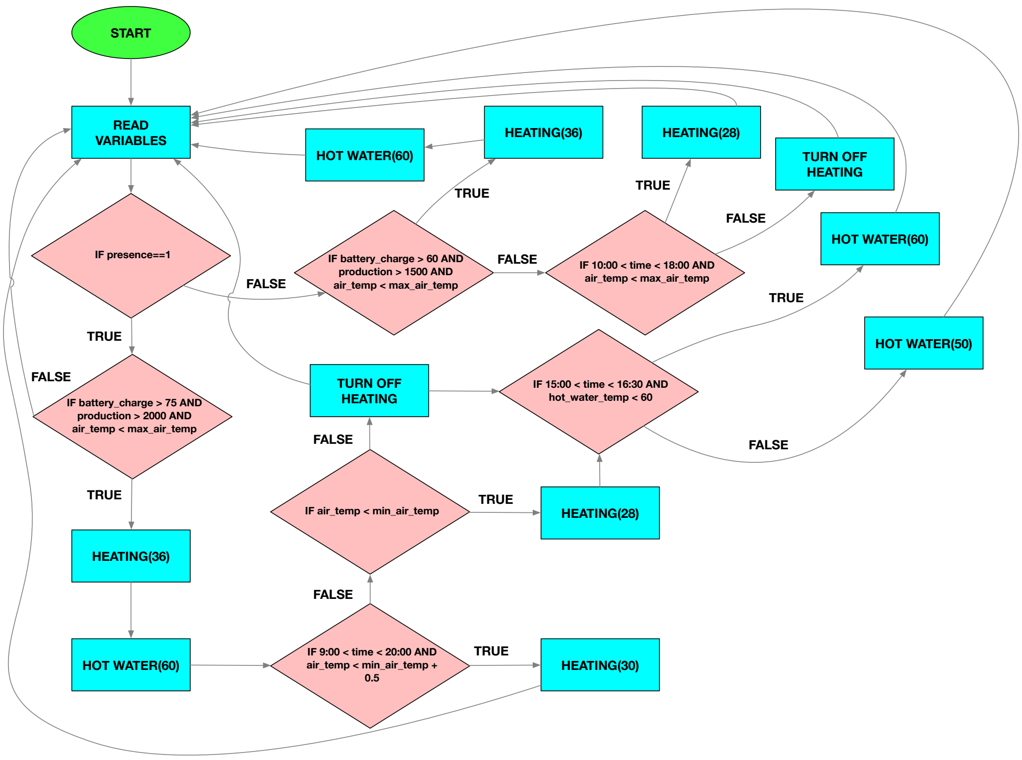

Figure 3. Example of an automatic control algorithm for efficient winter heating management.

Figure 4 displays a representative view of the user interface webpage designed for system control in solar-powered smart buildings. The interface, characterized by a clean design and a user-friendly layout, offers various interactive elements for controlling the system and displaying real-time data. The primary interaction zone in the interface consists of a set of control elements. It includes two binary sliders labeled 'In/Out of House' and 'DHW Boost'. The 'In/Out of House' slider allows users to set the system to maintain the comfort temperature range inside the house when they are inside or to relax this threshold, conserving energy but still ensuring a swift return to comfort levels when they return. The 'DHW Boost' slider gives users the ability to forcibly initiate the heat pump to generate domestic hot water (DHW), which is useful in situations where multiple household members require bathing facilities simultaneously. Additionally, two sliders are provided to define the acceptable temperature range: 'Temperature Minimum' and 'Temperature Maximum'. These give users the flexibility to modify the internal conditions based on external temperatures, photovoltaic production, and battery energy levels. The information display zone includes a variety of live-data feedback elements. These encompass 'Living Room Temperature and Humidity', 'DHW Temperature', 'Heat Pump COP' (Coefficient of Performance), and 'Heat Pump Electric Consumption'. An external temperature reading is also displayed, sourced from a sensor situated outside the house. Three indicators provide insight into the energy storage and consumption: 'Battery Charge Level', 'Battery Status', and External Grid Status'. The latter presents whether the building is currently charging or discharging from the battery or consuming from or feeding into the external electrical grid. Overall, this user interface allows occupants to manage their energy usage effectively and understand their consumption patterns, contributing to a more sustainable and energy-efficient lifestyle.

In the following section, we describe two test installations that have been used to put into action the system introduced in this paper, along with results obtained after several months of operation.

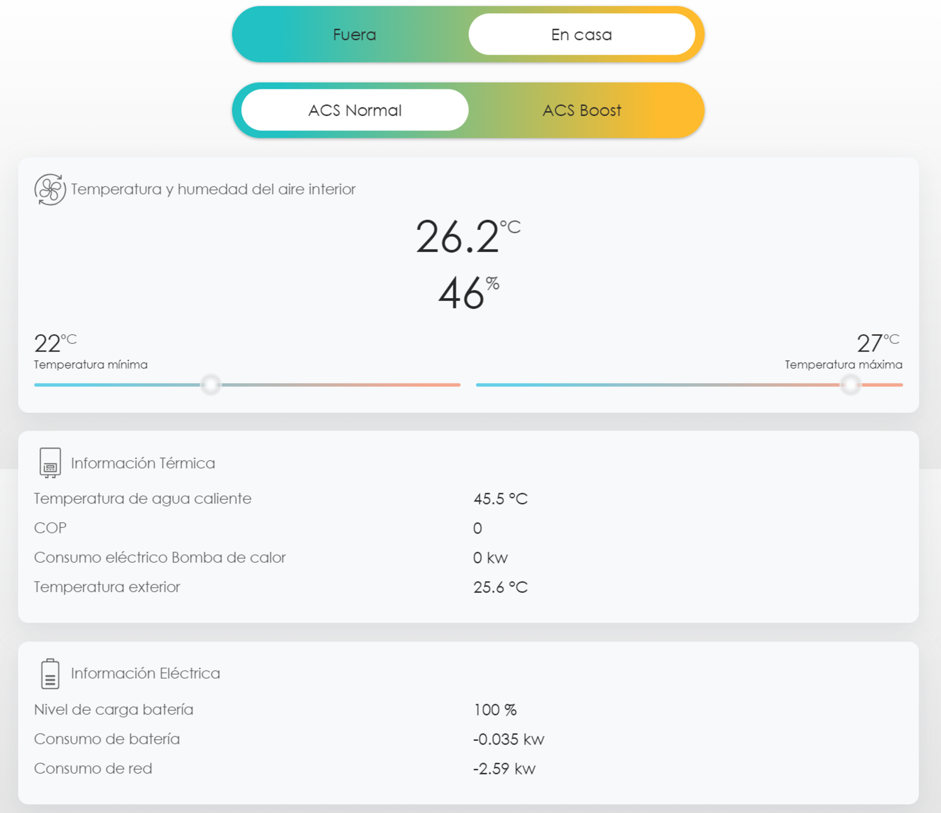

Figure 4. User interface webpage.

3. Real-World Experiments

In this section, we present the empirical demonstration of the implementation of the integrated energy management solution in two distinct settings: the use of the Sunthalpower solar generator, with a compact, yet thermally representative, model dwelling in Paris and the deep energy retrofit of a semidetached single-family house in Oviedo, northern Spain.

3.1. Test in Paris

3.1.1. Description of the System

Sunthalpower, the integrated solar generator developed by Sunthalpy Engineering [26], is an innovative system that combines different technologies to maximize the use of solar energy to provide electricity, heating, cooling, and hot water to buildings in an efficient and sustainable way. The system uses the intelligent control system described in the previous sections. The system consists of several key components, each of which contributes to the overall efficiency and sustainability of the energy solution. These components areas follows:

- Hybrid Solar Panels: These panels integrate photovoltaic and solar thermal power generation within a single unit. The Sunthalpower 1.0 model includes six of these panels, each with a front-facing photovoltaic panel with 405 Wp of output power and a rear-facing Sunthalpanel solar thermal panel. Collectively, the photovoltaic panels deliver a total power of 2.43 kWp, while the thermal component of the panels provides a total thermal solar power of 9.37 kWp. This design allows unconverted photovoltaic energy to be harnessed as thermal energy, feeding the heat pump's primary circuit. Additionally, the Sunthalpanel provides active cooling of the PV array during high solar irradiance, mitigating performance degradation due to temperatures above 25 °C. Figure 5 shows the 1.0 model of the Sunthalpower system.

- Electric Battery: The Cegasa eBick Ultra 175 has a capacity of 13.4 kWh and stores energy when PV production is high, ensuring a consistent energy supply at night and during periods of low solar irradiation.
- SMA Inverters: These inverters facilitate the conversion of DC power to AC power and vice versa. They are equipped with a Modbus TCP connection, providing data on photovoltaic production, electrical consumption, and battery status, including charging percentage and charging/discharging power.
- High-Efficiency Water-to-Water Heat Pump: The Ecogeo 1-6 Pro with the Ecoforest AU6 outdoor support unit, featuring a power range of 1–6 kW, enhances the system's thermal energy management capabilities, contributing to the overall energy efficiency of the system. It is connected via Modbus RTU, providing data on the heat source and heat distribution water circuits, compressor speed, electrical consumption, and other specific data.
- Carbon Steel Storage Tank: This 300-L tank serves as a heat storage and buffer, featuring HCFC-free, rigid injected polyurethane foam for thermal insulation. It is equipped with two NTC temperature sensors.
- Intelligent Control System: As the heart of the Sunthalpower generator, this system continuously monitors and adjusts the performance of the Sunthalpower components to maximize energy efficiency and ensure an adequate supply of heating and cooling. It is based on a Compute Module 4 (CM4), which is the industrial version of the well-known Raspberry Pi 4, with an RS-485 to USB interface for Modbus RTU devices and a gigabit Ethernet connection. This is our preferred choice as the system's controller, but due to the semiconductor shortage we have been experiencing, it has been challenging to find stock for the other projects we are involved in.

Figure 5. Sunthalpower: a system that integrates all the energy generation, storage, and distribution.

The Sunthalpower system was subjected to rigorous testing from February to August 2022, demonstrating its ability to efficiently provide heating and cooling to a synthetic model dwelling located in an open esplanade in Paris, France. The model building was a light, detached rectangular structure, devoid of windows and characterized by opaque walls, designed with a total thermal transmittance U-value of Ug = 24 W/K. Despite lacking thermal inertia due to its absence of mass, the model dwelling was engineered to mimic the energy coefficients of typical not-well-insulated flats or well-insulated single-family houses, thereby serving as a thermally representative environment. In this setting, the Sunthalpower system was employed in conjunction with low enthalpy wall and ceiling radiant panels by Sunthalpy, which further enhanced the system's efficiency and the indoor comfort level of the synthetic model building. The integrated control system networked all thermal, hydraulic, and electrical components, enabling precise control of energy generation, storage, and utilization, optimizing the energy efficiency and temperature levels of the model building.

3.1.2. Heating Results for March 2022

During the testing period in March 2022, the weather in Paris was varied, with 5 days of precipitation, 10 days of cloudiness, and 16 days of sunshine. The average daytime temperature was approximately 14 °C, while the average nighttime temperature was around 9 °C. The minimum and maximum temperatures recorded during the testing period were 0 °C and 21 °C, respectively. Despite these weather conditions, the Sunthalpower system was able to maintain a stable temperature within the synthetic model dwelling solely through the energy captured by the hybrid solar panels. The system was able to heat the bungalow to the targeted operative temperature range of 21 °C to 24 °C with temperatures between 23 °C and 25 °C at the surface of the radiant wall and ceiling panels. Furthermore, the Sunthalpower 1.0 was observed to reach the regulation temperature fast and smoothly, further attesting to its efficiency and the precision of the energy and control systems.

Figure 6 shows a comparative analysis of the external temperature, the internal temperature of the model building, the electricity produced by the photovoltaic panels, and the electricity consumed by the heat pump over the course of three days in March. The outdoor temperature fluctuated between 5.4 °C and 18.4 °C, while the indoor temperature of the model building remained stable between 22.1 °C and 22.6 °C. This stability demonstrates the efficiency of the Sunthalpower system in maintaining consistent indoor comfort conditions. The figure also illustrates the photovoltaic energy production during this period. The generation was relatively low, with values below 500 W, due to the cloudy days with low solar radiation. On the 15th of March, the system used the heat stored in the water tank from the previous days to maintain the indoor temperature, which explains why the heat pump did not operate on that day. On 16 and 17 March, however, the heat pump was activated, directly heating the radiant panels. This operation was powered by the energy generated by the photovoltaic panels and the electric battery.

3.1.3. Cooling Results for July 2022

During the testing period in July 2022, the weather in Paris was predominantly hot and sunny, with only 1 day of precipitation, 17 days of cloudiness, and 13 days of sunshine. The average daytime temperature was approximately 26 °C, while the average nighttime temperature was around 19 °C. The minimum and maximum temperatures recorded during the testing period were 13 °C and a scorching 41 °C, respectively.

Despite these challenging summer conditions, the Sunthalpower system, in conjunction with the radiant panels, was able to maintain the target temperature range of 21 °C to 24 °C. This was even the case during the heat wave that occurred on 18 and 19 July. The radiant panels were instrumental in cooling the surfaces, thereby creating a 'fresh atmosphere' feeling within the synthetic dwelling. The Sunthalpower system, operating as an off-grid solution, relied solely on the electricity generated by the solar panels. In the summer conditions, the heat pump was utilized to extract heat, employing the external air–water unit. This adaptability of the energy control system further demonstrates its capability to maintain a comfortable indoor environment under various weather conditions.

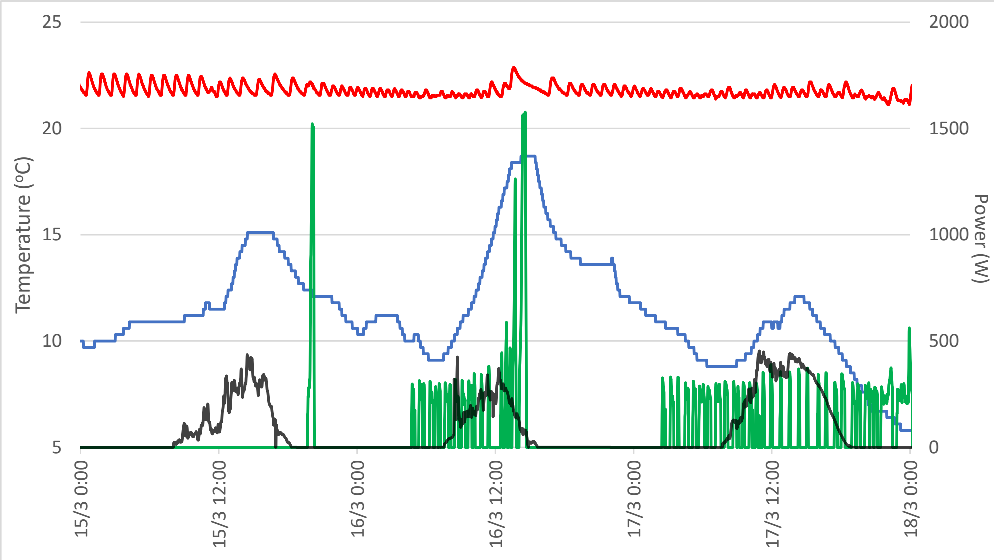

Figure 6. Sample data recorded with external temperature (blue) and temperature inside the model house (red), photovoltaic power (black), and heat pump electrical power consumption (green) for 15 to 17 March.

Figure 7 provides a detailed representation of the external temperature, the internal temperature of the model building, the electricity produced by the photovoltaic panels, and the electricity consumed by the heat pump during the peak of the heat wave that hit Paris in July 2022.

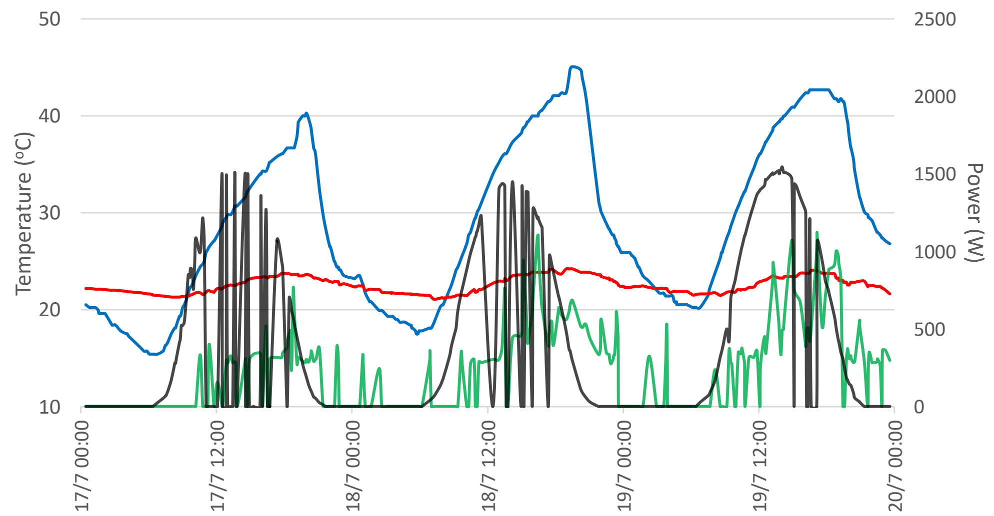

Figure 7. Sample data recorded with external temperature (blue) and temperature inside the model house (red), photovoltaic power (black), and heat pump electrical power consumption (green) for 17 to 19 July.

Despite the extreme fluctuations in external temperature, with highs of 44.8 °C and lows of 15.2 °C during the night, the internal temperature of the model building remained remarkably stable, ranging between 21.1 °C and 24.2 °C. This demonstrates the ability of the Sunthalpower system to maintain a comfortable indoor environment even under severe heat wave conditions. The figure also shows a drop in photovoltaic energy production during this period. This drop was not due to a reduction in solar radiation but rather because the battery had reached its full capacity, and the energy consumption of the heat pump was not sufficient to utilize all the energy generated.

3.2. Deployment in a Renovated Semidetached Single-Family House

3.2.1. Description of the House

The second case study focuses on a house in Oviedo, Asturias, northern Spain, occupied by a family of four. The kitchen and living room of the renovated home in Oviedo are shown in Figure 8. The semidetached house, with a total floor area of 165 m^2, was built in 2001 with a thermal insulation Ug value of 1.20 W/m^2/K. It was originally equipped with a gas boiler, which provided heating through conventional radiators and also met the household's domestic hot water needs. However, the house had no air conditioning or other means of cooling the space.

Figure 8. Interior of the semidetached home in Oviedo with deep energy retrofitting.

3.2.2. Renovation Performed

A deep energy retrofit was carried out to significantly reduce energy consumption and improve the thermal comfort of the house. The main element was the installation of 40 m^2 of Sunthaldress, Sunthalpy's low-enthalpy radiant wall system, to replace the original conventional radiators. This advanced heating and cooling technology was designed to work in synergy with the EcoGeo 1-9, a heat pump developed by Ecoforest with a maximum thermal output of 11 kW. The EcoGeo 1-9, connected via Modbus RTU, provides data on the heat source and distribution water circuits, compressor speed, electrical consumption, and other specific data. The EcoGeo 1-9 was also connected to an Ecoforest AU6 air source unit, which together formed an integrated system, effectively replacing the previously installed gas boiler. The exterior walls of the house were fitted with an additional layer of insulation integrated into the Sunthaldress panels, improving the overall Ug value from 1.20 to 0.95 W/m^2/K. The house was also fitted with a rooftop photovoltaic system consisting of 17 solar panels with a peak capacity of 6.46 kWp. The system includes SMA inverters with a Modbus TCP connection, providing data on photovoltaic production, electricity consumption, and battery status, including percentage charged and charge/discharge power. A 13.4 kWh Cegasa battery was installed for energy storage, providing a sustainable and more self-sufficient energy supply.

An integral part of the retrofit was the installation of a control system based on the architecture and processes described in this paper. A Raspberry Pi 4 with an Internet connection was employed to monitor and control the operation of the EcoGeo 1-9 heat pump, temperature and humidity sensors, and the SMA inverters. The Raspberry Pi 4 communicated with the EcoGeo heat pump and the sensors via the Modbus protocol. This enabled real-time monitoring and regulation of the heat pump's performance, as well as accurate tracking of the house's interior climate conditions. Simultaneously, the Raspberry Pi 4 connected to the SMA inverters via IP, allowing for efficient control and monitoring of the photovoltaic system's operation. Through this integrated control system, all components of the retrofit were effectively networked, enabling precise control over energy generation, storage, and utilization, thereby optimizing the house's energy efficiency and comfort levels.

3.2.3. Results for January 2023

In January 2023, the average daytime and nighttime temperatures in Oviedo were 8.9 °C and 6.1 °C, respectively, culminating in a monthly average of 7.2 °C. Weather conditions varied, with 9 sunny days, 12 cloudy days, and 10 days experiencing precipitation, with temperatures ranging between 1.1 °C and 17.2 °C.

The house consumed a total of 766.88 kWh of electricity, 451.29 kWh for heating and domestic hot water and 315.59 kWh for other domestic uses. The grid supplied 490.28 kWh, with the photovoltaic system contributing 317.62 kWh. The EcoGeo 1-9 heat pump operated with an average coefficient of performance (COP) between 4.5 and 6.0. The heating water supply was consistently maintained between 28 °C and 32 °C, and the surface temperature of the Sunthaldress panels ranged from 26 °C to 30 °C. It is important to note that the efficiency of the air-to-water heat pump is dependent on the temperature difference between the heating system supply and the outdoor temperature, indicating that heating systems operating at higher supply temperatures would have exhibited lower efficiencies, with COPs around 3.5.

3.2.4. Results for February 2023

In February 2023, the average daytime and nighttime temperatures in Oviedo were approximately 10 °C and 5.6 °C, respectively, resulting in an overall average temperature of 7.2 °C for the month. The weather was varied, with 12 sunny days, 12 cloudy days, and 4 days of precipitation. The recorded temperatures ranged from −0.6 °C to a high of 19.4 °C.

The total electrical consumption for the house was 686.4 kWh, with 431.97 kWh being used for heating and domestic hot water and 254.43 kWh for other domestic uses. The grid-supplied electricity amounted to 281.1 kWh, while the photovoltaic system contributed 405.3 kWh. The EcoGeo 1-9 heat pump achieved an average COP of 5.0. A consistent supply temperature for heating was maintained, with values ranging between 27 °C and 32 °C and averaging 29.2 °C. The Sunthaldress panels' surface temperatures varied between 25 °C and 30 °C, aligning with the efficient operation of the heating system.

3.2.5. Summary for January and February 2023

In January and February 2023, a significant reduction in energy consumption and CO_2 emissions was observed in the house retrofitted by Sunthalpy. The heat pump and associated systems consumed grid electricity primarily for heating and cooling, costing an estimated EUR 127 in January and EUR 50 in February. Without the retrofit, the total energy cost for gas and electricity consumption would have been significantly higher, estimated at EUR 527 for January and EUR 370 for February. Therefore, the implementation of the Sunthalpy system led to substantial cost savings, reducing energy costs by 75.9% in January and 86.5% in February. The retrofit resulted in an 89.8% and 94.1% decrease in nonrenewable primary energy consumption for January and February, respectively. Prior to the retrofit, the house would have consumed 4806.67 kWh and 4501 kWh of electricity and gas in January and February, respectively. After the retrofit, these numbers were drastically reduced to 490.28 kWh and 265.56 kWh of grid electricity for January and February. Consequently, the estimated CO_2 emissions of the house energy consumption declined by 87.4% in January and 92.8% in February. The table below (Table 2) summarizes these results, unequivocally demonstrating the considerable effect of deep energy retrofitting in reducing nonrenewable energy consumption, CO_2 emissions, and energy expenses.

Table 2. Reduction in main energy parameters with deep energy retrofitting.

Category	January 2023	February 2023
Nonrenewable primary energy	89.8%	94.1%
CO_2 emissions	87.4%	92.8%
Energy expenditure	75.9%	86.5%

3.2.6. Summary of Results Between 1 January and 31 May 2023

From 1 January to 30 May 2023, the amount of energy fed into the grid was 944 kWh, exceeding the grid consumption of 867 kWh. This shows that the house is energy-positive, generating more energy than it consumes. Our projections show that, even considering the potentially less favorable period from October to December, the house is expected to remain energy positivity throughout 2023, continuing to supply more energy to the grid than it consumes. This result illustrates not only the outstanding performance of the Sunthaldress panels but also the vital role of the integrated control system and IoT components in optimizing the overall efficiency of Sunthalpy's energy solutions. By seamlessly coordinating the various energy-related elements within the house, these digital technologies contribute significantly to energy management and the realization of the house's energy-positive status.

Figure 9 illustrates the energy balance of the house from the end of February to the 31st of May 2023. The y-axis quantifies the daily energy balance of the house. This is computed as the difference between the energy consumed from the grid by the house and the energy fed back into the grid by the system. Commencing around 15 March 2023, a noteworthy transition is observed in the graph, with all ensuing daily energy balance values being positive. This implies that the residence began to operate as a net producer of energy on an intraday basis from this point, generating more energy than it consumed. The surplus energy produced during this period compensates for the energy drawn from the grid between 1 January and 15 March 2023.

Regarding the heat pump's performance, it continues to show remarkable efficiency, with an average COP of 3.2 for domestic hot water production and a COP of 5.8 for heating. This excellent performance was achieved despite the heat pump's average supply temperature of 30.8 °C for heating, which corresponds to an average panel temperature of between 28 °C and 29 °C due to the use of a hydraulic needle. The interior temperature of the house remained at an average of 22.9 °C during these months, rarely dipping below 20.5 °C, except for specific moments such as ventilation or when the residents were away. The temperature recovery after such drops was usually quick, contributing to a significantly increased comfort level due to the uniform temperature throughout the house. This thermal equilibrium, characterized by minimal temperature variations across different parts of the house and rapid compensation for temperature drops by the system, truly defines the superior comfort provided by Sunthalpy's radiant systems.

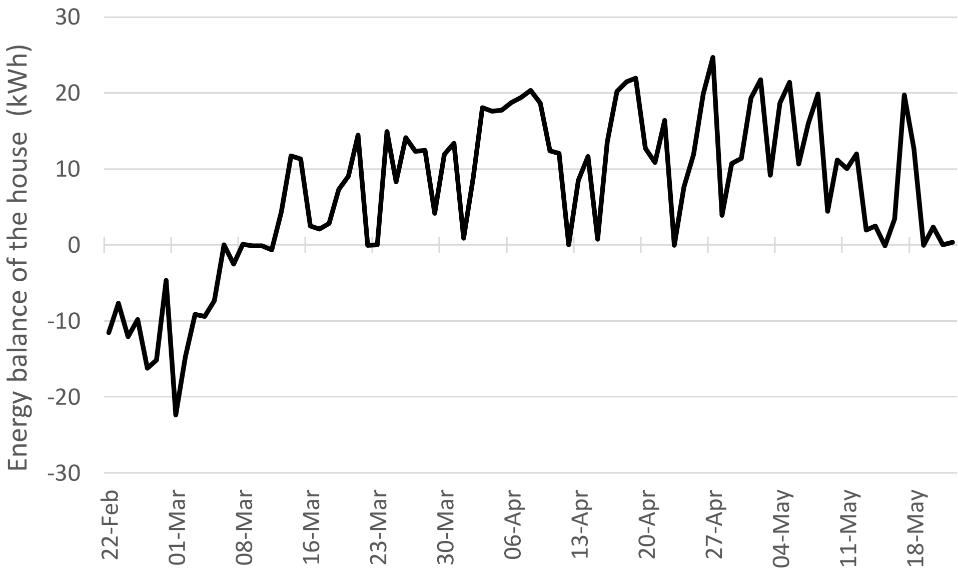

Figure 9. Energy balance of the house.

4. Conclusions

This investigation presents an in-depth analysis of the integration and performance of a hybrid energy system in residential settings. The use of Modbus, HTTP, and MQTT protocols has been instrumental in ensuring efficient interconnectivity, real-time monitoring, and remote management, thereby offering unique advantages over conventional energy management solutions. The IoT components and integrated control system are central to the system's ability to optimize efficiency and minimize grid dependency. The system's design maximizes energy efficiency and sustainability by harnessing solar energy and effectively managing, storing, and distributing the captured energy based on demand. The seamless interaction between the four main components, each fulfilling a specific function within the system, enables real-time monitoring and management, ultimately leading to enhanced energy efficiency and improved thermal comfort. The successful implementation of this system in diverse residential settings illustrates the potential for widespread adoption of solar-powered smart buildings as a key component in the global effort to mitigate the environmental impact of the building sector. As the global demand for sustainable building solutions continues to grow, the scalable and adaptable solutions demonstrated in this work can help meet the diverse needs and constraints of various building types and locations, thereby promoting the widespread adoption of IoT-enabled sustainable energy management systems. Future work will explore the development of more advanced algorithms, predictive systems, and machine learning techniques for optimizing energy consumption and management, which could significantly contribute to the overall efficiency of the solution. Another promising avenue for future research lies in investigating the potential of this integrated energy management solution in larger-scale applications, such as commercial, industrial, or district heating applications, and examining the potential synergies and challenges that may arise in such settings.

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Conflicts of Interest: Author Raúl del Coso and Daniel Álvarez were employed by the company Sunthalpy Engineering S.L. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Santamouris, M. Innovating to zero the building sector in Europe: Minimising the energy consumption, eradication of the energy poverty and mitigating the local climate change. *Sol. Energy* **2016**, *128*, 61–94. [CrossRef]
2. Minoli, D.; Sohraby, K.; Occhiogrosso, B. IoT Considerations, Requirements, and Architectures for Smart Buildings—Energy Optimization and Next-Generation Building Management Systems. *IEEE Internet Things J.* **2017**, *4*, 269–283. [CrossRef]
3. Yu, L.; Qin, S.; Zhang, M.; Shen, C.; Jiang, T.; Guan, X. A Review of Deep Reinforcement Learning for Smart Building Energy Management. *IEEE Internet Things J.* **2021**, *8*, 12046–12063. [CrossRef]
4. Qolomany, B.; Al-Fuqaha, A.; Gupta, A.; Benhaddou, D.; Alwajidi, S.; Qadir, J.; Fong, A.C. Leveraging Machine Learning and Big Data for Smart Buildings: A Comprehensive Survey. *IEEE Access* **2019**, *7*, 90316–90356. [CrossRef]
5. Li, X.; Luo, S.; Sun, H.; Sung, H.H.Y.; Yu, H.; Liu, T.; Xiao, Y.; Bai, F.; Pan, M.; Lu, X.; et al. Medium band-gap non-fullerene acceptors based on a benzothiophene donor moiety enabling high-performance indoor organic photovoltaics. *Energy Environ. Sci.* **2021**, *14*, 4555–4563. [CrossRef]
6. Ma, R.; Li, H.; Peña, T.A.D.; Xie, X.; Fong, P.W.K.; Wei, Q.; Yan, C.; Wu, J.; Cheng, P.; Li, M.; et al. Tunable Donor Aggregation Dominance in Ternary Matrix of All-polymer Blends with Improved Efficiency and Stability. *Adv. Mater.* **2023**, 2304632. [CrossRef] [PubMed]
7. Casas, C.; Jiménez Castillo, G.; Aguilar, J.; Carrasco, J.I.; Muñoz, F. Development of a Prototype for Monitoring Photovoltaic Self-Consumption Systems. *Electronics* **2020**, *9*, 67. [CrossRef]
8. Paredes-Parra, J.; García-Sánchez, A.; Mateo-Aroca, A.; Molina-García, A. An Alternative Internet-of-Things Solution Based on LoRa for PV Power Plants: Data Monitoring and Management. *Energies* **2019**, *12*, 881. [CrossRef]
9. Ożadowicz, A. A New Concept of Active Demand Side Management for Energy Efficient Prosumer Microgrids with Smart Building Technologies. *Energies* **2017**, *10*, 1771. [CrossRef]
10. Mohsenian-Rad, A.H.; Leon-Garcia, A. Optimal Residential Load Control With Price Prediction in Real-Time Electricity Pricing Environments. *IEEE Trans. Smart Grid* **2010**, *1*, 120–133. [CrossRef]
11. Al-Ghaili, A.M.; Ibrahim, Z.A.; Bakar, A.A.; Kasim, H.; Al-Hada, N.M.; Jørgensen, B.N.; Hassan, Z.; Othman, M.; Kasmani, R.M.; Shayea, I. A systematic review on demand response role towards sustainable energy in the smart grids-adopted buildings sector. *IEEE Access* **2023**, *11*, 64968–65027. [CrossRef]
12. Dong, J.; Winstead, C.; Nutaro, J.; Kuruganti, T. Occupancy-Based HVAC Control with Short-Term Occupancy Prediction Algorithms for Energy-Efficient Buildings. *Energies* **2018**, *11*, 2427. [CrossRef]
13. Esrafilian-Najafabadi, M.; Haghighat, F. Occupancy-based HVAC control systems in buildings: A state-of-the-art review. *Build. Environ.* **2021**, *197*, 107810. [CrossRef]
14. Al-Ghaili, A.M.; Kasim, H.; Al-Hada, N.M.; Othman, M.; Saleh, M.A. A Review: Buildings Energy Savings - Lighting Systems Performance. *IEEE Access* **2020**, *8*, 76108–76119. [CrossRef]
15. Chinchero, H.F.; Alonso, J.M. A Review on Energy Management Methodologies for LED Lighting Systems in Smart Buildings. In Proceedings of the 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Madrid, Spain, 9–12 June 2020; pp. 1–6. [CrossRef]
16. Abdulgader, M.; Lashhab, F. Energy-Efficient Thermal Comfort Control in Smart Buildings. In Proceedings of the 2021 IEEE 11th Annual Computing and Communication Workshop and Conference (CCWC), Las Vegas, NV, USA, 27–30 January 2021; pp. 22–26. [CrossRef]
17. Verma, A.; Prakash, S.; Srivastava, V.; Kumar, A.; Mukhopadhyay, S.C. Sensing, Controlling, and IoT Infrastructure in Smart Building: A Review. *IEEE Sens. J.* **2019**, *19*, 9036–9046. [CrossRef]
18. Liu, Y.; Yang, C.; Jiang, L.; Xie, S.; Zhang, Y. Intelligent Edge Computing for IoT-Based Energy Management in Smart Cities. *IEEE Netw.* **2019**, *33*, 111–117. [CrossRef]
19. Orlando, M.; Estebsari, A.; Pons, E.; Pau, M.; Quer, S.; Poncino, M.; Bottaccioli, L.; Patti, E. A Smart Meter Infrastructure for Smart Grid IoT Applications. *IEEE Internet Things J.* **2022**, *9*, 12529–12541. [CrossRef]
20. Motta, L.; Ferreira, L.; Cabral, T.; Lemes, D.; Cardoso, G.; Borchardt, A.; Cardieri, P.; Fraidenraich, G.; de Lima, E.; Neto, F.B.; et al. General Overview and Proof of Concept of a Smart Home Energy Management System Architecture. *Electronics* **2023**, *12*, 4453. [CrossRef]
21. Herez, A.; El Hage, H.; Lemenand, T.; Ramadan, M.; Khaled, M. Review on photovoltaic/thermal hybrid solar collectors: Classifications, applications and new systems. *Sol. Energy* **2020**, *207*, 1321–1347. [CrossRef]
22. Wang, Z.; Luther, M.; Amirkhani, M.; Liu, C.; Horan, P. State of the Art on Heat Pumps for Residential Buildings. *Buildings* **2021**, *11*, 350. [CrossRef]
23. *IEEE Standard 802.11*; Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Institute of Electrical and Electronics Engineers (IEEE): Piscataway, NJ, USA, 2016.

24. *ISO/IEC 14543-3:2016(E)*; Information technology - Home electronic system (HES) architecture—Part 3: Wireless Short-Distance Interconnection. International Organization for Standardization/International Electrotechnical Commission (ISO/IEC): Geneva, Switzerland, 2016.
25. Sun, C.; Guo, K.; Xu, Z.; Ma, J.; Hu, D. Design and Development of Modbus/MQTT Gateway for Industrial IoT Cloud Applications Using Raspberry Pi. In Proceedings of the 2019 Chinese Automation Congress (CAC), Hangzhou, China, 22–24 November 2019; pp. 2267–2271. [CrossRef]
26. Sunthalpy. Sunthalpower Product Page. 2023. Available online: https://sunthalpy.com/en/ (accessed on 19 December 2023).