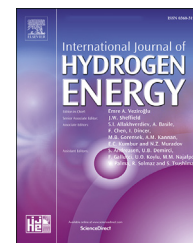


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# Real-time energy management in an off-grid smart home: Flexible demand side control with electric vehicle and green hydrogen production

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## HIGHLIGHTS

- Off-grid home energy management system using demand side control is proposed.
- The system utilizes PV, WT, FC and an electrolyzer for green hydrogen production.
- A FLC is used for real-time energy management and improved RES utilization.
- Reduced hydrogen consumption and increased fuel cell efficiency is achieved.
- Sustainable energy solution in remote areas without sacrificing user comfort.

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## ABSTRACT

A real-time energy management system for an off-grid smart home is presented in this paper. The primary energy sources for the system are wind turbine and photovoltaics, with a fuel cell serving as a supporting energy source. Surplus power is used to generate hydrogen through an electrolyzer. Data on renewable energy and load demand is gathered from a real smart home located in the Yildiz Technical University Smart Home Laboratory. The aim of the study is to reduce hydrogen consumption and effectively utilize surplus renewable energy by managing controllable loads with fuzzy logic controller, all while maintaining the user's comfort level. Load shifting and tuning are used to increase the demand supplied by renewable energy sources by 10.8% and 13.65% from wind turbines and photovoltaics, respectively. As a result, annual hydrogen consumption is reduced by 7.03%, and the average annual efficiency of the fuel cell increases by 4.6%

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## Introduction

Providing and maintaining access to electric energy are difficult goals to achieve for the rural areas where there is either limited or no link at all to the interconnected electric power grid. According to the International Energy Agency's (IEA) report, 9.7% of the world's population, which is above 770 million people, still lack access to electricity as of 2021 [1]. In such a situation, the first thing that comes to mind is to benefit from nature's blessings in terms of Renewable Energy Resources (RES). However, RESs are highly dependent on weather conditions and therefore require additional systems and subsystems to harvest the energy from various RES to store the energy and manage the demand side. These systems are also known as Microgrids [2]. Microgrids are typically supplied by multiple energy sources including energy storage systems, especially in small-scale or off-grid homes [3]. Microgrids not only provide a clean and effective solution for small communities that have no access to electricity, but they also improve the reliability and resiliency in grid-connected systems, where the primary source of energy is the central grid [2,4].

Home microgrids, also known as nanogrids, consist of various RES and energy storage systems. They tend to function at optimal performance when managed by a Home Energy Management System (HEMS) [5]. An HEMS aims to match current energy production with energy demand by controlling the energy consumption of appliances using statistical data and sometimes the forecasted data [6]; thereby maximizing the home's economy while respecting the user's comfort.

Alternative energy sources are inevitable in a home microgrid system, and available options are battery packs, fossil fuel-powered generators, flywheel systems, fuel cell (FC) systems [7]. An FC system converts chemical energy into electrical energy by utilizing hydrogen and oxygen, resulting in water as a byproduct. Therefore, the FCs are favored due to their environmentally friendly structure and quiet operation [8]. Despite their advantages, FCs can suffer from structural deformations like excessive humidification and membrane drying under rapid load demand variations, which makes them not suitable as the sole energy source in standalone systems [9,10]. However, if the FC is supported with various energy sources such as batteries and RES, and the energy demand is controlled by a demand-side management (DSM) system, the lifetime and efficiency of the FC and the entire system can be improved [11].

Various home energy management systems have been presented in the literature for grid-connected and off-grid (islanded) microgrid systems. In Ref. [12], a smart home application is reported in which a self-sustaining PV-powered building is managed with a DSM in the Middle East environment. The mentioned smart home uses the power value of the photovoltaic (PV) panels and the state of charge (SoC) of the battery pack data to control the loads for maximum home economy. In Ref. [13], an intelligent HEMS for residential users is proposed which reduces peak demand by shifting the loads based on the user's usage patterns (statistics) and environmental factors. In Ref. [6], a DSM system based on forecasting residential RES and electricity tariffs for a grid-connected smart home system is presented where the energy is

supplied by the grid, multiple RES, and a battery storage system. Here, the Fuzzy Logic Controller (FLC)-based DSM ensures the most economical operation without affecting the user's comfort level. A hierarchical energy management system that takes RES's uncertainty into account to make more accurate scheduling is proposed in Ref. [14]. In another study, uncertainties are dealt with a decentralized HEMS for day-ahead scheduling of residential loads, using the concept called mean-field [15]. In general, whether they are connected to the grid or not, home microgrids use variable energy sources to improve the reliability and resilience of the system, while trying to reduce energy cost as much as possible without affecting the user's comfort. To improve the algorithms, various forecasting and uncertainty-handling techniques have been used.

An efficient, stable, economically viable, and eco-friendly hydrogen generation system is a preferred energy storage system [16]. Recently, the advancements in electrolyzer technology have led researchers to use these systems in their energy management systems [17–20]. An off-grid application using wind, FC, electrolyzer, battery, and supercapacitor is reported in Ref. [18] where the goal is to achieve optimal sizing for minimum annual system cost and best energetic reliability. One promising energy storage solution is green hydrogen production, which can only be achieved through the renewabilization [21]. The commonly and most effectively used solution for this purpose is wind and solar energy. In Ref. [22], the potential for green hydrogen production through the use of solar energy was examined particularly in regions with high solar radiation levels. Similarly, the use of wind power was investigated in Ref. [23], which found that it has the potential to be a lower cost compared to other renewable energy sources.

In another study, the optimal scheduling of hydrogen storage for fuel supply and capacity-based demand response program is proposed, which takes dynamic hydrogen pricing into account. Through numerical analysis, the authors improved the profit of their system [19]. The FC/electrolyzer system is also used in a DC microgrid system where adaptive dynamic power-sharing is performed [24]. Despite their high cost, FC/electrolyzer systems are being used more and more in recent years. The projected cost of the electrolyzers is expected to decrease with the development of manufacturing technology and volume production [25].

In this paper, a smart home system that utilizes hydrogen, PV, and wind energy along with a real-time HEMS, is developed for purpose of maximizing home economy, user comfort, FC efficiency, and lifetime. The objective of this study is to investigate and develop a model for utilizing a hybrid electric generating system in terms of the combination of PV and WT generators that can satisfy the electric load requirements of a typical off-grid residential household. This system is also incorporated with energy storage based on the application of an electrolyzer, EV charging, and fuel cell technologies. The motivation for addressing this problem is to provide a sustainable energy solution for off-grid homes that can minimize the reliance on fossil fuels while also ensuring the comfort of the users. The proposed model aims to manage the use of the hybrid generating system through real-time monitoring of supply and demand profiles, using an FLC to determine the

ratings for generator and consumption device operation. By effectively managing the demand side of the energy system, the model aims to improve the efficiency of the FC and lower hydrogen consumption, ultimately reducing energy costs for the user. The original contributions of this work can be summarized as follows:

- Improved FC efficiency by using flexible loads such as EV
- Produced green hydrogen by absorbing surplus renewable energy
- Reduced energy cost without distracting user comfort
- Improved RES usage and overall average FC efficiency in an off-grid smart home system
- The use of the rate of change of hydrogen tank level as an input to the FLC allows for real-time monitoring of the difference between RES generation and load demand, enabling effective demand side control
- The proposed HEMS utilizing the FLC with this innovative input achieves improved RES utilization, reduced hydrogen consumption, and increased average FC efficiency in off-grid systems, making it a highly effective solution for smart home energy management.

This paper is organized as follows: In Section Smart Home System, the considered smart home system is presented, followed by the proposed HEMS in Section Proposed HEMS Topology. In Section Fuzzy logic-based HEMS controller, the details of the rule-based FLC structure and the decision-making process are explained. In Section Results and Discussion, the simulation results and a discussion about them are provided. Finally, conclusions are offered in Section Conclusion.

## Smart home system

The smart home shown in Fig. 1 has an Electric Vehicle (EV) charger, along with appliances that can be found in almost every home, such as a fridge, washing machine, stove, etc. Power generation data of the wind turbine (WT) and PVs along with all the appliances' power consumption data are yearlong recorded real data from Yildiz Technical University Smart Home Laboratory. The renewable energy sources WT and PVs, mounted on the roof of the building are shown in Fig. 2 (a) and (d) respectively. The appliances and the inside view of the smart home in the laboratory are shown in Fig. 2 (c) and the smart plugs, which are used to gather each appliance's consumption data and control them are shown in Fig. 2 (d). This system uses RES as the primary energy source, and to provide energy continuity, an FC/electrolyzer is used to support them. Additionally, to avoid rapid load variations on the FC, an HEMS using demand response and flexible loads is provided. FC/electrolyzer system is preferred over an FC/battery pack in a smart home because a battery pack requires additional equipment for monitoring, protection, and maintenance. While an additional battery pack can be beneficial in supporting the FC in the proposed smart home, the DSM system shifts the loads and uses RES more efficiently to distribute the peak demand and keep the loading varying slowly without affecting the user comfort. Therefore, almost all the benefits of battery packs are achieved without one. The energy

management system is developed with a rule-based FLC, and hydrogen tank level, rate of change of hydrogen tank level, and the FC power are selected as inputs, with the load shifting coefficient selected as output. Experimentally collected RES and load data are used as inputs to simulate the proposed system in MATLAB®/Simulink® in order to compare and validate the efficacy of the developed HEMS with conventional HEMS. The proposed HEMS makes a brief contribution to the literature by increasing RES usage, decreasing hydrogen consumption, and increasing overall average FC efficiency in an off-grid smart home system.

## Proposed HEMS topology

The proposed HEMS shown in Fig. 1 consists of an FC/electrolyzer, a WT, a PV array, various electrical loads including various home appliances, and an EV charger. In this concept, the WT and PV serve as primary energy sources, while the FC is used as a powerful secondary energy source that utilizes both hydrogen generated by the electrolyzer and externally filled tanks. The nominal ratings of the energy sources are presented in Table 1, and the specifications of the FC and the electrolyzer are given in Table 2 and Table 3, respectively.

In a conventional Energy Management Algorithm (EMA), multiple sources are present, where the renewable sources are operated at the maximum power point (MPP) to maximize the benefit from the "free" energy. However, in some conditions, the RES may generate more energy than the smart home demands. The proposed system uses this excess energy to generate and store the hydrogen for future usage by using an electrolyzer as a hydrogen generator. The purpose is to use hydrogen as an energy storage unit to store the surplus energy from the RES. In case the power generated by the RES is less than what the smart home demands, the additional power is supplied by the FC. This ensures that the maximum benefit is achieved for the residents. There may be some cases where power demand is less than the energy generated by RES and the hydrogen storage tank is full. In such a scenario, the RES cannot be operated at the MPP but rather at a lower power level without using any energy from the FC. Similarly, if the difference between the power generated by the RES and the power demand is greater than the rated power of the electrolyzer, RES cannot be operated at the MPP.

Possible operations for the sources can be found in Table 4 where  $P_{LOAD}$  is the total demanded load power,  $P_{RES}$  is the total power that can be supplied by the RES,  $P_{FC}$  is the power demanded from the FC, HL is the hydrogen tank level,  $\Delta HL$  is the rate of change of hydrogen tank level, and MPP indicates whether the RES can be operated in MPP.

Table 5 lists the loads that exist in the smart home system, their average power consumption, daily operation time and weekly usage duration, and controllability features. Each load has its own characteristic load demand curve, but average values are presented for a comprehensible demonstration. Here, some of the appliances are tagged as non-controllable because they need to be available whenever needed, such as TV, iron, or microwave, or the loads which have to work almost all the time like the fridge, to respect the user comfort. Among the loads presented in Table 5, the air conditioner (AC),

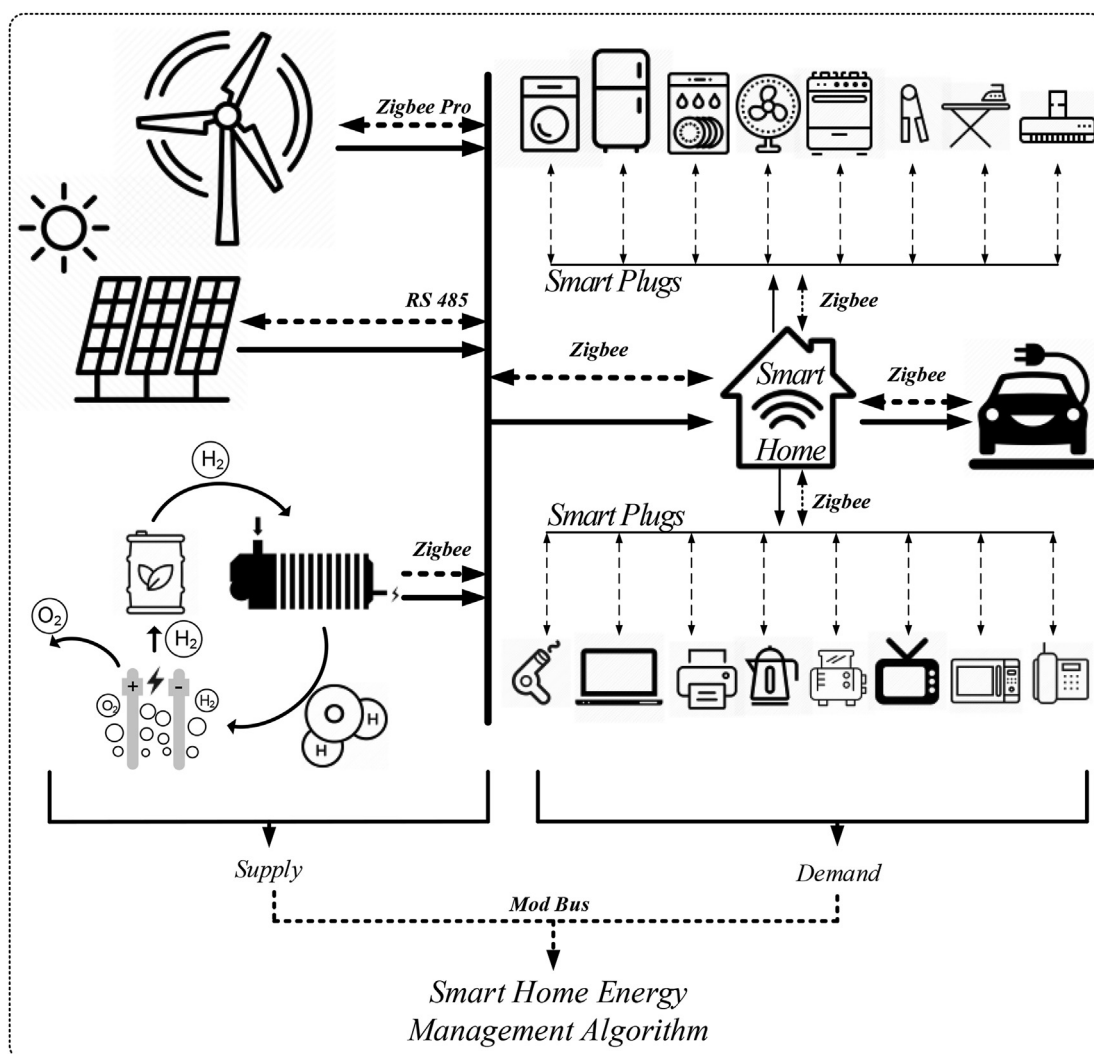


Fig. 1 – Smart home block diagram.

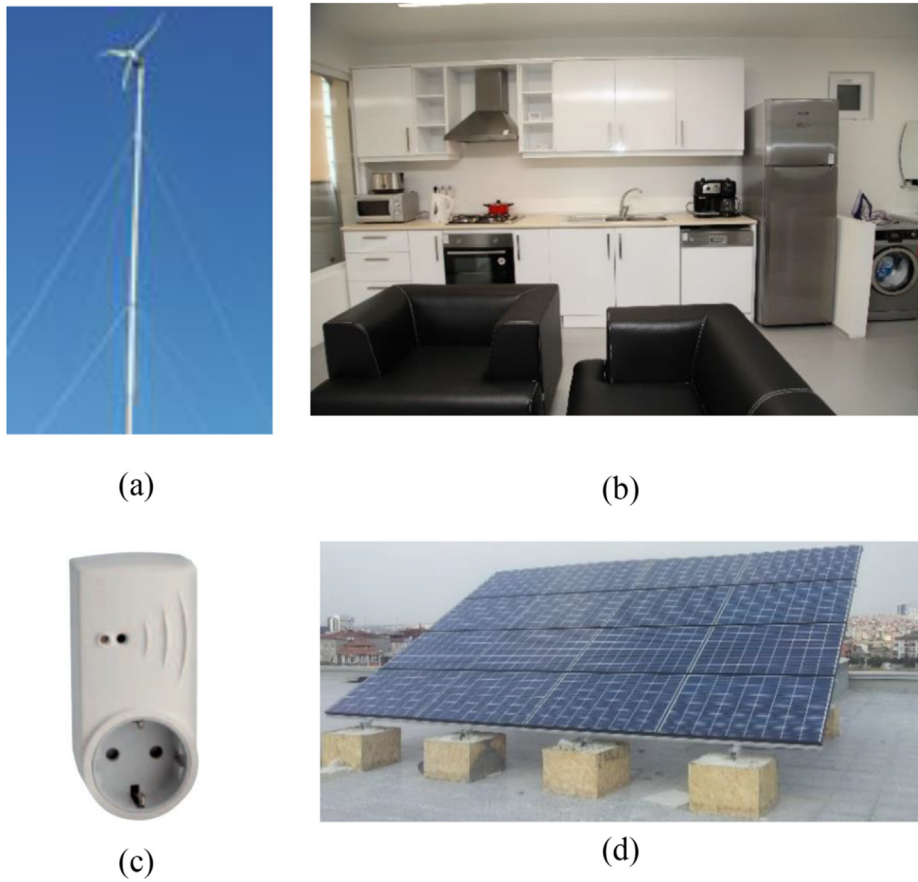
washing machine, and dishwasher are tagged as controllable because load curtailment of these loads does not or slightly affect the user's comfort. The EV is flagged as a flexible load as it can be charged with tunable power. Since relatively higher than others, shifting or adjusting these loads has a greater impact on the energy management performance.

### Fuzzy logic-based HEMS controller

A closer examination of the existing home HEMS controller structures reveals that they mostly consist of rules that orchestrate the harmony between nature and humans without having exact true and false statements. This fact brings the FLC structure forward as it grades inputs or outputs between 0 and 1 based on simple rules set by an expert. Therefore, in this study, the FLC is preferred. Fig. 3 shows the structure of the FLC, where the hydrogen tank level, rate of change of hydrogen tank level, and the FC power are defined as inputs, and the load shifting coefficient is defined as the output.

The use of the rate of change of the hydrogen tank level as an input in the FLC allows for real-time monitoring of the average values of all power sources in the system. For example, a positive  $\Delta$  Tank level indicates that the power generated by the RES exceeds the load demand, while a negative  $\Delta$  Tank level indicates the opposite. This innovative approach to load management, along with the defined 45 rules, ensures the safe, efficient, and sustainable operation of the system.

The load shifting coefficient is adjusted based on the level of the hydrogen tank in order to ensure the efficient operation of the FC. When the hydrogen tank is close to maximum capacity, the load shifting coefficient is set to zero as the energy generated by the RES is sufficient to meet the load demand. On the other hand, when the tank is near minimum capacity, the load shifting coefficient is set to its maximum value to maximize FC usage. In cases where the tank level is intermediate, the load shifting coefficient is adjusted to ensure that the FC operates in the linear region of its power curve, where efficiency is the highest. Detailed sample cases for the FLC, including specific rules and input/output values, are provided in Table 6 to ensure the reproducibility of the study.



**Fig. 2 – Smart home (a) wind turbine outside the building (b) inside view (c) Smart plug used to measure and control appliances (d) PV panels on the roof of the building.**

**Table 1 – Nominal ratings of the sources.**

Source	Type	Rating
Fuel Cell	PEM FC	6 (kW)
Wind Turbine	Permanent magnet brushless	2.4 (kW)
PV	Multi-crystal	210 × 16 (W)

**Table 2 – Specifications of FC.**

Specifications	Rating
Technology	Proton Exchange Membrane (PEM)
Rated Power	6 (kW)
Rated Voltage	45 (Vdc)
# of cells	65
Nominal stack eff. (%)	55
Operating temp. (Celsius)	65
Nominal Air flow rate (lpm)	300
Pressures [Fuel (bar), Air (bar)]	[1.5 1]

The controller also calculates the shifting times of the loads. However, without proper limitations on shifting times, the user may experience unpleasant consequences such as the EV not being charged when needed or the dishes not being washed the next morning, which can affect the user's comfort. The proposed HEMS is designed to prevent such incidents by

**Table 3 – Specifications of the electrolyzer.**

Specifications	Rating
Hydrogen flow	0-600 (ml/min)
Pure oxygen flow	0-300 (ml/min)
Output pressure	0–0.4 (MPa)
Over pressure protection	0.5 (MPa)
Hydrogen purity	>99.95%
Power input	300 W, 12 V DC
Dimension	650 mm × 110 mm × 410 mm
Weight	<30 (kg)

setting strict rules and constraints, ensuring that all shifted tasks are completed before 6:00 a.m. the next day. This structure is shown in Fig. 4.

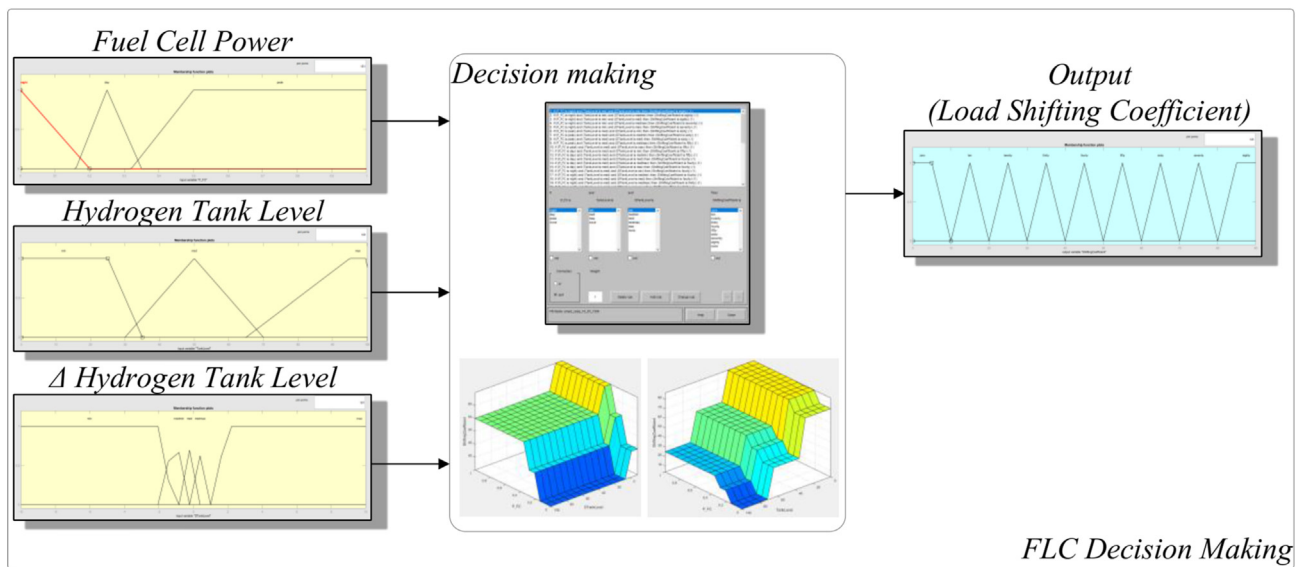
Conventionally, the HEMS used in the RES/FC combined standalone systems relies on the FC as a backup source to provide sustainability and eliminate the uncertainties of the energy generated by the RES. However, the energy supplied by RES may vary rapidly, which can increase the energy demand from the FC. In this case, the dynamic response of the FC may not be fast enough to satisfy the demand. Conventionally, this problem can be addressed by additional battery packs and operating the FC in standby mode. However, this increases the cost of the system or, if not applied, dramatically increases hydrogen consumption. Additionally, if batteries are used in

**Table 4 – Operation cases.**

Case	$P_{RES}$	$P_{LOAD}$	$P_{Elc}$	$P_{FC}$	HL %	$\Delta$ HL	MPP
1	$>P_{LOAD}$	$<P_{RES}$	0	0	100	0	–
2	$>P_{LOAD}$	$<P_{RES}$	$P_{RES}-P_{LOAD}$ (up to 300W)	0	Min-100	+	+
3	$>P_{LOAD}$	$<P_{RES}$	$P_{RES}-P_{LOAD}>300w$ (up to 300W)	0	Min-100	+	–
4	$= P_{LOAD}$	$= P_{RES}$	0	0	Min –100	0	+
5	$<P_{LOAD}$	$>P_{RES}$	0	$P_{LOAD}-P_{RES}$	Min –100	–	+
6	$<P_{LOAD}$	$>P_{RES}$	0	Fault	0	0	+

**Table 5 – The average consumption values of the electrical appliances in the smart home.**

Appliances	Type	Average Rated power [W]	Average Operation Time [h]	# of Weekly Use
EV	Flexible	3.000	4–5	6
AC	Controllable	1.140	6	7
Washing machine	Controllable	1.800	1.5	3
Dishwasher	Controllable	1.700	1	3
Iron	Non-Controllable	1.921	1	3
Fixed oven	Non-Controllable	2.050	1	2
Refrigerator	Non-Controllable	150	12	7
Cooker hood	Non-Controllable	180	1	7
Microwave	Non-Controllable	1.180	1.67	2
Water heater	Non-Controllable	1.700	0.20	7
Toaster	Non-Controllable	708	0.27	5
Hair dryer	Non-Controllable	1.536	0.08	7
Illumination	Non-Controllable	300	5	7
LCD television	Non-Controllable	90	5	7
PC	Non-Controllable	76	5	7

**Fig. 3 – FLC Decision Making scheme.****Table 6 – FLC example cases.**

Case	$P_{FC}$	HL %	$\Delta$ HL	$FLC_{OUTPUT}$	$P_{EV}$	AC	WM	DW
1	Max	Min	–	85	0	S	S	S
2	Max	Med	–	65	0	NS	S	NS
3	Med	Med	0	45	213 W	NS	NS	NS
4	Min	Med	+	35	638 W	NS	NS	NS
5	0	Max	+	0	3000 W	RO	RO	RO

\*S: Shifted, NS: Not-Shifted, RO: Re-operation after shifting.

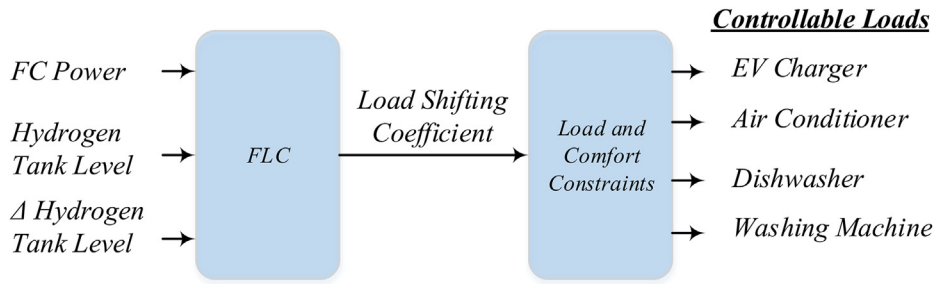


Fig. 4 – Load and comfort constraints handling.

the system, similar problems may occur when the batteries are fully discharged. The proposed HEMS ensures a smooth FC power output variation by shifting the loads or decreasing EV charging power to limit fuel flow level. As a result, structural deformations like membrane drying or FC flooding do not occur.

**Results and discussion**

In this paper, a comparative study of two off-grid smart home systems controlled by conventional and proposed HEMS has been conducted. In both systems, the FC serves as an electrical energy source, while the WT and PV are utilized as RES for both green hydrogen and supply power. The conventional HEMS lacks control over the loads, with every appliance and the EV charger operating according to the user's will. In contrast, the proposed system classifies the loads as controllable and non-controllable and adjusts the operation of controllable loads based on predefined rules.

Simulations of both algorithms covered a year-long operation using recorded real load demand and WT and PV power data from the Yildiz Technical University Smart Home Laboratory. To avoid complexity, only eight days of data including winter (January 21st - 25th) and summer (July 30th - August 3rd) conditions are presented as results, which also highlight the seasonal variations in the loading and RES generation conditions. Plots of total load demand for both conventional and proposed HEMS algorithms in the winter and summer periods are presented in Fig. 5.

Among loads of the smart home, the EV charger has the highest power rating. Hence, the EV charging periods can be easily depicted in Fig. 5. It can be clearly seen that the proposed HEMS shifts and adjusts the charging power. This way, the EV charging power is supplied by the FC and the RES, while RES working at MPP; hence, the FC is not excessively loaded. Different from the winter loading profile, the summer loading profile contains periodic power fluctuations due to the AC power and variable EV charging power.

Fig. 6 shows the power supplied by the FC, again in the same winter and summer periods. Thanks to the proposed HEMS, the total power supplied by the FC was reduced through the effective usage of RES, leading to a prolonged FC lifetime and improved efficiency.

Figs. 7 and 8 show the power output of the WT and the PV panels, respectively, in the winter and summer periods. These figures show that the RES are kept working at their maximum power point (MPP) for longer periods, which maximizes the benefits of renewable energy. There are exceptionally short periods of time when the conventional system uses higher RES power. In these times, mostly the EV charger dominates the loading and a large RES power is drawn from the RES. The reason the WT power in the conventional system is larger than in the proposed system is that the proposed HEMS shifts and adjusts the EV charging power, resulting in slower charging and lower load demand compared to the conventional system. During this period, if the surplus RES power is greater than 300 W, which is the rated power level of the electrolyzer, RES cannot be operated in MPP.

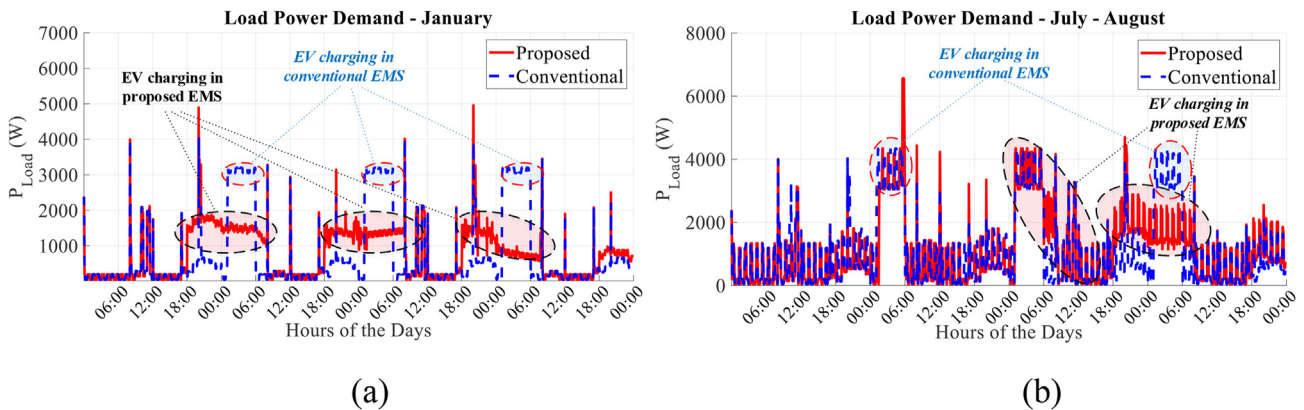


Fig. 5 – Load demand variations in (a) winter and (b) summer periods.

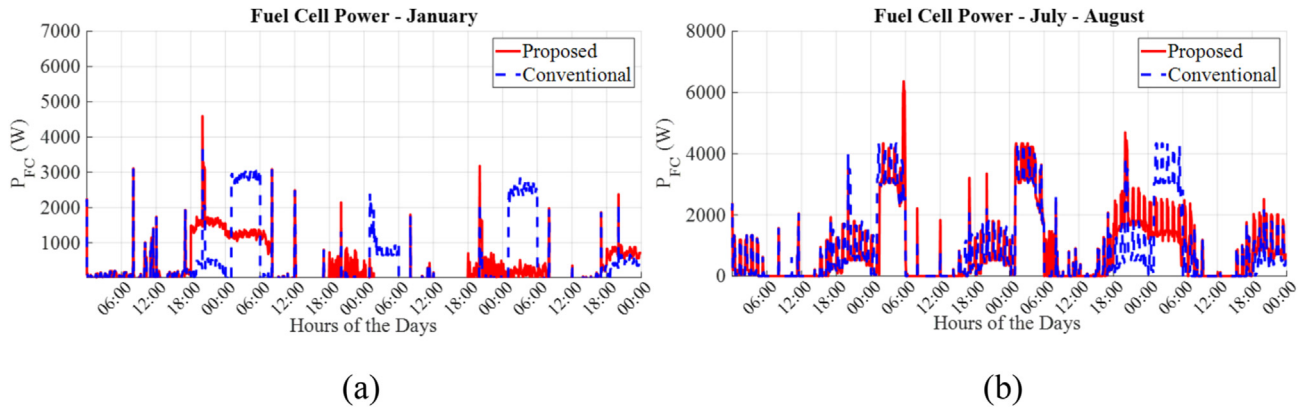


Fig. 6 – FC power variations in (a) winter and (b) summer periods.

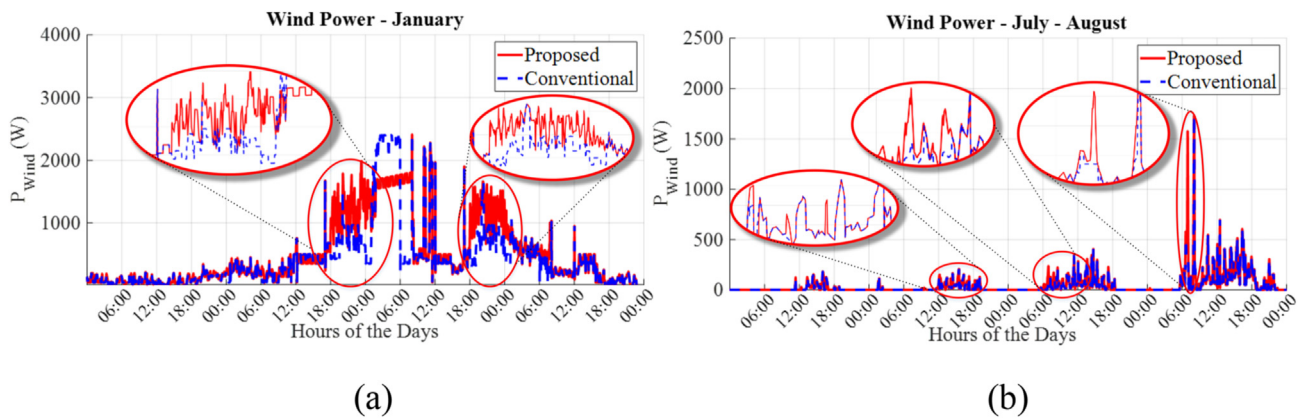


Fig. 7 – WT power variations in (a) winter and (b) summer periods.

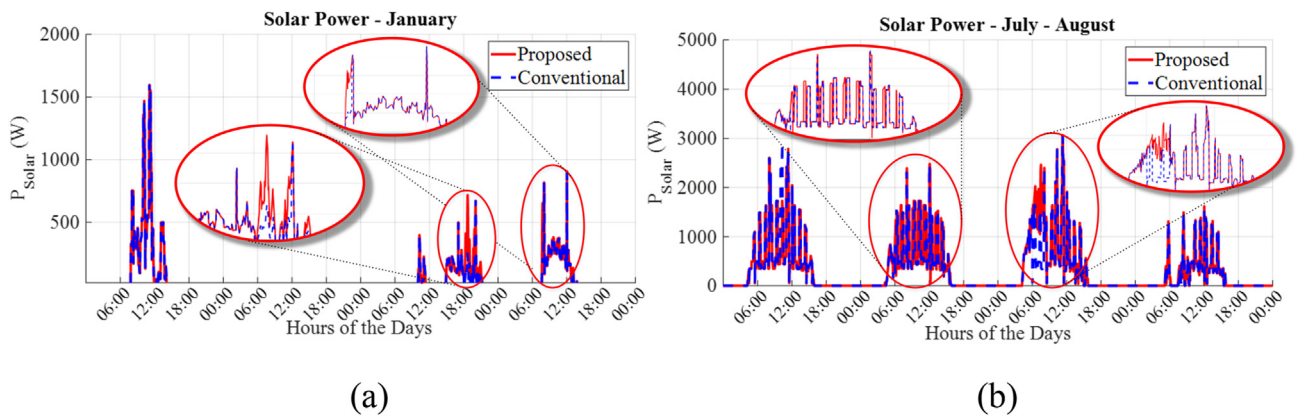


Fig. 8 – PV power variations in (a) winter and (b) summer periods.

In this system, a 250-L, hydrogen tank with a pressure of 200 bar is used. The tank is refilled with hydrogen every 24 h after its level reaches 25% to simulate a realistic scenario in which the smart home is located in a remote area. Fig. 9 shows the hydrogen tank level as a percentage during the winter and summer periods.

In the proposed system, the hydrogen tank level is lower at the beginning of the 4-day winter period, but higher at the end

of the period, as shown in Fig. 9.a. In the 4-day summer period shown in Fig. 9.b, refueling can be seen on the 2nd and 3rd days for the conventional and proposed systems, respectively, which occurred after reaching the 25% tank level. In the proposed system, when the tank level is below 25%, the HEMS maximizes load shifting to keep the important loads powered for a longer period. After refueling, the hydrogen consumption is higher in the proposed system for a short time as the shifted

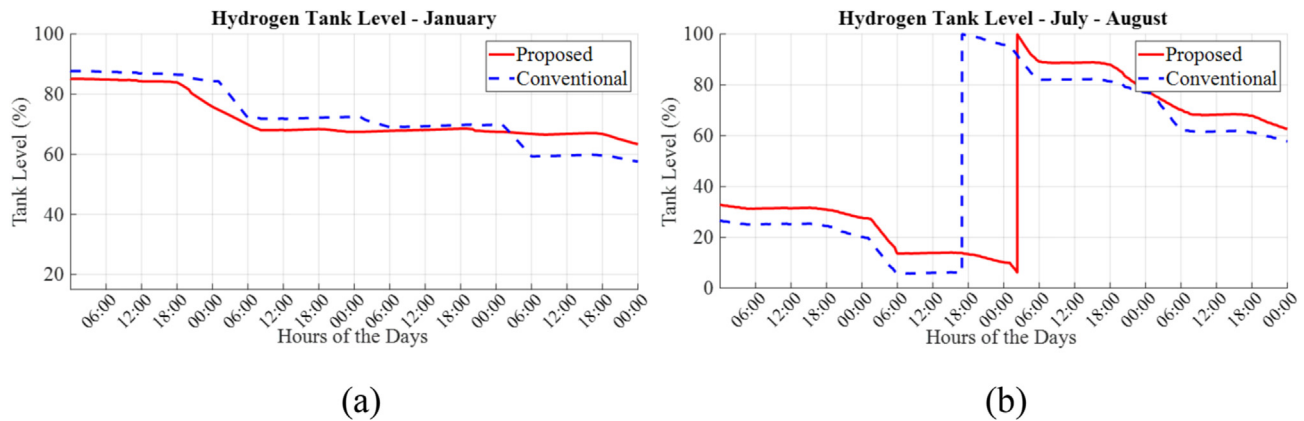


Fig. 9 – Hydrogen tank level variations in (a) winter and in (b) summer periods.

loads start drawing power to meet previously delayed demand. The RESs are utilized to supply the smart home loads whenever they are available during both winter and summer periods, and any surplus power up to 300 W is used for green hydrogen generation. Hence, the RESs are used in a more efficient way resulting in 7.03% reduced hydrogen consumption and 4.6% improved FC efficiency.

## Conclusion

An off-grid HEMS is proposed with the aim of reducing hydrogen consumption by absorbing surplus renewable energy with green hydrogen generating and managing the demand side using controllable loads, EV, and electrolyzer power without violating the user's comfort constraints. The energy demand of the home is supplied by an FC, WT, and PV panels, as well as surplus energy of the RES is stored in hydrogen generated through electrolysis. The smart home consists of various types of residential loads commonly found in a house, as well as an EV charger. The main purpose of the HEMS is to supply the home with a sustainable energy system without any blackouts while keeping the hydrogen consumption level at a minimum. Conventionally, load shifting is not utilized in these systems, but the proposed system uses a load shifting method that guarantees to reduce fuel consumption. The proposed HEMS controls the mentioned loads through smart plugs using a rule-based FLC as a supervisory controller to decide which load should be shifted, and how much power will be delivered to charge the EV. The proposed HEMS strategy introduces a novel approach to load management in off-grid smart home systems by utilizing a rule-based FLC to classify loads as controllable and non-controllable and shifting the controllable loads based on predefined rules. This allows for the effective absorption of surplus renewable energy, resulting in reduced hydrogen consumption and improved FC efficiency.

The proposed HEMS demonstrates significant improvements in both hydrogen consumption and FC efficiency, making it a promising solution for off-grid smart home systems looking to optimize their energy utilization. One major innovation of this study is the use of the rate of change of the

hydrogen tank level as an input to the FLC for real-time monitoring of the difference between RES generation and load demand. This novel input enables effective demand side control and represents a significant contribution to the literature on energy management in off-grid smart homes. The proposed HEMS utilizing this input in the FLC design achieves improved RES utilization, reduced hydrogen consumption, and increased average FC efficiency in off-grid systems, making it a highly effective solution for smart home energy management. Both the proposed and conventional HEMS are compared in a simulation in the MATLAB®/Simulink® environment with the results demonstrating the success of the proposed technique.

In conventional HEMS, the FC serves as the main energy source and supplies the demand when the power generated by the RES is insufficient. However, without the proposed HEMS, surplus renewable energy cannot be utilized when the load demand exceeds the maximum power of the hydrogen generator. The proposed HEMS strategy absorbs surplus renewable energy for green hydrogen generation and uses load curtailment to increase the portion of energy demand supplied by the RES by 13.65% from PV and 10.8% from wind. As a result, the annual hydrogen consumption of the FC is reduced by 7.03%. and the overall average annual efficiency of the fuel cell is increased by 4.6% points.

## 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.

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