Vehicle-to-Home: Implementation and Design of an Intelligent Home Energy Management System that uses Renewable Energy

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ABSTRACT

Using energy storage technology, such as batteries and electric vehicles, is crucial in combating energy shortages. Wind turbines and solar panels are two prominent alternative energy sources. This study examines the impact of Vehicle-to-Home (V2H) technology, specifically during the hours when solar radiation is at its highest. V2H enables electric car batteries to be a primary solution for home energy needs. An accurate scheduling system has been established to improve the organization's energy sustainability. The proposed algorithm effectively controls the allocation, availability, and retention of energy transported by electric vehicles (EVs). The model incorporates constraints to ensure that the family's electricity needs are met regardless of the prevailing weather conditions, whether sunny or cloudy. The Intelligent Home Energy Management System (IHEMS) is being developed to regulate energy use efficiently across different applications and sources. A multi-agent system (MAS) is used to improve operational efficiency and effectively meet the energy needs of devices in the system. An experimental database in Saudi Arabia examines and monitors production costs and energy consumption, considering weather conditions and equipment utilization. The results demonstrate the great potential of V2H technology as a practical storage option that efficiently addresses energy shortages.

Keywords-artificial intelligence; deep reinforcement learning; peer-to-peer energy trading; smart community; photovoltaic array; energy market

I. INTRODUCTION

Vehicle-to-Home (V2H) technology is a potential trend to enable Electric Vehicles (EVs) to power a home or other electrical systems. V2H systems facilitate two-way energy transfer between the vehicle and the home, allowing for a versatile management of energy resources. The process involves charging an EV with power from the grid or renewable sources when accessible and discharging the stored energy back to the home or the grid when needed, especially during power outages, peak demand periods, or high electricity cost periods. Bi-directional inverters in V2H systems convert the stored DC from the battery into AC for household appliances [1]. V2H systems offer emergency backup benefits [2]. The V2H implementation requires a suitable infrastructure, standardized protocols, and legislative backing. Firms and researchers have been investigating and advancing V2H technology since January 2022, so its level of adoption may have changed [3].

In [4], the authors reported that solar photovoltaic (PV) systems and smart home technology can enhance energy efficiency, comfort, and control. This text explores different ways of combining smart home technologies with solar PV systems. Smart home energy monitoring systems now include intelligent control and management features to monitor energy generation and use in solar PV systems. Users can evaluate current data and historical patterns to better understand their energy usage. Authors in [5] discussed smart meters, solar generation, and utility rates to optimize energy consumption. In [6], the authors stated that smart inverters combine enhanced inverters and communication features to enable real-time supervision and management of solar PV installations. The authors mentioned that power output based on network conditions tends to optimize system performance. In [7], the integration of energy storage into new systems and battery management were discussed. Intelligent technologies can optimize a solar PV system's charge and discharge cycles connected to energy storage or battery systems by considering energy demand, time-of-use rates, and solar generation patterns. Authors in [8] paralleled load shifting with a smart home system which automatically utilizes stored energy during peak demand or poor solar production, reducing costs. Authors in [9] stated that home automation and integration can be improved by linking smart thermostats to heating and cooling systems, considering solar generation and energy availability, thus enhancing energy efficiency. Automated control is optimized based on solar availability in an attempt to reduce power usage during periods of low solar power. In [10], it was reported that smart homes can participate in demand response programs by regulating the energy consumption predicated on signals derived from utilities. This may entail reducing energy use during periods of peak demand or when the grid is under stress. Intelligent charging systems for EVs can adapt charging schedules according to the solar availability and grid conditions, resulting in cost savings and increased utilization of Renewable Energy Sources (RESs). In this vein, the user interface can be integrated with mobile applications and voice command technology. In [11, 14], it was mentioned that integrating weather forecast data allows predictive analytics to anticipate fluctuations in solar generation. This permits smart home devices to optimize energy consumption. Technological developments are expected to enhance the integration of solar PV systems and smart home technology, providing more advanced and automated solutions for sustainable living.

Integrating Distributed Energy Resources (DERs) with smart home technologies can significantly enhance energy supply, efficiency, and management. This integration can provide many benefits. DERs include solar PV systems, energy storage, small-scale wind turbines, and other on-site generation and storage equipment. When joined with home automation systems, DERs offer real-time monitoring and control. The authors state that smart Home Energy Management Systems (HEMS) enable homeowners to monitor energy production from solar PV systems and other DERs in real-time, allowing them to track their energy availability. These systems can independently adjust resource usage based on energy requirements, weather conditions, and utility rates [12]. In [13], it was reported that smart home systems can assess the availability of energy from DERs and optimize the use of energy-intensive appliances, such as electric water heaters, electric vehicles, and Heating, Ventilation, and Air Conditioning (HVAC) systems, during periods of high-power generation. The combination of batteries and DERs facilitates the storage of excess energy generated during periods of high demand. This stored energy can be used during low or no power generation, improving energy accessibility and flexibility.

Energy management agents are one feature that maximizes energy efficiency by considering variables, such as electricity costs, demand-response signals, and the availability of renewable energy sources [15-18]. Security agents focus on monitoring and responding to security incidents, like intrusion detection and surveillance. Communication agents facilitate information exchange among different agents within the system [18]. Task Allocation Agents collaborate to distribute duties and control resources in the smart home, improving the system's overall performance [19]. Coordinated response agents can collaborate to address various situations, such as adjusting house configurations based on user preferences, energy availability, and security conditions [20]. Machine Learning (ML) agents can apply ML algorithms to comprehend user preferences and adapt automated processes as they develop. Adaptive system agents can adjust their behavior in response to changing environmental conditions, user habits, or external influences [21]. Sensor agents utilize data from various sensors to comprehend the context of the home environment, enabling more informed and context-aware decision-making. User context agents consider the user's context, preferences, and behaviors to personalize automation and suggestions. Energy optimization agents regulate energy usage based on user behavior, time-of-use pricing, and the availability of renewable energy sources [22]. In [23], it was analyzed that a well-designed multi-agent smart home system can create a more intelligent, adaptive, and user-friendly environment, improving both automation and user satisfaction in the house. The collaborative nature of agents allows for a comprehensive approach to oversee many aspects of smart home living.

The current study evaluates the effectiveness of traditional techniques and vehicle-to-home (V2H) technology while considering range and PV subsidies. PV and V2H have the potential to enhance the utilization of off-peak electricity and solar power, leading to economic advantages. Residential PV and V2H systems can meet energy needs during sunny and cloudy days but require a grid connection and have restrictions in rainy conditions. Previous research has identified substantial deficiencies in the proposed HEMSs. Many EMS-optimized systems do not accommodate V2H and PV systems. Further research is needed to fully understand the influence of weather conditions and driving behavior on the production and use of solar PV energy. In addition, V2H services need greater investigation for their effectiveness in transmitting energy from PV systems and reducing peak energy demand to be assessed. The economic viability of two-way V2H capabilities still needs to be determined and demands further exploration. To overcome these challenges, it is essential to create an effective HEMS, whether it includes V2H or PV capabilities. The improved HEMS should consider several elements, namely weather conditions, driving behavior, and the benefits of solar energy. A cost-benefit analysis of the proposed design is essential to determine the most efficient timing for the operation of the home appliances, with particular emphasis on planning for charging and discharging the EV. In addition, the study will examine four cost optimization scenarios based on state transition diagrams to identify the most cost-effective smart home system.

II. METHODOLOGY

A. *Intelligent Agent Concept*

Intelligent agents are fundamental to the creation of artificial intelligence and self-governing systems. These agents are vital in developing intelligent systems that function effectively in intricate and ever-changing contexts. Intelligent agents are utilized in various fields, such as robotics, virtual assistants, autonomous vehicles, smart homes, and other areas [24]. Intelligent agents are software entities specifically designed to perform particular tasks, solve problems, or make decisions without direct human involvement. They can perceive their surroundings, use logical reasoning based on observations, and execute actions to accomplish pre-established objectives [24]. In this vein, AI, robotics, computer science, and multi-agent systems are domains that commonly employ these agents. These agents can operate autonomously, perceive and gather sensor data, and use cognitive processes to analyze information and make informed decisions. Individuals can carry out tasks, acquire knowledge from past events or information, and operate aligned with their established objectives by making control and observations. Intelligent agents can interact with each other or other systems to function in a particular environment and collaborate in multi-agent systems to accomplish shared goals. The assessment of their performance considers bounded rationality and is grounded on criteria such as efficiency, accuracy, and resource allocation. They are indispensable for constructing intelligent systems in intricate and ever-changing environments. These systems are utilized in diverse domains like robotics, virtual assistants, self-driving cars, smart homes, and other areas. For this reason, this paper comprehensively compares V2H technology and conventional techniques, including many variables such as range and PV subsidies.

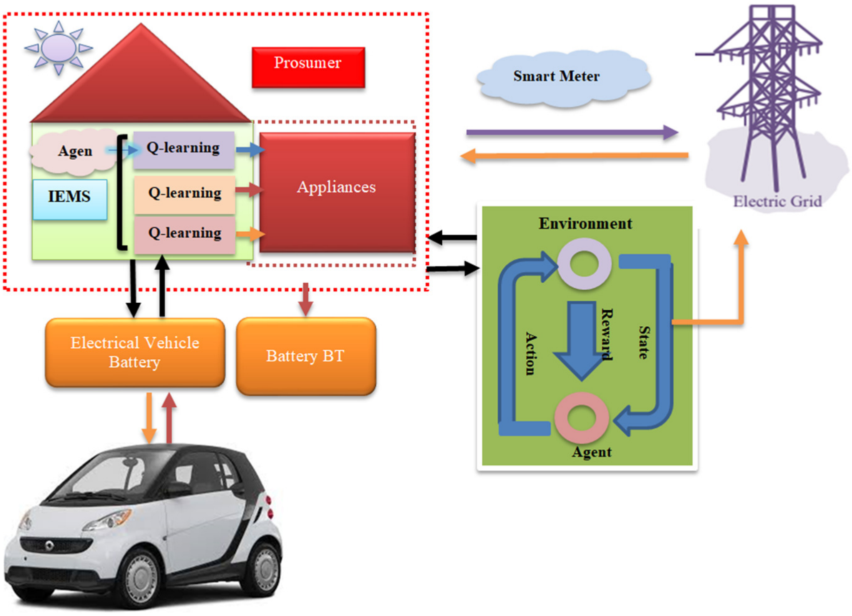

Fig. 1. Peer-to-peer energy system design.

B. *Multi Agent System*

A MAS approach in a smart home with solar energy integration and V2H facilitates holistic and intelligent management of resources. The collaboration among different agents enhances the overall efficiency of the system, making it more responsive to dynamic conditions and user needs. It enables a seamless integration of solar energy while optimizing energy usage and providing a comfortable living experience. MAS involves the employment of multiple intelligent agents working collaboratively to enhance efficiency, automation, and energy management within a home environment. The agent types in a smart home MAS are: Home automation agents that are developed to control and manage smart home devices and appliances and energy management agents that optimize energy usage, considering factors like solar energy production, energy storage, and EV/V2H.

The current study compares the efficiency of the PV systems and proposes an architecture that includes EVs, PV, Intelligent HEMS (HEMS), and appliances, as illustrated in Figure 1. The system aims to meet midday electrical demand and supply the excess PV energy back to the grid. Additionally, the EV battery can power the residence during the peak demand. The V2H device utilizes a bidirectional power converter, consisting of an AC-DC converter at the front and a DC-DC converter at the back, to convert EV battery power for home use. This allows the EV batteries to provide energy during the peak demand, while a stationary battery stores the excess energy and can be activated during times of power shortage.

1) *The PV Agent*

The PV intelligent agent is a micro-entity that autonomously optimizes PV system operation. The system's sensors and monitoring devices provide real-time data on solar radiation, temperature, and solar panel performance. The performance of the PV system is monitored for variations, errors, or suboptimal circumstances that may impair energy gathering. Predictive analytics are put into service to forecast solar radiation and energy production for hours or days, enabling preemptive decisions. PV agents efficiently distribute the solar-generated energy to meet the electrical needs of a home or facility [25]. Equation (1) is related to the computation of rooftop solar power generation.

$$P_{PV}(t,s)(\forall t) = G_{PV}^{rated} * \frac{G_{PV,s}^{rated}}{G_{PV,t}^{rated}} * \left[\phi_{pv}(T_{pv,t} - T_{pv,s}) + 1\right] \quad (1)$$

where $P_{pv,t}$ represents the solar power the rooftop solar system generates at a specific time t. $G_{pv,s}$ represents solar irradiance, $T_{pv,t}$ indicates the average temperature of the solar system under suitable conditions, ϕ_{pv} represents the electricity temperature coefficient, a factor that describes how the performance of a solar panel changes with temperature.

C. Battery Agent

The study compares the efficiency of range and PV subsidies. Integrating a battery agent into a smart home can enhance energy efficiency, reduce costs, and improve resilience through intelligent energy storage system management. The battery agent is a crucial component of the more extensive smart home system, working alongside other agents and gadgets to establish a more environmentally friendly and convenient living space. The primary role of a battery agent is to improve the efficiency of stored energy by considering energy production, consumption trends, and user preferences. In a smart home, a battery agent's essential elements and functions include controlling the energy storage system's charging and discharging processes [26]. The system determines whether to store excess energy generated by renewable sources, such as solar panels and when to release the stored energy to meet the household's electricity needs. The agent aims to maximize the self-utilization of solar energy by keeping excess power during abundant sunlight and discharging it during periods of low solar production or high demand. Additionally, it serves as an emergency backup. During a power outage, the battery agent can prioritize essential loads, enabling critical devices such as lighting and freezers to continue operating using stored energy (see (2)).

$$\begin{cases} \textbf{Power Constraint for Charging / Discharging}: \\ P^{BT}(ch/dis,i) \le P^{BT}(ch/dis,\max) * C^{BT} \\ \\ \textbf{Minimum Power Requirement for EV}: \\ P^{BT}(t) \ge P^{EV}\min(t) \\ \\ \textbf{State of Charge (SOC) Constraint}: \\ SoC^{EV}(t) \le \chi \le D_\beta \parallel SoC^{BT}(t) \ge \chi \ge D_\beta \end{cases} \quad (2)$$

where P^{BT} $(Pch/dis,\ i) \le P_{ch/dis}(max) \times C^{BT})$ represents a power constraint where the power consumed during charge or discharge P^{BT} $(Pch/dis,\ i)$) should be less than or equal to the maximum allowable power times the state of charge (SOC) over the capacity of the battery. $P^{BT}(t) \ge P^{EV}{}_{min}(t)$ represents a power constraint, where the power consumption at time t should be greater than or equal to the minimum power required for the EV. The minimum SOC should be less than or equal to the charge and discharge efficiencies (η_{ch}, η_{dis}) of the maximum SOC of the EV. The SOC should match the daily driving distance (χ) to the maximum driving distance of the EV (D_β). The SOC should be within the specified range, considering the minimum and maximum SOC and the charging and discharging efficiencies (see (3)) [27].

$$\left| \begin{array}{l} P^{BT}(ch/dis,i) \le P^{BT}(ch/dis,\max) * \left(\dfrac{\eta^{BT}}{C^{BT}} \right) \\ SoC_{\min} \le SoC(t) \le SoC_{\max} \end{array} \right. \quad (3)$$

where P^{BT} $(ch/dis,\ i)$ indicates the consumed power during charging or discharging in the i-state and $P(ch/disch,$ max) represents the maximum permissible power for charging or discharging, and C^{BT} refers to the BT maximum amount capacity. $SoC_{\min}$ is the minimum battery capacity required for the electric vehicle.

2) EV Agent

This agent collaborates with other smart home entities to create a seamless, intelligent environment that optimizes electric vehicles, energy sources, and electrical grid interactions. EV agents optimize charging based on power pricing, grid demand, renewable energy availability, and customer preferences. An electric vehicle agent in a smart home has essential features, including vital Load Support and Optimized Charging hours. The EV Agent can prioritize vital loads during a power loss to keep emergency charging and climate control running on stored energy. It also considers off-peak electricity pricing, grid demand, and renewable energy sources like solar energy to find the best charging hours for the electric vehicle. Time-of-use management is also optimized to reduce costs. The electric vehicle can be charged at lower electricity rates using time-of-use pricing. The EV agent can also alter the charging schedule based on grid signals to stabilize the grid during peak demand. To maximize renewable energy consumption for electric car charging, the EV Agent coordinates with solar energy generation in smart homes with solar panels. The study compares the efficiency of a range of PV subsidies. $SOC^{EV}(i)$ is the state of charge of the EV battery at time t. Equation (4) gives the SOC limits for both the EV and the V2H system:

$$\begin{array}{l} SoC_{EV,\min} \le SoC_{EV,i}\left(\eta_{ch},\eta_{dis}\right) * SoC_{EV,\max} \\ SoC_{EV,0} = 100\% \left(1 - \dfrac{\chi}{D_\beta} \right) \end{array} \quad (4)$$

where $SOC_{EV,min}$ and $SOC_{EV,max}$ represent the minimum and maximum acceptable SOC for the EV (the initial SOC is 100%), while χ is the daily and D_β the maximum driving distance of the EV, and η_{ch} and η_{dis} are the charging and discharging efficiencies

D. Agent V2H Constraints

By incorporating a V2H agent into the smart home system, homeowners can utilize the EV as a versatile and adaptable power supply. The agent works with other smart home components to improve energy efficiency, flexibility, and cost-effectiveness. A V2H agent is a software entity or module designed to intelligently oversee and regulate the bidirectional power exchange between an EV and a home's electrical system. During a power outage, a V2H operator can use the energy stored in the EV to prioritize critical loads in the house and ensure that necessary appliances continue running. Additionally, a V2H agent can participate in demand response initiatives by adjusting the timing of charging and discharging in response to grid signals, which can enhance grid stability during periods of high demand [29]. Equation (5) sets the requirements for the SOC of both the EV and the V2H system, considering efficiency factors and operational constraints [30]:

$$\begin{gathered} SoC_{V2H,\min} \le SoC_{V2H,i}\left(\eta_{ch},\eta_{dis}\right) * SoC_{V2H,\max} \\ SoC_{V2H,0} = 100\%\left(1-\frac{\chi}{D\beta}\right) \end{gathered} \tag{5}$$

The constraint guarantees that the EV's SOC at time i is within certain limits defined by the minimum and maximum SOC, the initial SOC, and the driving distance. $SOC_{V2H,min}$ is the minimum acceptable state of charge for the V2H system. and $SOC_{V2H,max}$ the maximum.

E. Appliance Agent

The appliance agent is a central control system for managing various smart home devices, including lighting, thermostats, and smart plugs. It automates the operation of appliances according to predefined rules or schedules, including switching off lights in unoccupied rooms or adjusting thermostats at specific times. The appliance agent optimizes energy use by adjusting appliance usage to reduce peak energy demand and incorporating RESs. Agents regulate the operation of energy-intensive equipment to optimize electricity consumption and prevent peak loads. Household consumption profiles are defined as $B_{a,s}$ (shiftable), $B_{a,n}$ (non-shiftable), and $B_{a,f}$ (fixed) [31]:

$$B_{a,s} = \begin{bmatrix} b_{a,s,1} & 0 & \dots & 0 \\ 0 & b_{a,s,2} & 0 & 0 \\ 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & b_{a,s,t} \end{bmatrix}, \tag{6.1}$$

$$\forall s \in I^s, \forall a \in A^s$$

$$B_{a,n} = \begin{bmatrix} y_{a,n,1} & 0 & \dots & 0 \\ 0 & b_{a,n,2} & 0 & 0 \\ 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & b_{a,n,t} \end{bmatrix}, \tag{6.2}$$

$$\forall n \in I^N, \forall a \in A^N$$

$$B_{a,f} = \begin{bmatrix} b_{a,f,1} & 0 & \dots & 0 \\ 0 & b_{a,f,2} & 0 & 0 \\ 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & b_{a,f,t} \end{bmatrix}, \tag{6.3}$$

$$\forall f \in I^F, \forall a \in A$$

F. Objective Function

Equation (7) is the mathematical expression of the objective function to optimize energy usage for a smart home. The objective function typically enhances energy consumption, comfort, security, or a combination of these factors. The smart home system's goals and restrictions are established by this function. The objective function of the IHEMS optimization consists of two parts, each with different decision variables (*Bn* (*s*, *i*), *Bm* (*s*, *i*)) [32]:

$$\begin{gathered} \min X = \sum_{s\in S} \varsigma^{N} Bm(\mathrm{s,i}) + \sum_{s\in S} \varsigma^{G} Bn(\mathrm{s},i) \\ \sum_{s\in S} \varsigma^{N} Bm(\mathrm{s},i) = \sum_{s\in S} \varsigma^{N} e^{NET}(\mathrm{s},i) + \sum_{s\in S} \varsigma^{N}\left[T_{a,s} - T^{set}{}_{a,s}\right] \\ \sum_{s\in S} \varsigma^{G} Bn(\mathrm{s},i) = \sum_{s\in S} \varsigma^{G} \sum_{s\in S} \varsigma^{N} e^{NET}(\mathrm{s},i) \end{gathered} \tag{7}$$

III. INTELLIGENT HOME ENERGY MANAGEMENT SYSTEM

A. IEMS Communication Design

Developing the communication component of an IHEMS requires establishing a strong and effective network that allows smooth interaction between different smart devices. The communication design should facilitate real-time data exchange, control commands, and even integrate intelligent decision-making algorithms. Figure 2 illustrates the communication component of an IHEMS.

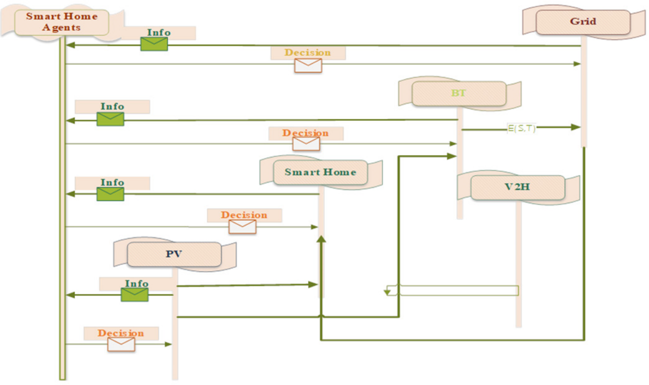

Fig. 2. IHEMS communication design: The communication system.

B. HAS Scheduling Controller Condition

A comprehensive smart home device management system's sophistication increases with BT/V2H and off-grid power alternatives. The objective function influences device scheduling and operational decisions. Appliances are classified according to their ability to operate during reduced electricity costs.

C. Scenario-Based MAS Scheduling Algorithm

This section concentrates on integrating V2H as a RES in the proposed system. The focus is on the states of electricity distribution, including the PV system, and the study of EV situations. Figure 3 shows different power distribution scenarios, such as regular EV charging, V2H charging and discharging, and configurations with and without a PV power supply. Each state entails additional overall cost and energy balance requirements and appropriate planning patterns. The proposed design seeks to manipulate how the V2H system affects energy use efficiency and reduces costs.

Real-time monitoring of power generation and consumption for EVs, and power exchange between microgrid, home, V2H, EV, and PV are considered. The utility grid provides power for both smart homes and EV charging. Agents, such as sinks, EVs, and smart home devices work together to control supply and timing. Equation (8) is used to determine the net cost of electricity consumption. This equation predicts the typical state-to-state charging model [33-34]:

$$\begin{cases} C_{HAs}^{T,SP} = G_{HAs}^{1} + G_{HAs,p}^{2} \\ = \sum_{j=1}^{j=T} P_{HAs}^{\cos t}(j) + \sum_{j=1}^{j=T} P_{Elec}^{\cos t}(j) + \Delta SoC_{EV} * Q_{EV}^{c} \\ Q_{EV}^{c} = \dfrac{C_{EV}^{rated}}{\eta^{ch}} * P_{Elec}^{\cos t} \\ \Delta SoC_{EV} = SoC_{EV},_{\max} - SoC_{EV},_{peak} \end{cases} \tag{8}$$

$$\begin{cases} C_{HAs}^{T,SP} = G_{HAs}^{1} + G_{HAs,p}^{2} \\ = \sum_{j=1}^{j=T} P_{HAs}^{\cos t}(j) + \sum_{j=1}^{j=T} P_{Elec}^{\cos t}(j) + \Delta SoC_{EV} * Q_{EV}^{c} \\ Q_{EV}^{c} = \dfrac{C_{EV}^{rated}}{\eta^{ch}} * P_{Elec}^{\cos t} \\ \Delta SoC_{EV} = SoC_{EV},_{\max} - SoC_{EV},_{peak} \end{cases} \tag{8}$$

Equation (8) is essential for calculating the average charging model, considering cost, energy balance, and scheduling. The aim is to reduce costs through the strategic use of PV and V2H and to highlight the need to integrate V2H as an alternative energy source. V2H supplies energy to the Home Agents (HAs) without the inclusion of PV, and the energy exchanged is solely sourced from the grid. The interaction involves coordination between the Sink, the V2H agents, and the HAs to manage supply and schedule. During normal conditions, V2H supplies energy to the Has and the PV is not involved. The Sink and V2H agents collaborate with HAs to manage energy supply and scheduling. The EV supplies power to HAs in this state. The EV operates with a minimum SOC, ($SoC_{(V2H),\ min}$). Equation (9) is utilized to calculate the total cost:

$$\begin{cases} G_{Net}^{2} = C_{sys,PV} + C_{sys,HAs} + C_{sys,TR} \\ C_{sys,PV} = \sum \phi(i) * C_{sys,HAs} * g(\delta) \end{cases} \tag{9}$$

PV and grid generate loads at specific time intervals (T_{PV}, T_{EV}), where T_{PV} refers to the typical period and T_{EV} represents the evening peak period. $\sum\phi(i)$ represents the installation cost (kW), where ϕ=on (1), Ω=off (0), and I is 0 or 1. The symbol δ denotes the net capacity and $g(\delta)$ denotes the investment interest rate (1/year (PV lifespan)) [35].

IV. SIMULATION RESULTS

A. Initialization

An experimental simulation was conducted to assess the performance and efficiency of the proposed algorithm designed to reduce the daily electricity cost of a smart home. Electrical appliances, solar energy, EVs, and storage systems were considered.

Solar radiation and outdoor temperature data were obtained from a meteorological database in Saudi Arabia [37].The experimental simulation lasted four days, and the computations were completed in 12 hours. The radiation and temperature data were acquired from the experimental database of the King Abdulaziz University. The daily solar meteorological data were employed to compute the anticipated solar output curve for both summer and winter.

Figures 4(a) and (b) illustrate the expected patterns of residential energy consumption during the summer and winter seasons. Figure 4(c) displays the input irradiance ranging from 0.8 to 1.0 W/m^2 between 8 a.m. and 3 p.m., while Figure 4(d) illustrates the overall usage, peaking at 10 kW during summer and 8 kW during winter. The simulation results demonstrate the efficiency of the proposed algorithm. EVs are often charged at home, and the recommended charging capacity is between 1.8 and 6 kW. According to Figure 4(e), the EV schedule includes departure and return at specific times, i.e. 8:00 am, 12:00 noon, 2:00 pm and 5:00 pm. The EV can travel up to 60 miles daily, the typical distance in Saudi Arabia. The assumptions consider aspects relevant to Saudi Arabia, such as mileage expectations and different toll situations. Figure 4(f) illustrates the daily schedule of the EV, including the times of departure and return. It is possible to consider assumptions about EV charging and travel patterns within the broader household energy management and planning context. According to the study results, the household energy use projections during the summer and winter months were accurate. EV charging habits and travel patterns can impact household energy dynamics and management techniques, particularly in Saudi Arabia. Time-Of-Use (TOU) costs for residential users are shown in Figure 4(e), which illustrates the residential energy price signal, including off-peak, average, and peak prices, and represents the pattern of the TOU energy price at different times of the day. Compared to Figures 4(e) and (f), the figure shows prices significantly higher during peak hours when demand exceeds generation. This way, users are incentivized to charge their electric vehicles and stationary battery storage at cheap electricity prices using 4 scenarios:

Scenario A: Solar radiation input: In winter, solar radiation decreases due to shorter daylight hours and increased possibility of cloud cover. Solar panels produce a relatively small amount of electricity, leading to increased reliance on stored energy or grid power. Solar radiation increases in summer due to longer daylight hours and more explicit weather conditions. Solar panels are highly efficient in generating electricity, reducing dependence on the grid and allowing excess energy to be sold back into the grid.

Scenario B: Energy consumption overall: Winter is characterized by high total energy consumption due to the need for heating. Energy consumption is highest in the early morning and evening hours when the temperatures are the lowest. In summer, the demand for cooling increases, resulting also in higher energy consumption. In the afternoon and early evening, when temperatures are highest, the energy consumption is highest.

Scenario C: Energy balance-excess electricity produced: Winter profile: The availability of surplus electricity is limited due to reduced solar output. Batteries accumulate and store excess electricity for later use. The summer profile has a significant surplus of electricity produced throughout the day, which can be stored or sold back to the grid. In winter, electricity demand is high, leading to frequent power shortages. As a result, replacing electricity from the grid is necessary, especially during peak demand periods. In summer, intermittent shortages occur, typically between early morning and late evening, when solar power production is at its lowest.

Scenario D: Vehicle connection status: EVs are typically charged during off-peak times, such as late at night or early in the morning, to take advantage of lower TOU costs. During the day, the electricity consumed is minimal due to low solar generation. Optimizing EV charging around midday, when solar generation is highest and TOU tariffs are lowest, allows for the most efficient use of solar energy while reducing costs. Overnight shipping is optimized to reduce tariffs.

Scenario discussions: These scenarios illustrate how energy management strategies must adapt to seasonal variations in solar radiation and energy consumption patterns. Efficient use of solar power and energy storage systems can lead to significant cost savings and improved energy security, particularly in regions with high energy demand and generation variability, such as Saudi Arabia. Integrating electric vehicles further enhances the energy system's flexibility, allowing optimized charging and discharging based on TOU pricing and energy availability

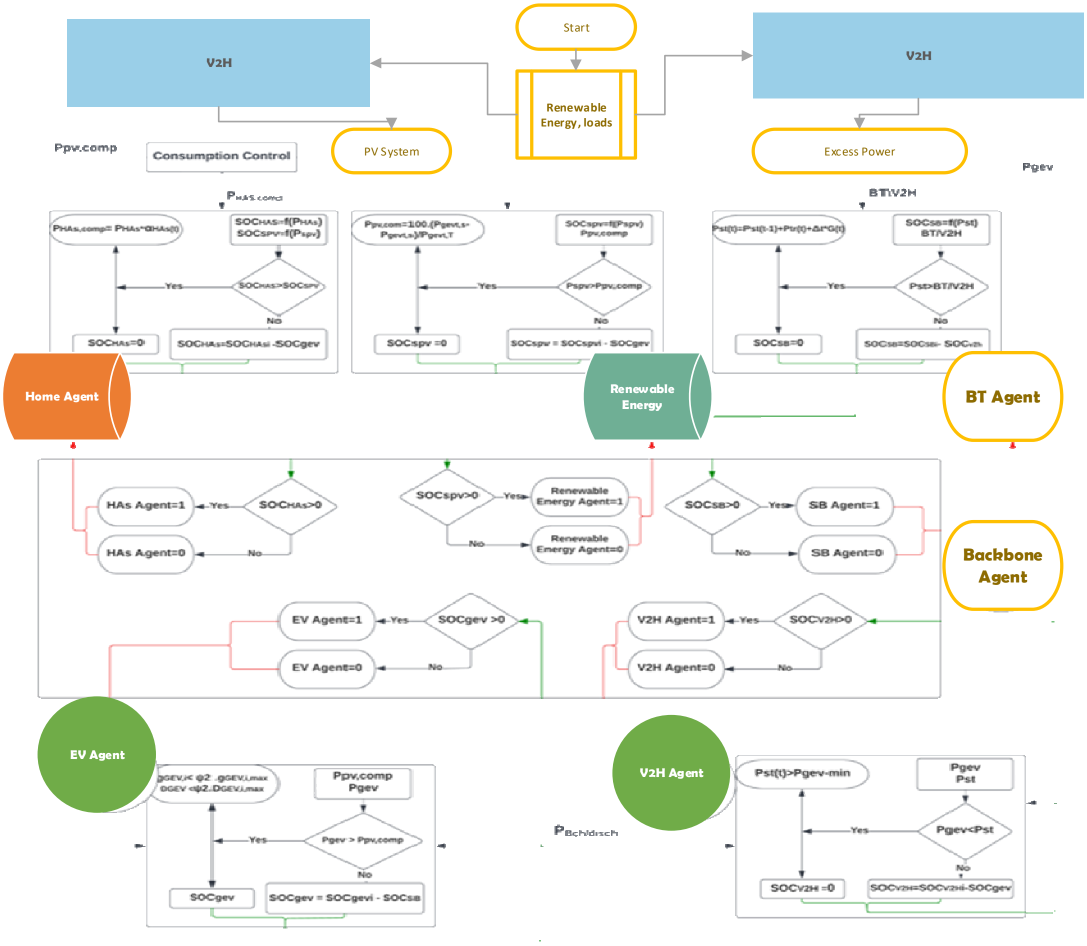

Fig. 3. The proposed IHEMS scheduling algorithm.

B. *Load Scheduling Capability Investigation*

Load scheduling capacity analysis is essential for optimizing energy use, lowering expenses, and improving system efficiency. To achieve this, it is crucial to list the appliances for load scheduling and demonstrate their load distribution patterns. Various appliances have various load distributions. Some appliances have set schedules, while others are flexible. Moving appliances to off-peak hours can save money and improve energy efficiency. Load scheduling can lower peak demand and reduce costs. Table I displays the convertible and nonconvertible appliance load distributions for each period. The portable appliances consumed 19.1 kW during the first and second periods. The Table also discloses the intervals required to turn on each device 24 times in advance. The households work primarily when solar PV panels generate excess energy during the peak hours (8 a.m.–2 pm) or when the real-time energy price is low. Before charging the V2H system, PV power is used to offset the residential energy consumption.

TABLE I. HOUSEHOLD PARAMETERS

Home Households	Total working duration	Minimum power (kW)	Maximum power (kW)	Starting Time	Ending Time
Φ1- Washing machine	1.00 h	1.58	2.50	09 pm	010 pm
Φ1- Vacuum cleaner	00.550 h	1.30	2.10	01 pm	03 pm
Φ1- Air conditioner		3.000	4.10	08 am	08 am
Φ1- Rice cooker	00.78 h	00.85	1.10	010 am	012 pm
Φ1- Humidifier	4.001 h	0.160	00.50	08 am	012 am
Φ1- Computer phones light	Full- time-24h	01.25	1.70	08 am	08 am
Φ1-Oven	2.00 h	2.000	5.00	05 pm	007pm
Φ1-Hairdryer	00.30 min	1.8000	01.90	08 am	08.30 am
Φ1-Dishwasher	3.00 h	1.8500	2.400	08 am	011am
Φ1-Electrical water pump	Full-time-24 h	1.500	02.300	08 am	08 am
Φ1-Robot	2.00 h	2.000	3.600	011am	0012 pm

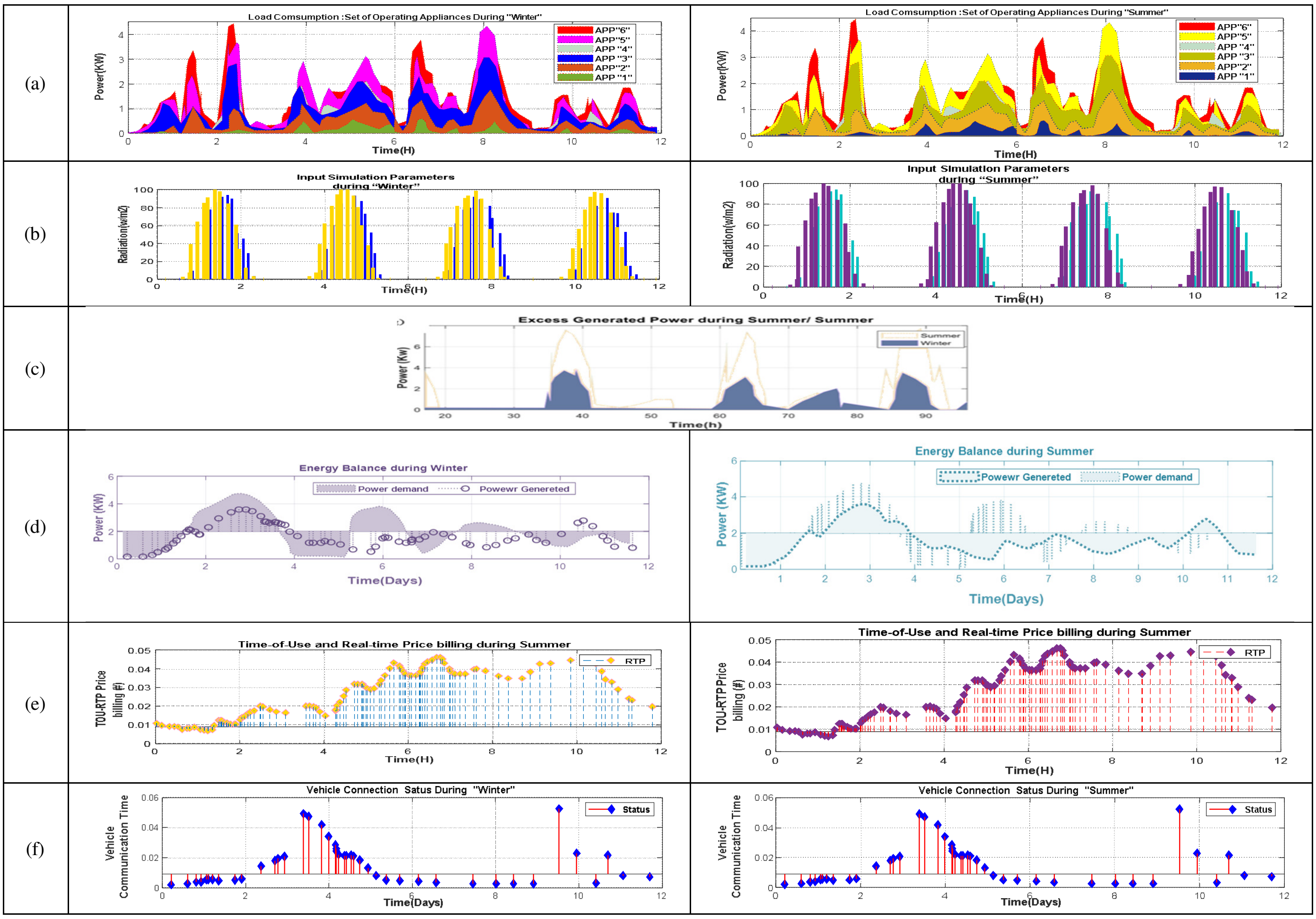

Fig. 4. (a) Load consumption (b) simulation input, (c) excess generated power, (d) energy balance, (e) TOU and real time price billing, (e) vehicle connection status during summer and winter.

C. Discussion

We conducted a full 12 flight in various weather conditions, including sunny and cloudy. Our results show that the amount of energy used was almost the same in all scenarios. This suggests that variations in meteorological conditions over a short time may not significantly impact energy consumption. Extending the observation period is essential to effectively identify changes in energy consumption patterns influenced by weather or other environmental factors. By extending the interval to three days, we may obtain a more comprehensive data set, allowing us to detect and analyze subtle fluctuations in energy use that may go unnoticed over shorter periods. Extending the duration of the study could provide a better understanding of how different weather conditions affect energy consumption over time.

D. Power Generation and Consumption Timing

V2H/EV systems can affect household energy consumption by using PV to recharge electric vehicles. V2H charging allows surplus PV energy to be deployed, which can be sold back to the grid. This setup provides financial benefits to local consumers and promotes renewable energy utilization during specific times. The system provides V2H power data to meet power requirements or offer additional power as needed. Solar PV systems can supply power to households during certain times, reducing the need to purchase electricity from the grid during peak-cost hours. V2H employment is limited to specific times due to its low capacity. EVs are connected to the grid from 8 pm when the PV power is minimal (Figure 5(b)). Then, the EVs transfer the V2H energy load, reducing grid electricity consumption.

Charging employing grid energy is recommended during times of minimal hourly costs. To ensure driver satisfaction, charging the battery before departure is crucial (Figure 5(a)). Limiting V2H and EV discharge cycles is advised to prolong battery life. Figure 5(c) illustrates the relationship between the grid and IHEMS. The findings suggest that implementing dynamic systems with PV and V2H/EV technologies can improve energy efficiency, reduce expenses, and promote the use of RESs. Integrating V2H and Grid-to-Vehicle (G2V) charging and discharging operations can improve the efficiency and sustainability of these systems (Figure 5(d)).

E. The Impact of Travel Distance on V2H

This work discusses the SOC of the H2V (SoCV2H) for varying journey distances and the effects of vehicle travel characteristics on scheduling day trips in Saudi Arabia. Additionally, it explores how climatic circumstances can impact fluctuations in full-day load power distribution and surplus solar energy distribution (Figure 7). Day trips are categorized based on average travel distances: 80 km, 120 km, and 180 km. In this vein, EV control depends mainly on the vehicle's movement activity, which can vary greatly. For short travel distances, the SOC drops by less than 50% after 8:00 pm.

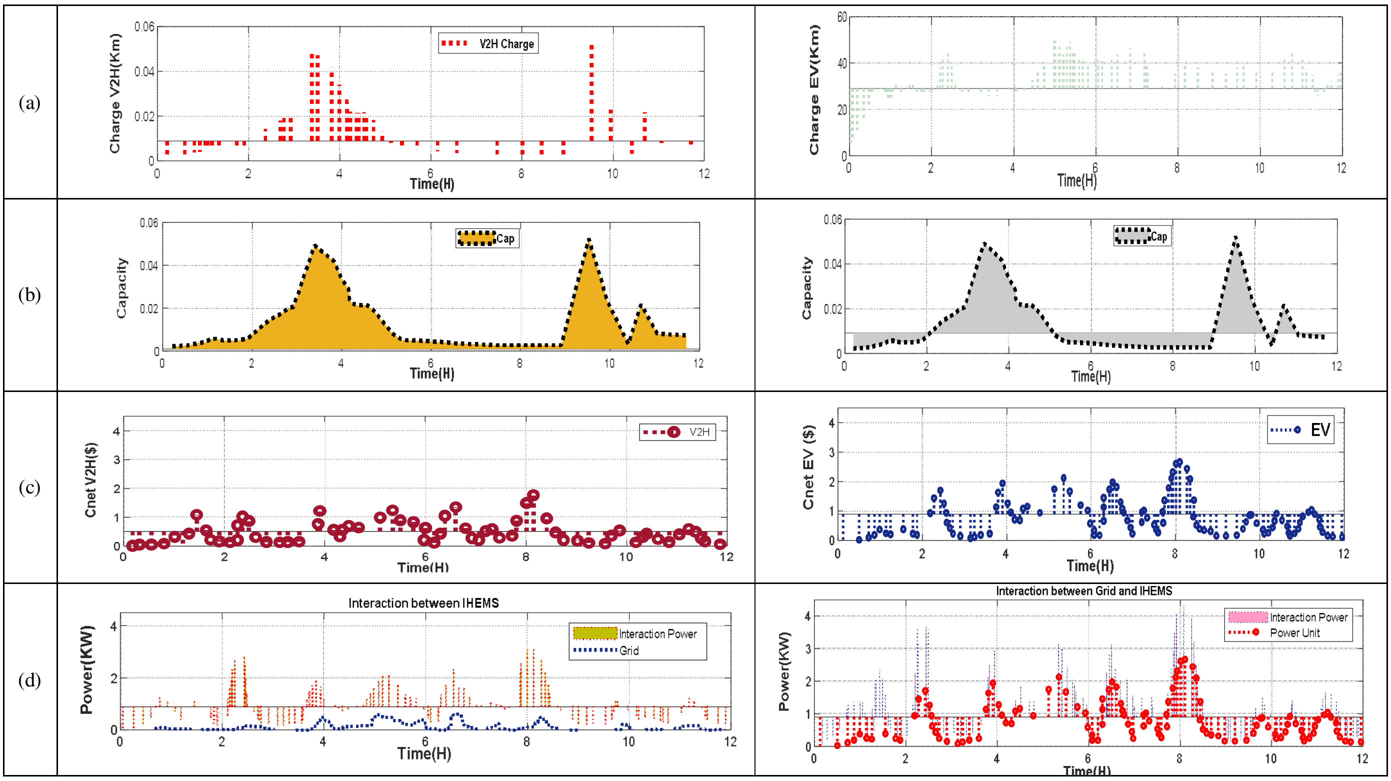

Fig. 5. (a), (c) Power trading between the Grid and IHEMS, (b) total power storage capacity of V2H/V2G, (d) charging/discharging power.

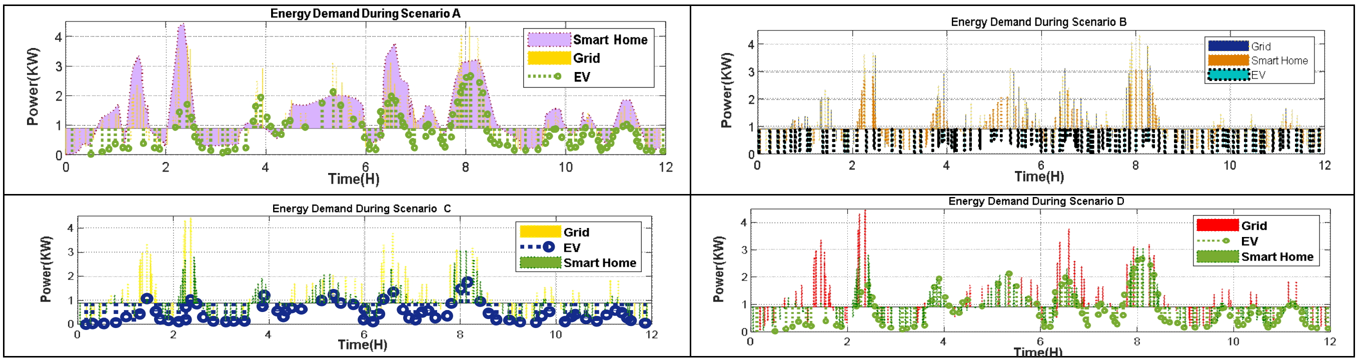

Fig. 6. Energy demand of scenarios A, B, C, and D.

After 2 hours, the charging state voltage drops by less than 55% for medium travel distances. At 6:30 pm, the extended travel distance exhibits that the SoCV2H begins to decrease and becomes less than 50% after 10:30 am, manifesting the effect of different trip periods on the charge level in the car battery. The energy distribution of full-day demand and the excess solar energy fluctuates depending on the prevailing weather conditions. Residential energy use peaks between 5:00 pm and 10:15 pm. So, the power distribution strategies should take weather patterns into account to achieve maximum efficiency. When scheduling daily trips in Saudi Arabia, factors such as travel time, vehicle movement, and their impact on SoCV2H must be considered. Climate-related differences in energy distribution highlight the need for adaptable solutions to improve the use of RESs, and that of particularly solar energy.

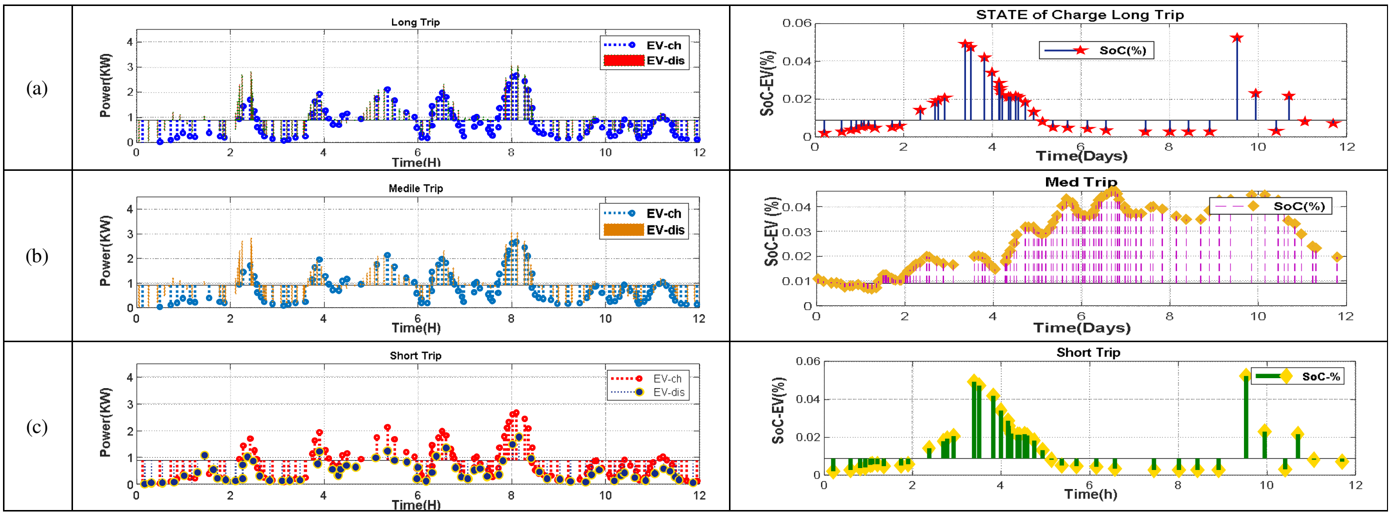

Fig. 7. Effect of travel distance on SoC V2H: (a) long trip, (b) medium trip, (c) short trip.

F. Discussion: The Environmental Impact

PV systems, EVs, and V2H technologies are popular research topics due to their significant impact on the environment, the adoption of RESs, and the associated costs. This paper examines the benefits of low-carbon energy and the cost-effectiveness of solar energy. While the initial investment is significant, the system has low long-term operating costs. The use of clean energy grids can have a positive effect on the environment of Saudi Arabia.

To achieve sustainable mobility, EVs and RESs must work together. Although EVs have a higher initial cost, they are more cost-effective in the long run due to their reduced operating and maintenance expenses. Government subsidies and advancements in battery technology are driving down the costs of electric automobiles. It is crucial to consider the environmental consequences of the energy decisions taken. V2H enables the sharing of electricity between EVs and households, which can increase the utilization of RESs. It stores and distributes surplus energy, minimizing waste and enhancing efficiency. V2H improves the storage of renewable energy, increasing dependability and adaptability. It also helps maximizing the PV energy during peak sunlight hours.

Integrating PV, EV, and V2H technologies can optimize stored energy consumption, reduce grid usage during peak demand, and reduce cost. Consistent innovation, supportive legislation, and infrastructure development are all necessary to achieve maximum benefits in Saudi Arabia's Sectors.

The findings of this study reveal that integrating RESs and smart homes with an MAS has a significant positive impact on the environment. This study explores the interaction and support of these environmental sustainability components. Integrating MASs with RESs and smart homes can reduce carbon emissions, increase energy efficiency, reduce waste, and align energy use with clean energy sources, thus encouraging sustainable living. The proposed methodology aims to harmonize energy consumption with ecologically friendly practices and promote a culture of conscious consumption. This approach enhances energy production, transmission, and consumption, reducing environmental damage and creating a more robust and efficient energy grid in Saudi Arabia.

V. CONCLUSION

This paper examines the use of Vehicle-to-Home (V2H) and solar systems to effectively manage peak energy consumption, reduce costs, and develop a precise Integrated Home Energy Management System (IHEMS) strategy. It delves into the intricate dynamics of V2H technology, analyzing its impact on reducing peak energy demand and consequently lowering prices within renewable energy systems. The study also emphasizes the strategic integration of renewable energy and energy recovery systems during peak hours. The IHEMS system is designed to use storage and recovery mechanisms to manage and mitigate fluctuations in energy production and consumption effectively. In particular, the system is designed to adjust autonomously to avoid unanticipated oscillations, thereby increasing the overall stability. Through meticulous analysis, this study aims to unravel the influence of V2H and photovoltaic (PV) systems on household energy consumption and net electricity use, shedding light on their potential as transformative elements within residential energy management paradigms.

When considering EVs, it is essential to contemplate the duration of driving and align the energy consumption with the vehicle usage. Global weather conditions highlight the impact of climate change on energy production and consumption. The results indicate that the proposed system meets HEMS's charging power quality and fluctuation resistance criteria. In this vein, it is vital to practice energy conservation. Deploying the proposed methodology, combining V2H technology with an IHEMS can save up to 40%. In a MAS simulation, the V2H charge state achieved a success rate of 51% when solar generation was restricted.

Future work could improve the scalability and efficiency of solar and V2H systems for peak energy control in residential environments. Developing sophisticated control systems and optimization algorithms designed explicitly for V2H integration can improve energy efficiency and save costs. In addition, exploring the possible links between V2H technology and emerging energy storage technologies, such as advanced battery systems or hydrogen storage, may open up new prospects for reducing peak energy demand and improving grid adaptability.

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