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Efficient Energy Distribution for Smart Household Applications

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Abstract: Energy distribution technique is an essential obligation of an intelligent household system to assure optimal and economical operation. This paper considers a small-scale household system detached from the power grids consisting of some electrical components in day-to-day life. Optimal power distribution generated from a photovoltaic system is vital for ensuring economic and uninterrupted power flow. This paper presents an optimal energy distribution technique for a small-scale smart household system to ensure uninterrupted and economical operation. A photovoltaic (PV) system is considered as the primary generation system, and a battery energy storage system (BESS) is viewed as a backup power supply source. The actual load and PV generation data are used to validate the proposed technique collected from the test household system. Two different load profiles and photovoltaic power generation scenarios, namely summer and winter scenarios, are considered for case studies in this research. An actual test household system is designed in MATLAB/Simulink software for analyzing the proposed technique. The result reveals the effectiveness of the proposed technique, which can distribute the generated power and utilize the BESS unit to ensure the optimal operation. An economic analysis is conducted for the household system to determine the economic feasibility. The capital investment of the system can be returned within around 5.67 years, and the net profit of the system is 2.53 times more than the total capital investment of the system. The proposed technique can ensure economical operation, reducing the overall operating cost and ensuring an environment-friendly power system. The developed strategy can be implemented in a small-scale detached interconnected smart household system for practical operation to distribute the generated energy optimally and economically.

Keywords: smart household system; photovoltaic system; battery energy storage system; energy distribution technique

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1. Introduction

Global energy use has increased dramatically in recent decades, resulting in huge increases in air pollution. Furthermore, the increasing cost of fossil fuels and their dwindling supply have led industry researchers and engineers to examine and suggest a more sustainable energy resource alternative [1,2]. The proportion of home power use is in-

creasing day by day as residents' living standards keep advancing [3,4]. Household energy demand consumes more than a third of the total primary energy supply [5]. In this regard, a cost-effective energy management approach for households is urgently needed to meet sustainable long-term requirements [6]. Solar photovoltaic (PV) and an energy storage system (ESS) offer a compelling opportunity to address various concerns to our energy supply's security and economic sustainability [7–9]. As PV output is affected by weather, home PV systems are commonly combined with a stationary battery as an ESS to optimize the use of surplus energy. However, coordination of PV, ESS and load is not straightforward. Therefore, optimal energy management for a household is becoming increasingly popular [10]. Most energy distribution techniques for household systems reported in the literature are based on optimal controllers [11]. Loads and energy resources must be forecasted in advance for these researches; hence, the efficiency of optimal techniques is largely determined by the accuracy of prediction models. Besides, computation times for these optimal home energy management systems (HEMSs) can potentially be much longer, especially when applying multiple constraints and shorter sample intervals.

To reduce daily household energy expenses and maximize photovoltaic self-consumption, Elkazaz et al. proposed a hierarchical two-layer home energy management system. This study assumes perfect forecasting of PV and load data. The developed technique can reduce the daily energy cost and can increase PV self-consumption. However, it is difficult to achieve in practice in a detached interconnected household system due to the uncertain load and intermittent output of the PV system [12]. A stochastic dynamic programming framework for a smart house has been developed in ref. [13] to address the issues associated with intermittent PV sources. In this research, grid to vehicle, vehicle to home and vehicle to grid are among the operational modes defined. The developed technique can achieve the overall cost savings of the system. However, the key problem of this technique is the availability of electric vehicles (EVs) as EVs can only deliver electricity while parked. Furthermore, EVs are yet to be widely deployed. Besides this, this technique is more suitable for a grid connected residential power system rather than an islanded interconnected household system. Basit et al. proposed a dijkstra algorithm to reduce the optimization complexity of a smart home. The proposed technique shows less optimization complexity. However, the generated energy distribution technique is not well investigated for a smart household system [14]. Piazza et al. developed a two stage optimization-based energy management technique for a smart building to reduce load uncertainty. Low computational complexity and single directional data transfer are the significant advantages of the developed method. Thus, this research does not present analysis on the PV power utilization for optimal and economic operation of a detached household system [15]. A mathematical method-based study for smart household energy management (EM) algorithm is developed in ref. [16]. The developed algorithm can minimize the operational cost of the system. However, the EMS proposed in this research ignored the economic impacts on smart household system.

Xiaolong et al. proposed an EM technique for office building. A virtual energy storage system (VESS) and a vehicle to building control technique is presented in this research. The proposed technique can smoothen the power exchange on the point of common coupling (PCC) of a grid connected household system. The research does not present energy distribution for a detached household system for economical operation and the forecasting operation is not clear [17]. Xinda et al. proposed the three controlling and sizing technique of energy storage to ensure optimal energy management. The developed techniques can achieve the research objectives including the power imbalance reduction. Thus, computational duration and complexity are the main disadvantages of the proposed techniques [18]. The effect of load shifting with a battery system has also been overlooked in ref. [19]. In day-ahead and real-time energy markets, a hybrid robust-stochastic optimization model for smart home energy management is investigated in ref. [20]. However, no economic analysis is presented in this research. Thus, the applicability of these studies for a smart household system in a real scenario remains ill defined. Markakis et al. proposed

an intelligent energy brokerage blockchain based framework for a small energy producer, i.e., solar system. The created system inhales massive volumes of bigdata derived from smart metering on distributed smart energy grids and enables automated power trades between participants in a specialized marketplace [21]. A multi-layer method combined with binary particle swarm optimization is presented in ref. [22] for optimizing a smart grid. Both techniques are suitable for a smart grid; hence, they are limited for optimal power distribution for a small-scale detached household system.

Overall, the available literature suggests that the research in this area is still in its infancy, with a slew of unresolved concerns. To the authors' best knowledge, efficient energy distribution in the detached interconnected smart household system context is still unreported in the existing studies. As a result, this work investigates an optimal energy distribution technique concept for a detached interconnected smart household system. A novel energy distribution technique is proposed, and the results of the simulations are reported using real system data. The contributions of this study are as follows:

An optimal, simple and effective energy distribution technique for a detached small-scale smart household system is developed in this research to distribute the generated electrical energy optimally and economically. An economic benefit analysis of the energy distribution technique is presented in this research to demonstrate its economic feasibility. The novelty of this research lays on the development of an energy distribution technique for a small-scale interconnected smart household system which is completely isolated from the primary grid.

The proposed energy distribution technique is validated under real circumstances with actual variable load and PV generation data. A test smart household system is designed using MATLAB/Simulink software to investigate the developed energy distribution technique.

Simulation case studies are conducted to evaluate the performance of the proposed strategy. The developed technique shows robust behaviour which can utilize the PV and BESS unit in a concise manner. The developed technique can enable use of the generated surplus energy to charge the BESS unit as well as the energy arbitrage operation with the interconnected smart household system.

This paper is organized as follows: A small-scale smart home simulation model is designed using the real PV and load data (Section 2). This test household system is used to analyze the proposed energy distribution technique. An optimal energy distribution technique is developed for a small-scale smart household system by considering cost minimization (Section 3). The proposed technique was tested using simulation case studies under real load conditions and actual PV data (Section 4). The economic impact of the proposed energy distribution technique is investigated (Section 5). Finally, this research is concluded with key findings and future directions are provided (Section 6).

2. Household System

A small-scale smart house is considered in this study which is fully detached from the primary grids. This system is designed considering a remote area in Malaysia where there is no access to the national grid. This designed household model is also feasible for any type of remote area around the globe. This household system is interconnected with the neighbourhood household system by a common bus bar to share the surplus energy among each other. This household system is operated independently and has its own power generation systems, connected loads and integrated battery storage system. A photovoltaic system is considered as a primary power generation system and BESS is considered as a backup power source for the connected loads. The PV system is considered as 2.5 kW to support the connected loads and to charge the battery storage as well as to perform the energy arbitrage operation. The rated power of the BESS unit is considered as 0.6 kW and the energy capacity is 4.5 kWh. The energy capacity of the BESS unit is calculated considering the load profile and the operational periods of the BESS unit to support the

connected loads. The capacity of the PV system is determined based on the demand profile of the system, the required energy of BESS unit to charge and the energy arbitrage operation. The surplus generated energy from the PV unit will perform the energy arbitrage operation after the battery is fully charged. Therefore, there will be no energy wastage of the system. A maximum power point tracking (MPPT) inverter is connected to the PV system to extract the maximum output from it. The system frequency and supply voltage are 50 Hz and 220 V, respectively. A schematic diagram of the household system is shown in Figure 1 and the key information of the test household system is recorded in Table 1.

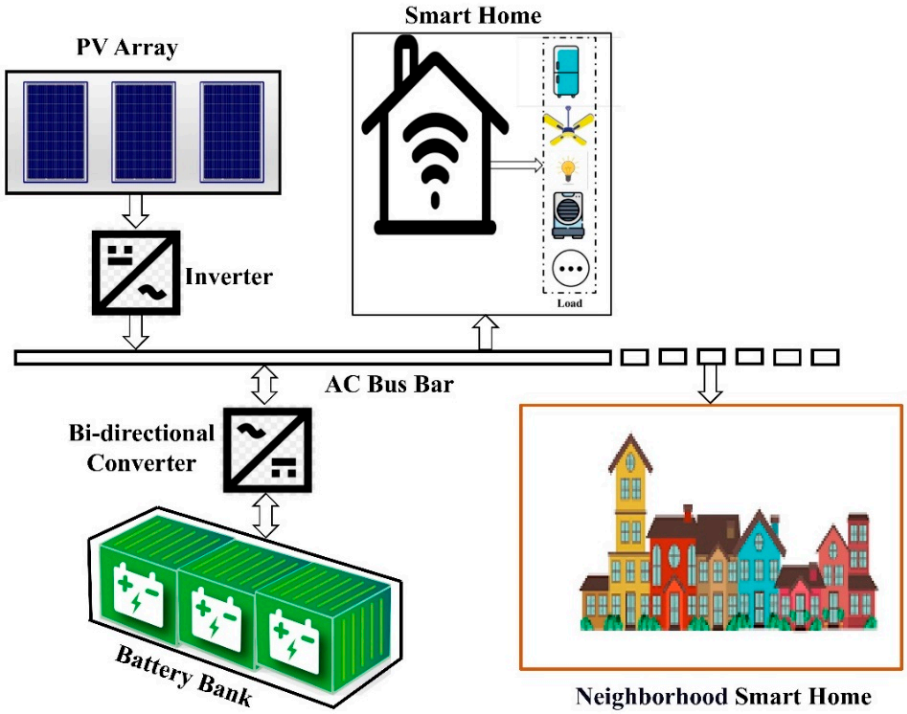

Figure 1. Schematic diagram of the test household system.

Table 1. Key information of the test household system.

No.	Consideration	Description
1	Operation type	Detached from main grid
2	Primary generator	PV system
3	Type of PV cell	Second generation PV cell
4	Backup power source	BESS unit
5	Power supply for connected loads	AC power
6	System frequency	50 Hz
7	Supply voltage	220 V

An isolated microgrid system model with photovoltaic and battery storage system can be found in ref. [23] which is similar to the designed model of this research. The test household system is designed in MATLAB/Simulink environment and MATLAB 2021a version is used to design the Simulink model. Basic Simulink blocks and Sim-power blocks are mostly used to develop the test household system. The time varying load model of the smart household system, the PV system model with MPPT inverter, the BESS model with Bi-directional converter and the transmission line along with interconnected smart homes are the major sub-models of the designed test household system. Three phase RLC loads with timer blocks are used to design the variable load model, IGBT with LC filter is used to designed bi-directional converter and a DC–AC inverter with LC filter and Math-

function to implement MPPT algorithm are used to design the MPPT inverter in MATLAB/Simulink software. The variable loads are considered for 15 min time intervals to achieve more accurate and realistic load profile. The Perturb and Observe (P&O) algorithm is implemented as an MPPT algorithm to extract maximum benefit from the PV system.

2.1. Electrical Demands and Connected Loads

The daily demand profile of a day in summer and winter of the test household system is shown in Figure 2. Two different load profiles are considered in this work. The real-time load data is collected from a real household system located in Malaysia to validate the proposed energy distribution technique. For the day of summer, the maximum demand is around 0.98 kW where the minimum demand is around 0.28 kW. In contrast, the maximum and minimum demands are around 0.86 kW and 0.25 kW, respectively, for a day in winter. The demand of the household system gradually increased from the beginning of the day and reached the peak level around 11:30 am and 12 pm for the days of summer and winter accordingly. Due to the daily activities of the considered household system, most of the residents remain at home during these periods. The operation of more connected electrical components results in these peak demands. After the peak demand, the demand profile starts to decrease gradually and during the evening periods the evening peak appears on the system for both load profiles. The required power of the household system is highly dependent on the connected loads at a particular time period.

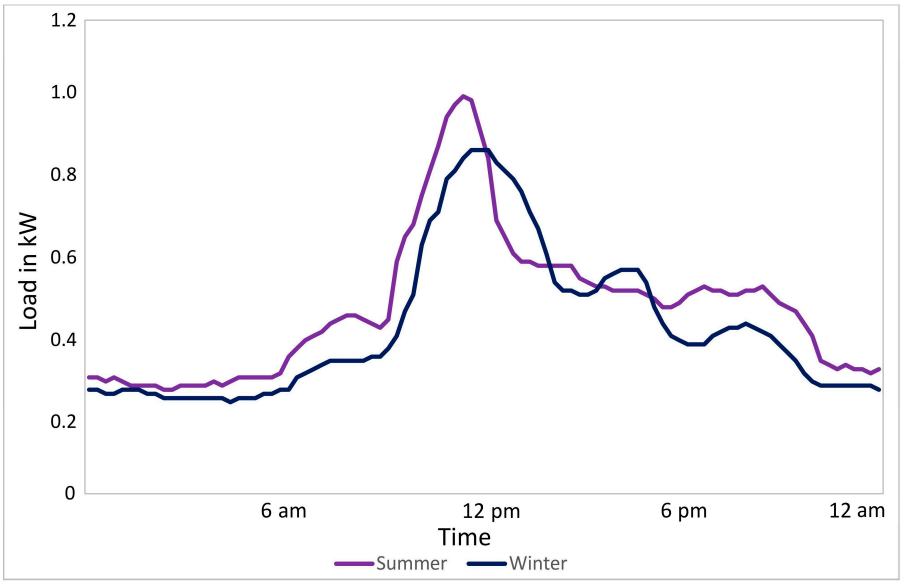

Figure 2. Demand profiles of the test household system.

The connected available loads and electrical components are listed in Table 2. The household system is a small-scale detached power system that is equipped with some electrical components including a refrigerator, fans, LED light bulbs, an LED television, an air cooler, exhaust fans and some other equipment. The connected loads operate at a certain time based on the availability of the operators and operating conditions.

Table 2. Electrical equipment of the test household system.

No.	Electrical Components	Quantity	Rated Power of One Component (Watt)
1	Refrigerator	1	250
2	Fan	4	75
3	LED Light bulb	6	15
4	LED Television	1	80
5	Air Cooler	1	150
6	Exhaust Fan	4	75
7	Others	-	100

2.2. Generation of Electrical Power

The household system is fully detached from the primary grid, which operates independently. The household system has its own power generation system. A renewable energy resource, i.e., a PV system, is used to generate electrical power to meet the demand profile. The test household system is a low-capacity power system where a PV system is considered as a primary generator, and the capacity is 2.5 kW. An MPPT inverter is connected with the PV system to achieve the maximum benefit from it. The Perturb and Observe (P&O) algorithm is applied to design the MPPT inverter. An RC filter is connected with the MPPT inverter to compensate for the unnecessary ripples from the PV generation. A battery energy storage system is considered as a backup power source to meet the demand when the PV generation is unavailable with the system. A bidirectional converter is connected with the BESS system to convert AC power to DC and DC power to AC.

The power generated from the PV system is highly dependent on natural conditions. During high solar irradiation and satisfiable module temperature, the generation power from PV is high and low generation power extracts for the opposite conditions. This research considers two different scenarios including summer and winter for investigation purpose. For a day in summer, the PV generation is higher than that of winter because of the variation of solar irradiation and module temperature. The real-time solar data is collected from a practical PV generation site. Figure 3 shows the power generation from the PV system of two different scenarios. The key information of the generation sources is recorded in Table 3.

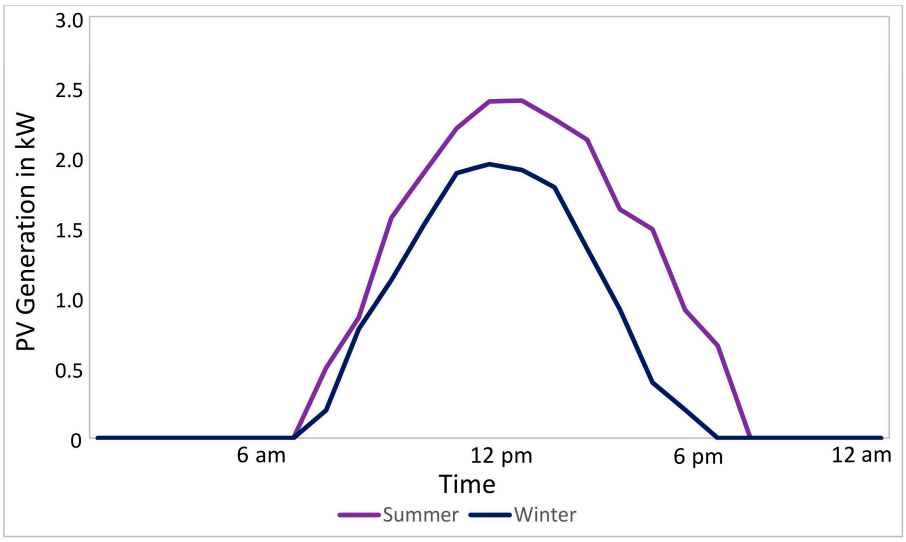

Figure 3. PV generation in a day of summer and winter.

Table 3. Key information of the power supply resources.

No.	Consideration	Description
1	PV system size	2.5 kW
2	Type of inverter	MPPT inverter
3	PV output voltage	220 V
4	BESS size	0.6 kW
5	BESS storage capacity	4.5 kWh
6	Type of converter	Four switch bi-directional converter
7	BESS storage voltage	12 V
8	BESS output voltage	220 V

3. The Proposed Energy Distribution Technique

The proposed energy distribution technique is developed to share the generated power to all the connected electrical components of a small-scale smart household system optimally. The purpose of this study is to propose an optimal energy distribution technique and evaluate its effectiveness. Under realistic circumstances, this proposed technique shows robust behavior even with different load cases under various circumstances, which indicates the effectiveness of the technique. It also revealed that the proposed technique can provide the desired performance regardless of variation in load and PV data. Therefore, any missing, abnormal or changes of data do not affect the performance or the optimal operation of the developed energy distribution technique.

The developed technique can handle the power absorption and injection of the BESS unit. When the battery needs to be charged and discharged, the developed technique can identify and control the operation. It can also perform energy arbitrage operations which can provide extra earnings for the household system and reduce the wastage of electrical energy. The proposed techniques control three major operations including optimal energy sharing among the electrical resources, proper utilization of the PV system and optimal utilization of surplus power for reducing the operational cost of the system. The household system with the developed energy distribution technique can achieve some significant benefits including: Energy crises such as energy shortfall can be reduced, surplus energy and energy mismatch can be mitigated and overall operational cost can be decreased, which will minimize the financial crisis. The flowchart of the proposed technique is shown in Figure 4.

Let,

PV_{out} = Output power from PV system
D_P = Demand of the system
$BESS_{out}$ = Output power from BESS
$S_P = PV_{out} - D_P$ = Surplus power from PV generation system
C_P = BESS charging power
SOC = State of charge
SOC_{max} = Maximum State of Charge
SOC_{min} = Minimum State of Charge

3.1. Operating Principle of the Developed Energy Distribution Technique

The energy distribution technique is developed in this research to ensure optimal and economic power sharing among different electrical resources connected to the detached smart household system. The considered household system is interconnected with another neighbourhood smart household system to share electrical power.

The proposed energy distribution technique starts working with checking an operational condition such as $PV_{out} \geq D_P$. If the output power from the photovoltaic system is not greater than or equal to the demand of the system, the proposed technique will enable two different operations based on the state of charge (SOC) condition of the battery storage system, $SOC > SOC_{min}$. When the SOC is greater than the minimum state of charge

(SOC_{min}), the required power will be supplied from the BESS system. This means that the proposed technique will enable to discharge the BESS unit to deliver the stored energy to the system. The discharging operation will continue until the SOC is less than or equal to zero $SOC \leq SOC_{min}$. If the system requires energy after completing the discharging operation, the system will move forward to shut down or the system will purchase energy from the interconnected household system. When the SOC is not greater than the minimum state of charge (SOC_{min}), the system will also move forward to shut down operation. This means the proposed technique will shut down the system due to insufficient power supply or the system will purchase the electrical energy form the interconnected neighborhood smart household system. The system will return to normal condition when the supply power is sufficient to handle the connected loads.

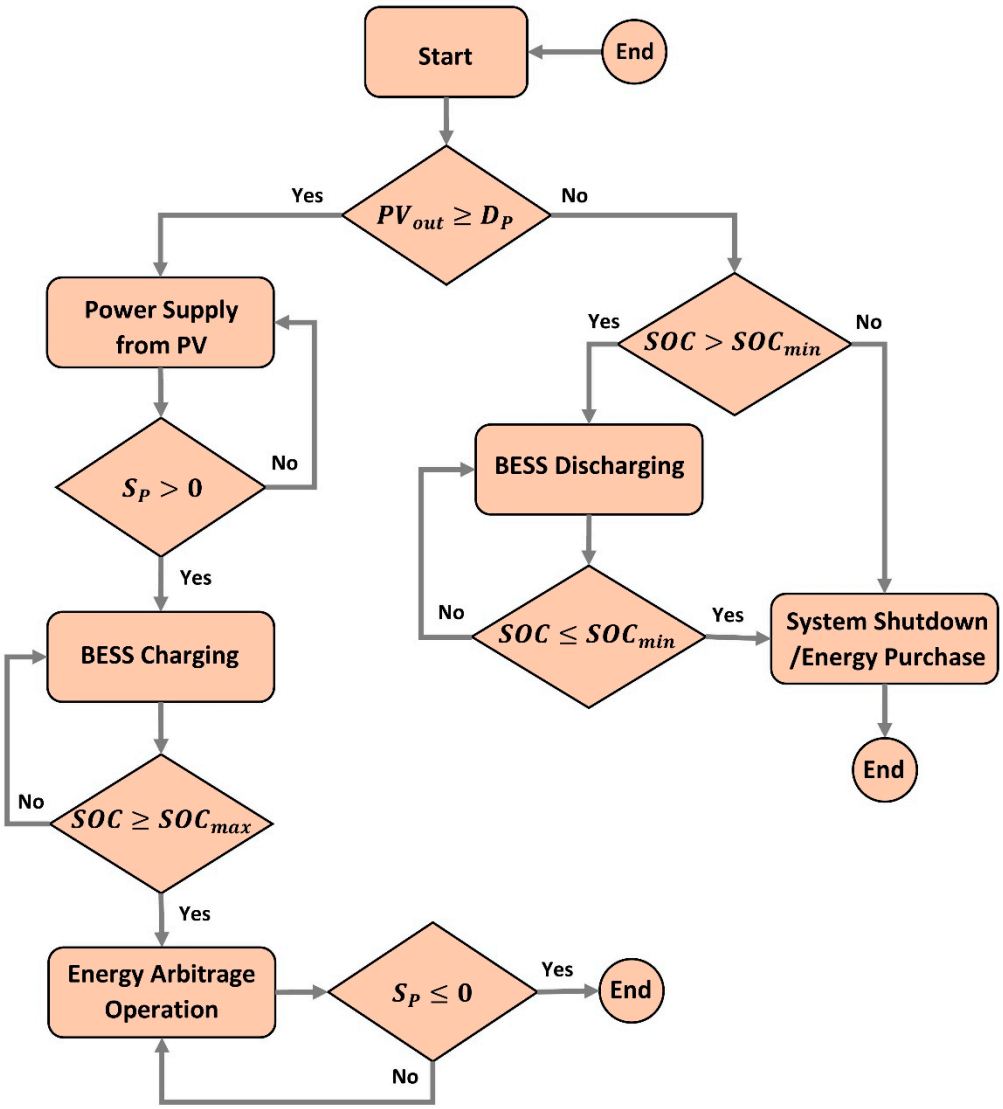

Figure 4. Flow chat of the developed energy distribution technique.

In contrast, if the output power from the photovoltaic system is greater than or equal to the demand of the system $PV_{out} \geq D_P$, the power will be supplied from the PV system. After enabling the power supply from the PV system, the developed technique will check if there is any surplus energy (S_P) available with the system. If S_P is greater than Zero $S_P > 0$, it means surplus energy is available with the system and if the surplus energy is enough to charge the battery storage system, the BESS unit will start absorbing the surplus energy for further operation. On the other hand, if S_P is not greater than Zero (0), it means

surplus energy is not available with the system. Then, the PV unit will continue to deliver electrical energy to the system, and the proposed technique will wait for sufficient surplus energy for further operation.

After starting the charging operation of the BESS unit, the proposed strategy will keep checking the state of charge (SOC) level to enable the next decision. If SOC is not greater than or equal to the maximum state of charge (SOC_{max}), the BESS unit will keep charging. Besides this, if SOC is greater than or equal to SOC_{max} ($SOC \geq SOC_{max}$), it means the BESS unit is fully charged and the proposed strategy will enable the energy arbitrage operation.

The energy arbitrage operation basically consist in supplying or selling the extra electrical energy to the interconnected smart household system. The operation will be enabled until the system has excess available surplus energy. The proposed technique will check whether the surplus energy is less than or equal to zero ($S_P \leq 0$). If surplus energy is not less than or equal to zero, it means the system still has surplus energy for energy arbitrage operation. In contrast, if surplus energy is less than or equal to zero, it means the system does not have surplus energy for the energy arbitrage operation. The condition of the energy arbitrage operation is discussed in the next section in detail. After completing this operation, the proposed technique will complete one full cycle and will start its operation from the beginning.

3.2. Description of the Different Individual Operations

In this section, the description of the different individual operations of the proposed energy distribution technique are discussed to provide better insight.

3.2.1. Power Supply from PV

In this method, a photovoltaic system is the primary power generation source. Sufficient power generation from the PV runs the system uninterruptedly. When the generated power is higher than or equal to the existing demand profile of the system, the connected loads receive the required power from the PV system. The conditions of the power supply from the PV are as follows.

$$\begin{cases} PV_{out} > 0 \\ PV_{out} \geq D_P \end{cases}$$

3.2.2. Charging Operation of BESS

The proposed energy distribution technique handles the charging operation of battery storage prominently following some operational conditions. When the system satisfies all conditions of the developed technique, the power absorption operation will be enabled, and the BESS unit will start charging from the photovoltaic system. If the output power from PV system is greater than or equal to the demand of the power system, BESS charging power is greater than surplus power from the PV system, and the state of charge (SOC) is less than the maximum SOC (SOC_{max}), BESS will be allowed to charge from the PV system. When surplus power in the system produced by the primary generator exits, BESS will absorb the surplus power for the further operation. The charging operation of BESS will follow the dynamic charging rate adjustment formula [24]. Higher generation of PV will allow to charge the BESS rapidly. During midday, the output power from PV is usually higher than at other times. At that time, the battery storage will absorb the surplus power rapidly. In contrast, when the output power from PV is lower, BESS will be allowed to store the surplus power slowly. The developed strategy fixes the state of charge to prevent the BESS from overcharging or undercharging. This mechanism will maintain the lifecycle of the battery storage and improve the lifetime as well. The charging conditions of the battery storage from PV are as follows.

$$\begin{cases} PV_{out} \geq D_P \\ C_P > S_P \\ SOC < SOC_{max} \end{cases}$$

3.2.3. Discharging Operation of BESS

The BESS unit is considered as a backup power supply source in this research. The connected loads of the system will get the required electrical energy from the battery storage unit when the photovoltaic output power is absent or insufficient with the system. The stored energy of the battery has to be sufficient to fulfil the demand, which is the major condition for the discharging operation of BESS. If the output power from the PV system is lower than the demand of the power system, the state of charge (SOC) is higher than minimum SOC (SOC_{min}), and total output power from PV and BESS is higher than or equal to the demand, the BESS will be allowed to discharge to fulfil the demand. The discharging operation of BESS will follow the dynamic discharging rate adjustment formula [24]. The discharging power of the battery unit will follow the load profile. When the system requires more energy, BESS will discharge more power. In contrast, when the system requires lower power to support the connected loads, BESS will be allowed to deliver lower energy. This type of discharging operation will mitigate the energy wastage and improve system efficiency. The proposed strategy fixes the state of charge for the discharging operation to prevent over-discharging which will maintain the battery health and prevent the lifetime degradation. The discharging conditions of the battery storage to support the connected loads are as follows.

$$\begin{cases} PV_{out} < D_P \\ SOC > SOC_{min} \\ PV_{out} + BESS_{out} \geq D_P \end{cases}$$

3.2.4. Energy Arbitrage Operation

The output power from the primary generator is the main power source of this research. The photovoltaic system generates solar power during the daytime, which supports the connected loads as well as charges the battery unit. During a sunny day, the photovoltaic output power is usually high and more surplus power exists in the system. The surplus power is mostly utilized for charging the battery storage, whereas the excess energy after completing the charging operation of BESS performs the energy arbitrage operation. The excess energy will be sold to the neighbourhood household system to earn extra money. If the output power from the PV system is greater than or equal to the demand of the power system, state of charge (SOC) is higher than or equal to maximum SOC (SOC_{max}), and surplus power is higher than zero, the excess power can be sold to the neighbourhood smart houses. The conditions of the energy arbitrage operation of the system are as follows.

$$\begin{cases} PV_{out} \geq D_P \\ S_P > 0 \\ SOC \geq SOC_{max} \end{cases}$$

3.2.5. System Shutdown/Energy Purchase Operation

When the power supply resources fail to deliver the required energy of the system, the power system will shut down until sufficient power is available with the system to meet the connected loads or the system will purchase the required energy from the interconnected smart household system. If the output power from the PV system is lower than the demand, and the total output power from PV and BESS is also lower than the existing demand of the power system, the proposed energy distribution strategy will allow the system to perform a shut down operation or purchase the required energy from the interconnected smart household system until the power generation is enough to supply for the

connected loads. The conditions of the proposed strategy for system shutdown/ energy purchase operation are as follows.

$$\begin{cases} PV_{out} < D_P \\ PV_{out} + BESS_{out} < D_P \end{cases}$$

4. Results and Discussions

The simulation results of the proposed technique with two different scenarios including a day of summer and a day of winter are presented and discussed in this section. Case studies were conducted through MATLAB/Simulink environment with actual data which were collected from test household system.

4.1. Case Study 1: A Day in Summer

A sunny day in the summer season is the first consideration to evaluate the performance of the proposed technique. The power consumption in the summer season is slightly higher than that of the other season of the test household system. The load profile fluctuates from 0.31 kW to 0.32 kW from midnight to early morning, 12 am to 6:30 am. After 6:30 am, the electricity demand starts increasing gradually and around 11:30 am it reaches its peak value. The peak demand is around 0.99 kW a day in summer, which occurs for a very short period. The electricity demand starts decreasing gradually after the peak period and during the evening time it again increases slightly for a few moments.

Summer season is comparatively bright and heated for the test household system where power production from the PV system is relatively higher than that of other seasons. The capacity of the PV system used in this research is 2.5 kW. Around midday, the power generation is the highest where more surplus energy available to charge the battery storage system as well as to sell the excess energy to the neighbourhood household system. Figure 5a shows the load profile of a day in summer and the power generation from the PV system.

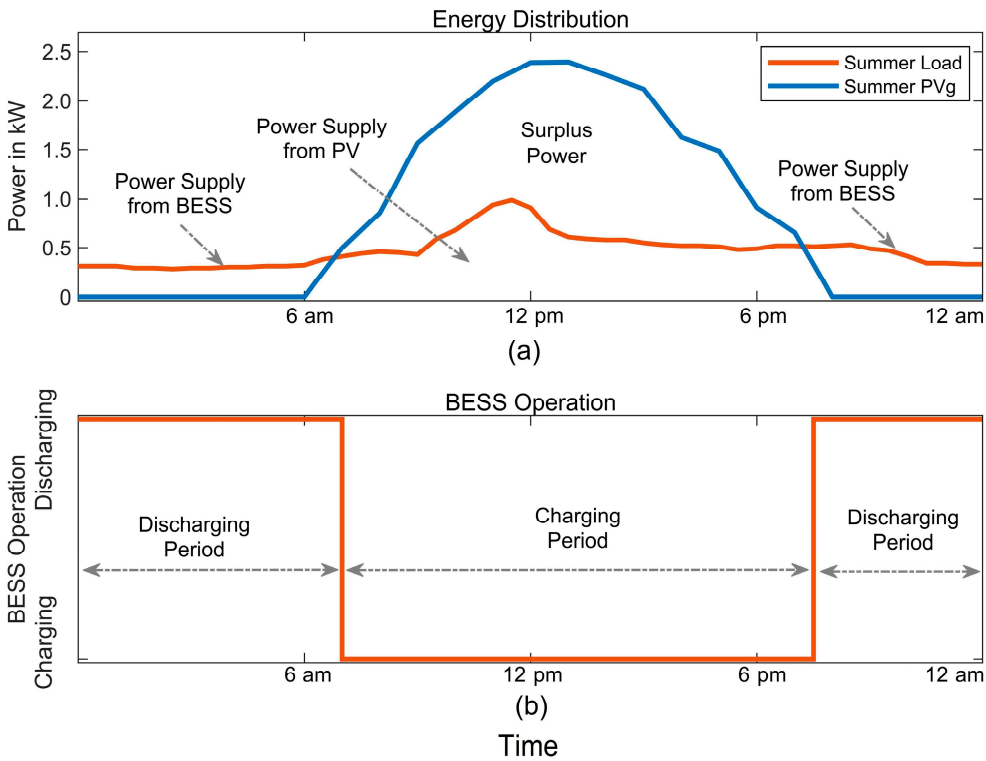

Figure 5. (**a**) Optimal power sharing operation of a day in summer, (**b**) Power absorption and delivering operation of BESS.

From midnight to early morning, from 12 am to 6:30 am, power supply from the PV system is not sufficient to fulfil the demand where the backup power source BESS unit delivers power to the connected loads. When PV generation is sufficient to fulfil the demand and the surplus power is available with the system, the BESS unit is allowed to absorb the extra power for further discharge operation. The charging operation follows the dynamic charging rate adjustment method. If PV generation is high, the BESS unit will charge rapidly, and the opposite is true for the low power generation. For the whole daytime, the power production from PV is satisfiable to charge the BESS unit as well as to perform the energy arbitrage operation. After that, during evening time the BESS unit starts the discharging operation to deliver the stored energy to fulfil the demand. The discharging operation also follows the dynamic discharging rate adjustment method. The household system can operate uninterruptedly because of the sufficient power generation and availability of backup power source. Figure 5b shows the charge–discharge operating periods of BESS unit.

During the whole daytime, the power generation from the PV system is sufficient to fulfil the demand profile and to charge the BESS unit properly. The PV system is considered as 2.5 kW in this research work. Sufficient surplus energy can be generated from the PV system for the charging operation of the BESS as well as to perform the energy arbitrage operation. Figure 6a shows the available surplus power generated from the PV system during the daytime.

The surplus power is absorbed by the BESS unit to enable the discharging operation for the connected loads. State of charge (SOC) exhibits the charging and discharging state of a storage system. Figure 6b shows the change of SOC for charging and discharging operation. At the evening time, power from the PV system is not available where the BESS unit needs to be discharged and SOC starts decreasing from 90%. The maximum SOC is considered as 90% in this research for optimal operation of the BESS unit. From midnight to early morning, the discharging operation continues and the SOC decreases gradually. At the availability of PV power, the BESS absorbs electrical power and the SOC starts increasing up to its maximum limit.

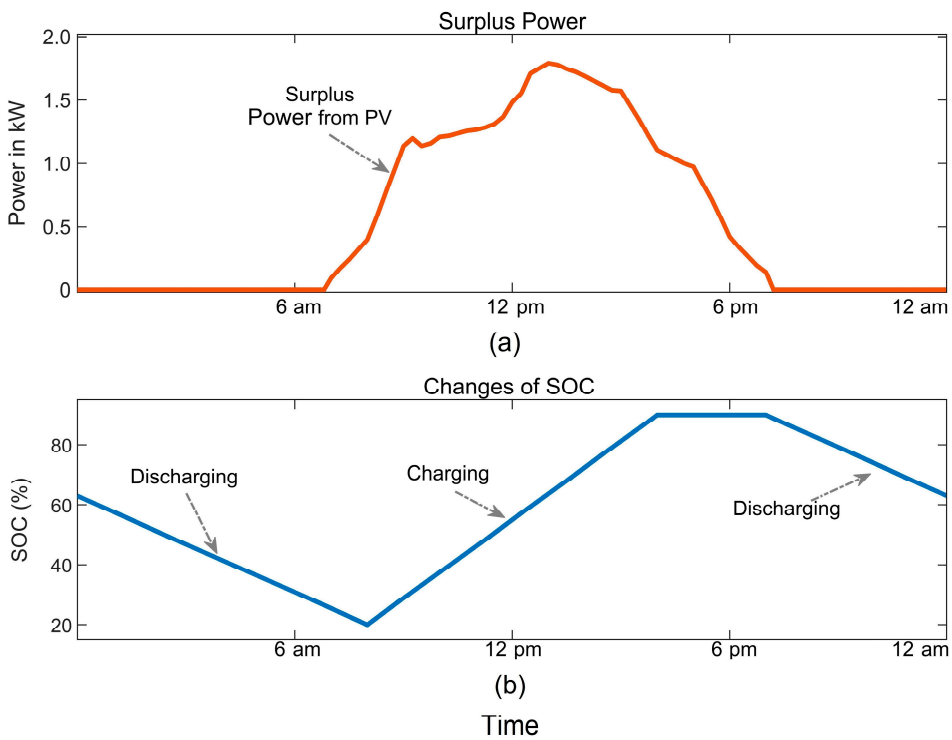

Figure 6. (**a**) Available surplus power generated from the PV system of a day in summer, (**b**) State of charge of the BESS unit.

4.2. Case Study 2: A Day in Winter

Winter season is relatively cold for the test household system where the solar irradiation varies from time to time. The electricity demand of a day in winter season is comparatively lower than that of summer season. The minimum demand of the test household system is 0.25 kW, which occurs at night-time, and the peak demand is around 0.86 kW, which occurs at around 11:45 am. After that, the demand profile starts decreasing gradually and during the afternoon and evening times, the demand profile slightly increases due to the operation of some electrical equipment of the test household system.

The variation of solar irradiation during the daytime results in the variation of output power from the PV system. In a day of winter, the power generation from the PV system is slightly lower than that of a day in summer. The output power from the PV system is enough to fulfil the demand during the daytime and the surplus energy is sufficient to charge the battery storage. The household system can operate uninterruptedly; hence, the energy arbitrage operation can hardly be operated. Figure 7a shows the electrical demand of a day in winter and the generated power from the PV system.

From 12 am to around 7:15 am, the BESS unit operates to deliver electrical energy to fulfil the demand. After the discharging operation, the BESS unit starts absorbing power at the availability of sufficient surplus power from the PV system. During the whole daytime, the surplus power from PV is enough to charge the battery unit for further operation. The energy arbitrage operation can hardly be found in winter due to the lack of PV power generation. At the afternoon and evening periods, the power is supplied from BESS though the demand is limited. The operating period of the BESS unit is longer than that of summer; hence, the required energy is comparatively lower than that of summer. Therefore, the BESS unit is able to serve the system to avoid shutdown operation. Figure 7b exhibits the charge–discharge operation of the BESS unit of a day in winter.

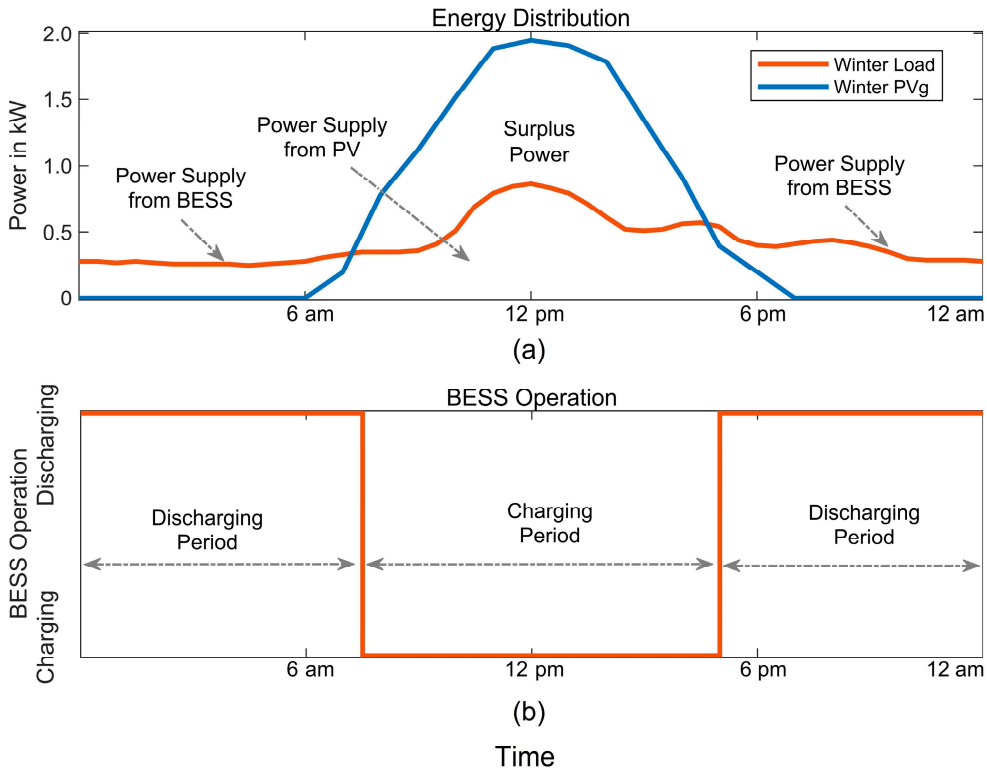

Figure 7. (**a**) Optimal power sharing operation of a day in winter, (**b**) Power absorption and delivering operation of BESS.

The generation power from the PV system is enough to fulfil the demand profile during the whole daytime, and to operate the charging operation of the BESS unit properly.

After fulfilling the demand profile, the surplus energy from the PV system is sufficient to allow the dynamic charging rate adjustment operation. The maximum surplus power is more than 1 kW, which allows to charge the battery unit rapidly. During the whole midday, the generated surplus energy stands for a certain satisfiable time duration to complete the required energy to be charged concerning the battery unit. Figure 8a shows the available surplus power generated from the PV system during the daytime in a day of winter season.

The energy arbitrage application is rarely found in winter due to the lack of more surplus energy. The generated surplus energy is mostly absorbed by the BESS unit during the whole daytime. The changes of SOC highlight the charging and discharging operation of the BESS unit. The minimum SOC is considered as 20% where the maximum SOC is 90%. From the evening to midnight and midnight to early morning, the BESS unit injects the stored energy to the loads. Therefore, the SOC decreases gradually from 90% to about its minimum level. When the PV system starts generation surplus power, the BESS unit starts to absorb energy and SOC starts to increase up to its maximum level. Figure 8b demonstrates the changes of SOC of a day in winter. The sufficient power supply from the power sources ensures the uninterrupted power flow to the load and support to avoid system shutdown operation.

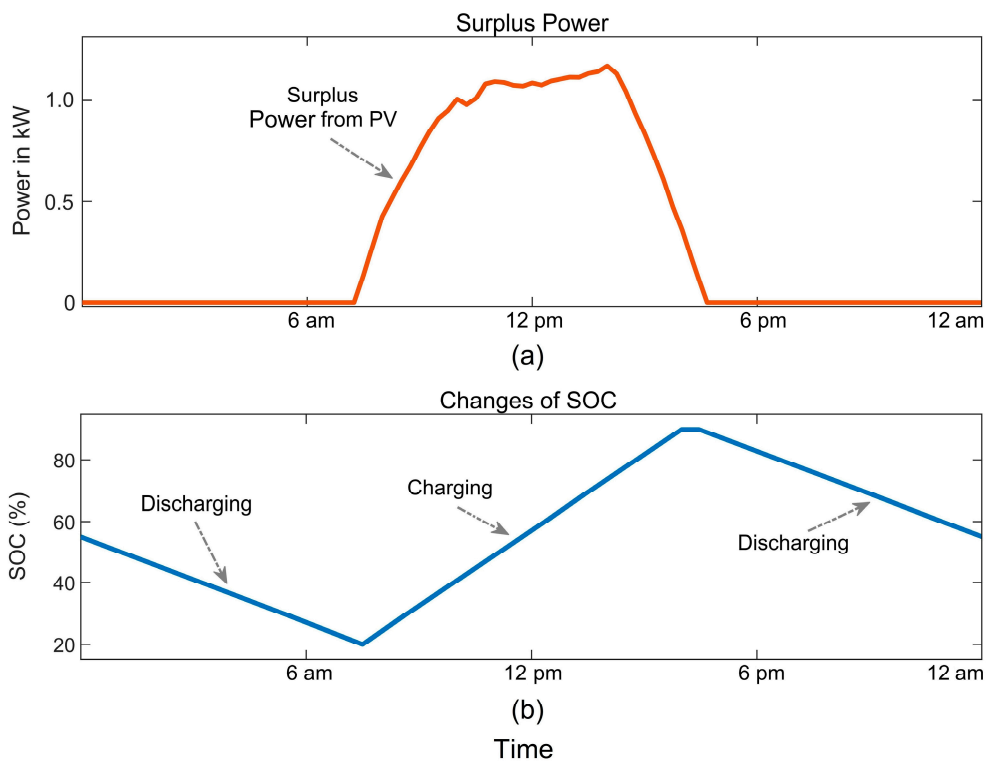

Figure 8. (**a**) Available surplus power generated from the PV system of a day in winter, (**b**) State of charge of the BESS unit.

5. Cost–Benefit Analysis

The economic feasibility analysis of the proposed technique highlights the economic operation for the small-scale smart household system. The economic analysis has been conducted considering some factors including investment cost of the system, price of generated energy used by the connected electrical components, earning from energy arbitrage operation, expenses for energy purchase from the interconnected household system and the lifetime of the system. The general analytical method is used to develop the following equations in the following sections based on ref. [25–28] as well as to determine the economic benefit of the system.

5.1. Capital Investment

The investment costs of the primary generation system, the PV system, the MPPT inverter, the backup power source, the BESS unit and the bi-directional converter are considered to determine the total capital investment of the system. The total capital investment, including PV panel, BESS unit, MPPT inverter, bi-directional converter, cost of cables and connectors, Solar PV and BESS profile structure, transportation cost, workmanship for installation work is determined as around 3350 USD for the test household system which is calculated with respect to Malaysia based on real-time data collected from a real household system in Malaysia. The cost functions utilized of this numerical analysis are presented in Table 4.

Table 4. Different cost function utilized for capital investment calculation.

No.	Consideration	Amount
1	Cost of PV panels (for total 10 panels)	Around 1400 USD
2	Cost of BESS (for 1 unit)	Around 750 USD
3	Cost of MPPT Converter	Around 520 USD
4	Cost of Bi-directional inverter	Around 380 USD
5	Others cost for PV and BESS system including, cost of cables and connectors, 1 layer of inclined Solar PV profile structure, transportation cost, workmanship for installation work	Around 300 USD
	Total	Around 3350 USD

The capital investment of the PV and BESS systems can be determined by using Equation (1).

$$C_t = (C_{iPV} + C_{iBESS} + C_{others}) = (n_1 \times C_{PV/panel}) + C_{iMPPT} + (n_2 \times C_{BESS/Unit}) + C_{iBDC} + C_{others} \quad (1)$$

Here,

C_t = Total capital investment of the system
C_{iPV} = Capital investment of PV system
C_{iBESS} = Capital investment of BESS
C_{others} = Others cost
$C_{PV/panel}$ = Cost of PV for one $250\frac{Wp}{ea}\ panel$
C_{iMPPT} = MPPT inverter cost
$C_{BESS/Unit}$ = Cost of BESS for one unit
C_{iBDC} = Bi-directional converter cost
n_1 = Number of PV panels
n_2 = Number of BESS units

5.2. Cost of Generated Energy Used by the Connected Electrical Components

The primary power generation system is a PV system which can generate solar energy directly from the sunlight. The total generated energy from the PV system which is used by the connected loads and BESS system is around 3.942 MWh in one year. The cost of electricity is 0.15 USD per kWh. The total cost of electrical energy used by the connected electrical components is around 591.30 USD in one year, whereas it is around 11,826 USD for 20 years.

This price can be calculated by using Equation (2) defined as follows.

$$E_p = (T_n \times E_{P/kWh}) \quad (2)$$

Here,

E_p = Cost of electricity used by the electrical components
T_n = Total amount of consumed energy by the electrical components
$E_{P/kWh}$ = Per kWh electricity cost

5.3. Earnings from Energy Arbitrage

During the daytime, the power generation from PV is more than the demand, which can result in the implementation of the energy arbitrage operation. Excess energy generated from the PV unit can be sold to the neighbourhood smart houses to earn extra money. During the day in summer, the household system can perform the energy arbitrage operation, whereas for the day in winter, the energy arbitrage operation is rarely performed. The earnings from energy arbitrage can compensate the storage losses, power conversion losses, other correspondence losses including T&D line losses and system maintenance costs. The household system considered in this research is a small-scale islanded power system where these expenses are small in amount. Therefore, the earning from energy arbitrage is sufficient to compensate these expenses.

The earning amount from the energy arbitrage operation can be calculated by using the following equation.

$$E_a = \left(EA_n \times E_{P/kWh}\right) \tag{3}$$

Here,

E_a = Earning from energy arbitrage operation
EA_n = Total amount of excess energy generated from PV system

5.4. Revenue

The lifetime of the system is considered to be 20 years. The economic feasibility of the household system depends on the overall economic advantages. This cost–benefit analysis is conducted considering one year PV generation and load data. Investment cost of the system, output power from the power supply sources, demand profile of the household system, cost of generated energy used by the connected electrical components, earning from the energy arbitrage operation, expenses for energy purchase from the interconnected household system, system losses, maintenance costs and lifetime of the system are the main factors of this numerical analysis. Overall, the system can return its capital investment within around 5.67 years and can proceed to the net profit further. The overall profit of the system is around 8476 USD, which is 2.53 times higher than the capital investment. A summary of the cost–benefit analysis is recorded in Table 5.

The net revenue of the system can be calculated by using Equation (4). As mentioned earlier, in Section 5.3, the earning from energy arbitrage can compensate for the storage losses, power conversion losses, other correspondence losses including T&D line losses and system maintenance costs. Therefore, the earnings from energy arbitrage value is 0 (zero) for cost–benefit calculation with the following equation.

$$R_{net} = (E_p + E_a) - C_t = (E_p + E_a) - (C_{iPV} + C_{iBESS} + C_{others}) \tag{4}$$

Here,

R_{net} = Amount of net revenue

Table 5. Summary of the cost–benefit analysis.

No.	Consideration	Description
1	Investment cost of PV and BESS	Around 3350 USD
2	Lifetime consideration	20 years
3	Cost of electricity used by the electrical components (for 20 years)	Around 11,826 USD
4	Earning from energy arbitrage	Compensate different losses and the system maintenance costs of the household system
5	Payback periods	Around 5.67 years
6	Revenue (for 20 years)	Around 8476 USD
7	Overall cost benefit (for 20 years)	2.53 times higher than the capital investment

6. Conclusions and Future Aims

The optimal energy distribution is an important factor for a small-scale smart household system to assure an uninterrupted and economic operation. This paper presents an optimal energy distribution technique that can distribute the generated power from a PV system to the connected electrical components in day-to-day life. The test household system was developed in the MATLAB/Simulink environment for investigation purposes. Real-time load and photovoltaic generation data are used for the investigation case studies. The key findings and the advantages of the developed technique in this paper are presented as follows:

- The proposed energy distribution technique demonstrates a simple, effective and optimal power-sharing strategy in a concise manner for a small-scale detached smart household system.
- The proposed method can utilize the generated power from the PV system properly and can perform a prominent operation for the BESS unit.
- The generated surplus energy can be used properly to charge the BESS unit and the excess energy can be utilized for the energy arbitrage operation.
- A cost–benefit numerical analysis is conducted to assure the economic feasibility of the system with the proposed method. The proposed method confirms an economic operation of the household system.
- The numerical analysis shows that the overall economic benefit of the household system is 2.53 times higher than the capital investment and the payback period is around 5.67 years.
- The developed household system with the proposed method can reduce the overall operating cost of the system for long-term operation and assure an environmentally friendly power system.

The sudden changes in PV power generation can result in interrupted power flow of the system. Insufficient power generation from the PV may also result in system shutdown or energy purchase from the interconnected household system. During this critical situation, the developed technique is limited to achieve more economic benefit for the household system. A small-scale conventional generator, i.e., a diesel engine generator, can be used with the developed smart household system to ensure an uninterrupted power supply. This study can be extended further with the integration of a diesel engine generator to ensure uninterrupted power flow. Besides this, this research, however, does not present the comparative analysis among the developed energy distribution technique with the existing methods. This research also can be extended with a comparative analysis among the developed technique with the existing energy distribution methods for a detached interconnected small-scale household system.

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Abbreviations

PV	Photovoltaic
ESS	Energy Storage System
BESS	Battery Energy Storage System
HEMS	Home Energy Management System
EM	Energy Management
VESS	Virtual Energy Storage System
EV	Electric Vehicle
MPPT	Maximum Power Point Tracking
PCC	Point of Common Coupling
LED	Light Emitting Diode
SOC	State of Charge
SOC_{max}	Maximum State of Charge
SOC_{min}	Minimum State of Charge
P&O	Perturb and Observe
O&M	Operation and Maintenance
EM	Energy Management
T&D	Transmission and Distribution

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