Application of Internet of Things in Residential Distribution Systems

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Abstract: Enabling an internet of things (IoT) application in residential distribution systems by integrating houses with IoT windows and occupant behavior can provide numerous advantages to the power grid, including, but not limited to, demand diminution, congestion reduction, and capacity deferral. This paper presents a new framework that mathematically enables an IoT application in residential distribution systems by integrating IoT windows and occupant behavior with houses for load management and energy conservation. With the proposed framework, we model residential loads considering the IoT concept, and then develop a mathematical optimization model that facilitates the integration of IoT-based houses into the residential distribution system. Different case studies considering a 33-bus distribution network are presented and discussed to demonstrate the effectiveness of penetrating IoT-based houses on distribution system operations and household profitability. It is observed that the profit of the local distribution company decreases when houses are transformed to IoT-based houses due to the fact that less energy is sold to the households. On the other hand, the operation cost of the IoT-based house is lower than that of the conventional house because of the better-managed house energy use, thereby resulting in saving money. It is found that 10% and 20% penetrations of IoT-based houses help reduce the maximum power imported through the distribution substation by 30 kW and 60 kW, respectively. It is also found that the load of IoT-based houses and power availability of a rooftop photovoltaic generation are not compatible, and hence, without an action from the customer and/or utility to coordinate them through a demand response program, IoT-based houses would not contribute to increasing the connectivity of PV-distributed generation in the smart grid.

Keywords: energy conservation; internet of things; load management; optimization; mathematical model

1. Introduction

The provision of flexibility in power systems has been traditionally accomplished by conventional generation units through adjustments to their power output in order to balance supply and demand and ensure that the system frequency remains within an acceptable range [1]. Despite the persistence of this practice, the growing adoption of renewable energy sources leads to a decrease in the proportion of conventional generation
capacity, resulting in a reduction in generation reserves. To circumvent this issue, it is imperative to provide more flexibility from the demand side.

Residential houses are undergoing a transformation in the smart grid environment, wherein they are being converted into internet of things (IoT)-based houses. This conversion aims to enhance the management of energy consumption by enabling more effective monitoring of power usage and reducing energy consumption during peak hours. This, in turn, enhances system flexibility and efficiency, and yields benefits through the postponement of distribution system reinforcements and energy investments. The integration of IoT applications in intelligent energy systems is expected to enhance demand-side management, leading to improved system flexibility, and promoting sustainability by coordinating the house loads with the availability of renewable energy for a more sustainable energy future.

Private businesses and policymakers have expedited the implementation and progression of smart grid technological advancements that are capable of facilitating intelligent energy systems. A review of various facets pertaining to the smart energy system and the IoT system is presented in [2]. The practical challenges associated with the implementation of demand response through load shifting for IoT-enabled home energy management systems are discussed in [3]. The authors of [4] provided an analysis of various sensing and communication methodologies utilized in the context of the IoT within sustainable energy systems. In [5], the specifications and fundamental principles of the intelligent infrastructure of buildings considering IoT technology are presented. In [6], an investigation is conducted on the architecture of an IoT system for the purpose of a smart grid application. The system is designed to accommodate a substantial quantity of residential users and the requirement of rapid response times. A review on the use of artificial intelligence in the power and energy sectors is provided in [7]. The presented review covers various applications of AI, such as load forecasting, renewable energy generation, and energy commodity price forecasting, as well as discussing the potential benefits and challenges associated with AI implementation. Examples of AI-based companies operating in the power and energy sectors are provided, and the need for a customer-centric business model is highlighted and discussed. The review is a valuable resource for those interested in the intersection of AI and the power and energy sectors. The authors of [8] report a VO$_2$-based smart window that partially utilizes light scattering to solar cells around the glass panel for electricity generation. This smart window combines energy saving and generation in one device, and offers the potential to intelligently regulate and utilize solar radiation in an efficient manner.

An overview of the integration of the IoT with smart grids is provided in [9], wherein various aspects of IoT-enabled smart grids, including technologies, architectures, applications, and challenges are covered. It highlights the benefits of IoT integration with smart grids, such as improved data acquisition and analysis, asset management, and decision making in the energy sector. It also addresses the challenges associated with this integration, such as interoperability, data management, and grid security. It is suggested that standardization and secure communication protocols are necessary to ensure the reliability and efficiency of IoT-enabled smart grid systems. Furthermore, the potential of cutting-edge technologies is highlighted, such as blockchain, machine learning, and artificial intelligence to improve the performance of smart grid systems. A survey of various AI-based solutions for achieving energy sustainability in IoT networks is provided in [10], wherein different design strategies, including energy-aware and opportunistic designs, data aggregation, and energy sustainable computing are covered. The importance of accurate modeling and response to the stochastic nature of energy availability to optimize IoT performance in terms of quality of service is discussed. Future directions are presented and discussed, including the utilization of edge and fog computing and the development of lightweight algorithms to improve energy efficiency.
The development of an IoT-based smart grid for energy management and analysis is presented in [11]. The reported system operates in three scenarios: normal conditions, high demand, and low demand. During normal operation, the power generated by renewable sources meets the load demand in the microgrid. During high demand, the devices check the probability of running with a microgrid, and if not possible, they check with a nearby utility microgrid. During low demand, the IoT charges the battery when its state of charge is lesser and trades the excess energy generated by the microgrid. The developed system is compared with competitive technologies and is identified to have higher performance efficiency. The challenges and future scope are highlighted and discussed for implementing smart grids with IoT-based energy management systems, smart metering, and cloud security. A generic middleware architecture is proposed in [12] for IoT-based environments in the context of smart cities. The proposed middleware architecture is based on service-oriented architecture and integrates services provided by different vendors in the city. It addresses the challenges of data acquisition, scalability, heterogeneity, flexibility, data analytics, and security in smart-city applications. A basic implementation of advanced data analytics and artificial intelligence components are included, in addition to three applications that are provided: web-based, mobile device-based, and data acquisition for the actuation of connected IoT devices. The results show satisfactory performance of the generic middleware architecture, and they are compared to those of other middleware for request completion times and load testing for concurrent users, showing an advantage in performance. The middleware could be used in IoT application development for future cities. The authors of [13] discuss the application of machine learning and data science in the industrial IoT concept of power plants. The authors propose a vertical industrial IoT concept with edge, fog, and cloud levels, and describe the data-processing flows and the application of machine learning models at each level. The need to modernize existing power plants is highlighted by introducing machine learning models and algorithms, and the importance of dimensionality reduction in dealing with high-dimensional data is discussed. The proposed concepts represented management and maintenance improvements with minimal investment and the avoidance of production downtime. Moreover, the benefits of industrial IoT and artificial intelligence in power plants are highlighted, including better fault and aging prediction, comprehensive failure classification, timely decision making, cost reduction, and maintenance planning. A multi-criteria-based decision-making tool is developed in [14] to include important criteria, such as the process controllability, suitability, and cost of the biogas plants, for an appropriate selection of biogas plants, which are promising renewable energy sources.

In order to achieve the maximum energy efficiency for a single IoT device, an optimal power allocation scheme is proposed in [15]. In [16], a framework is introduced for smart energy management utilizing IoT networks and deep learning. The framework is designed to predict future energy consumption over brief time intervals and establish effective communication channels between energy distributors and consumers. A performability index based on graph theory and matrix method is proposed in [17] to evaluate the performability of a biogas production unit, which is a function of factors such as sustainability, safety, maintainability, reliability and quality. The performability index is highly desirable for monitoring the performance of the plant, thus ensuring dependable and sustainable operation over its whole life cycle. The authors of [18] present an intelligent energy-saving monitoring system for urban buildings considering IoT technology. The aim of this system is to enhance the level of energy-saving supervision in urban buildings and consequently mitigate the overall energy consumption in urban areas. Developing IoT-enabled applications, for example, within a smart house is presented and discussed in [19]. A mechanism is proposed in [20] for managing energy consumption in a smart home by monitoring user behavior. The system under consideration comprises a day-ahead optimization scheduling mechanism for the user, along with a real-time control algorithm that effectively reduces power consumption during peak hours. In order to mitigate power outages resulting from unexpected grid fluctuations in load and reduce the peak to-average ratio, an algorithm...
considering IoT technology is proposed in [21]. The proposed algorithm aims to facilitate smart-direct load control and load shedding, providing real-time load control. The authors of [22] introduce a sensorless energy control system for reducing the electricity consumption of home appliances. The presented design combines intelligent wireless socket and IoT technology to introduce four distinct control approaches for the activation and deactivation of household devices.

For the establishment of prosumer communities that utilize the smart grid to enhance energy production and consumption patterns, a model is proposed in [23] to decrease the peak-to-average ratio and the amplitude of energy peaks. The authors of [24] describe a method that can be used to predict the unemployment of individual residential occupants. The technique can be performed using smart meter data processed by a machine learning algorithm for classification. Vanus et al. [25] develop a solution for accurate air quality prediction by introducing a Python environment implemented artificial neural networks mathematical technique to store and process temperature and humidity measurements. The study in [26] utilizes the future weather data in a machine learning-based memory model to enhance the energy usage of HVAC systems. An intelligent home energy management system based on a thermal dynamics model is presented in [27]. The use of the thermal model enhances energy usage by suitably scheduling heating, air circulation, and air conditioning systems. A combined IoT energy harvesting system is proposed in [28] to increase the interoperability of several connected energy resources. This combined system is used to reduce the storage system without affecting performance. Another IoT solution in energy management uses a technique [29] that focuses on peak load shifting for end users to diminish energy shortage. In [30], reducing energy consumption is realized for the residential building by offering new artificial intelligence air conditioning (AC) operational settings instead of the AC settings that the user selects. In order to appropriately use the existing power supply, an adapting consumption model based on IoT technology is presented in [31]. The authors introduce a model that arranges energy demands using several control methods. The authors of [32] present an IoT-developed intelligent energy management system for smart residential house applications that aim at facilitating energy consumption management. The system contains a data server that collects data from home devices to understand consumer demand. Efficient control is studied in [33] for monitoring temperature using computational intelligence so as to provide an IoT convection system based on data from several installed sensors to improve living quality. Non-intrusive load monitoring in an IoT environment is considered for low-cost smart home applications [34] by installing a single-entry point sensor to determine the required power for each home appliance, leading to improved appliance safety. In [35], the feasibility of integrating energy storage and energy harvesting applications to produce smart windows technology is reviewed along with its potential for net-zero buildings. It is suggested that multifunctional smart windows technology could be applied to more buildings and retrofits to reduce energy consumption and increase human comfort.

The aforementioned literature review reveals that none of the existing studies have explored the technical and economic implications of integrating IoT-enabled homes into residential distribution systems. In an earlier work [36], the impact of IoT windows on heating and cooling loads is examined by designing a novel window that can change its solar heat gain coefficients (SHGCs) with a smart mid-shade. The work in [36] is extended here to penetrate houses integrated with an IoT window and occupant behavior into residential distribution systems, for the load management and capacity enhancement of a power distribution grid. The impact of the IoT window and occupant behavior on distribution system operations and households is investigated.

The innovations and contributions of the work presented in this paper can be summarized as follows:
Enabling an IoT application in residential distribution systems by integrating IoT-based houses for the load management and capacity enhancement of power distribution systems.

A novel framework for the mathematical quantification of load management and energy conservation in houses that utilize IoT technology is proposed. The proposed framework entails the incorporation of IoT windows and occupant behavior in the modeling of residential loads, and the formulation of a mathematical optimization model that aims to optimize load management and enhance the capacity of a distribution system by penetrating IoT-based houses.

The assessment of distribution system operations and household profitability, with taking into account the different penetration levels of IoT-based houses.

Investigation of the compatibility of IoT-based house loads with the power availability of rooftop photovoltaic (PV) generation, and whether it can contribute to increasing the connectivity of PV-distributed generation in the smart grid.

The remainder of the paper is organized as follows. Section 2 presents and discusses the proposed framework and associated mathematical models. Section 3 presents the test system and input data, followed by the analysis and discussion of the findings in Section 4 to demonstrate the effectiveness of the proposed framework. In Section 5, conclusions are drawn.

2. Proposed Framework

2.1. Modeling of Residential Load Considering the IoT Concept

Smart windows can change their SHGCs to control the ability of the house in terms of solar gain (heat and visible light). The maximum and minimum SHGC ranges of smart windows have an influence on transmitting solar heat and visible light into the house. IoT windows not only have a wider range of SHGC than commercial smart windows [37] but also their materials are cheaper than those of the commercial smart window. Hence, it is used in modeling the house load in this work. This IoT window is comprised of a dual-pane window and an intermediate shading layer. The double-glazed window exhibits a relatively high SHGC, while the intermediate shade possesses the ability to reflect over 95% of solar radiation. Figure 1 presents an overview of IoT and conventional windows under varying weather conditions. The IoT window is designed to modify the SHGC of the window, taking into account various weather conditions and occupant behavior. The IoT window exhibits a maximum SHGC during cold weather conditions, irrespective of occupancy status, with the aim of retaining heat within the room and promoting warmth. This approach contributes to a reduction in daily energy consumption of the heating system. In the event of a room being unoccupied during warm weather conditions, the IoT window is designed to possess a minimal SHGC to mitigate the buildup of heat within the room in the absence of the HVAC system. As a result, the energy consumption of the HVAC system decreases on a daily basis. The thermodynamic properties of the IoT window are obtained through the utilization of Window software [38]. Furthermore, EnergyPlus [39] is employed to simulate various household appliances such as the fridge, washing machine, dryer, electric oven, and dishwasher.
2.2. Proposed Methodology

This subsection proposes a methodology based on a mathematical optimization model that maximizes the profit of the local distribution company (LDC) while penetrating IoT-based households in a residential distribution system.

Objective function: Maximize the LDC profit, given by

$$\text{Max} \sum_i \sum_h \rho_{TOU}^i [P_{d, h} (1 - \gamma_{H^{IoT}}^i) + \gamma_{H^{IoT}}^i P_{H^{IoT}}^i] - \sum_{h=1}^{24} \rho_{Grid}^h p_{Sub}^h - [(\rho_{PLC}^{\text{grid}} / n_d) P_{PK}]$$  \hspace{1cm} (1)

The first term denotes the net revenue from selling power to households and households with IoT-based load management. The second term represents the cost of purchasing power from the grid. The peak demand charge is denoted by the third term.

Power flow equations: The conventional power flow equations limit the power supplied to the substation bus and the power consumed by the load, given as

$$P_{Sub}^h - P_{d, h}[(1 - \gamma_{H^{IoT}}^i) n_i^H] - \gamma_{H^{IoT}}^i n_i^{H^{IoT}} = \sum_{j \in N} V_{i,j} Y_{i,j} \cos(\theta_{i,j} + \delta_{i,j} - \delta_{i,j}) \quad \forall (i, i) \in N, \forall h$$  \hspace{1cm} (2)

$$Q_{Sub}^h - Q_{d, h} = - \sum_{j \in N} V_{i,j} Y_{i,j} \sin(\theta_{i,j} + \delta_{i,j} - \delta_{i,j}) \quad \forall (i, j) \in N, \forall h$$  \hspace{1cm} (3)

Constraint of peak load: The peak load is determined based on the constraint, given as

$$P_{Sub}^{\text{peak}} \leq P_{PK} \quad \forall SU, \forall h$$  \hspace{1cm} (4)

Constraints of feeder capacity: The constraints on feeder capacity guarantee that the power transmitted through a distribution feeder is limited, given as

$$- V_{i,j}^2 Y_{i,j} \cos \theta_{i,j} + V_{i,j} Y_{i,j} \cos(\theta_{i,j} + \delta_{i,j} - \delta_{i,j}) \leq S_{\text{peak}}^{\text{feed}}(\cos \theta_{(i,j)h}) \quad \forall (i, j) \in N : \exists (i, j), \forall h$$  \hspace{1cm} (5)

$$V_{i,j}^2 Y_{i,j} \sin \theta_{i,j} - V_{i,j} Y_{i,j} \sin(\theta_{i,j} + \delta_{i,j} - \delta_{i,j}) \leq S_{\text{peak}}^{\text{feed}}(\sin \theta_{(i,j)h}) \quad \forall (i, j) \in N : \exists (i, j), \forall h$$  \hspace{1cm} (6)
Substation capacity limits: The constraint ensures that the capacity substation is within its limit, given as
\[
(P_{\text{Sub}}^h)^2 + (Q_{\text{Sub}}^h)^2 \leq S_{\text{Sub}}^\text{cap}^2 \quad \forall h
\]  

Voltage constraint: The bus voltage is constrained, given by
\[
V_{\text{Min}} \leq V_i^h \leq V_{\text{Max}} \quad i\in N, \forall h
\]

3. Test System and Simulation Data

The present study considers the 33-bus radial distribution system as described in [40] and depicted in Figure 2. The peak demand of the system is 4.4 MW, while the base voltage is 12.66 kV. The system load profiles are obtained from the IEEE Reliability Test System (RTS) [41]. The calculation of the number of houses at each bus is based on the assumption that the peak load of the house is 2.08 kW [42]. Time-of-use (TOU) and grid prices for a typical day are shown in Figure 3.

A single-family detached home that consists of two bedrooms, a living room, a kitchen and a garage is considered for load modeling of an IoT-based house. A light-emitting diode with linear control is used for lighting the house. The window-to-wall ratio of the designed house is about 28%. A VRF with heat recovery and a dedicated outdoor air system is used as the HVAC system of house. The gross rated cooling and heating COP of the system are equal to 4.7 and 2.9, respectively. The sensible effectiveness of heat recovery has an efficiency equal to 75% efficiency. Due to the fact that the effect of the occupant behavior uncertainty is lower than 2%, the data of occupant behavior is adopted from [43]. The system set points for heating and cooling are 72 °F (22.2 °C) and 75 °F (23.9 °C). All the thermodynamical parameters include the U-value of façade and fenestration, and the required air changes per hour meet the requirements of the International Residential Code (IRC) [44]. The SHGC values of both conventional and IoT windows under varying weather conditions were utilized from the paper cited as [36]. The SHGC of conventional window is considered to meet the IRC, while the SHGC of the IoT window is calculated using Window software. As there are only on and off mid-shade window simulations, the IoT window has a higher SHGC than the conventional window when a room is occupied in warm weather. However, in total, the IoT window has a positive impact on the energy consumption of the household, as presented in Section 4.
4. Results and Discussions

4.1. Modeling of Residential Loads Considering IoT Windows and Occupant Behavior

To create diversity among households, various weather conditions are taken into account and placed in the distribution system in an arbitrary manner. It is assumed that each group engages in similar activities at the household, resulting in a similar load profile for the house. Figures 4–6 present the load profiles of both conventional houses and IoT-based houses across varying weather conditions. It is observed that energy conservation is achieved when transforming houses to IoT-based houses. The load profiles presented herein serve to illustrate the effectiveness and need for an IoT-enabled application in residential distribution systems for better managing house energy use, hence reducing the energy consumption.

Figure 3. TOU and grid prices for a typical day.

Figure 4. House load profiles considering conventional and IoT windows at locations (2–6) and (19–25).

Figure 5. House load profiles considering conventional and IoT windows at locations (26–33).
4.2. Impact of IoT-Based Houses on Distribution System Operations

Table 1 presents the optimal economic benefits that can be derived by LDC through the implementation of IoT-based load management in residential buildings. The average operation cost of the household is also reported in Table 1. It is observed that the profit of LDC decreases when the LDC has sold less energy to the households with IoT-based houses. On the other hand, the operation cost of the IoT house is lower than that of the conventional house, due to better management of house energy use, thereby resulting in saving money. It is noted that 10% and 20% penetrations of IoT-based houses help reduce the maximum power imported through the distribution substation by 30 kW and 60 kW, respectively.

Figure 6. House load profiles considering conventional and IoT windows at locations (7–18).

The number of houses with IoT-based load management in the distribution system, considering their penetration levels presented in Figure 7, is used to investigate the impact of penetrating such houses on the economical and technical aspects of the distribution system.

Figure 7. Number of houses with IoT-based load management in the distribution system considering different penetrations.

Figure 6. House load profiles considering conventional and IoT windows at locations (7–18).
Table 1. Optimal operation cost of the LDC and household.

<table>
<thead>
<tr>
<th>Penetration of IoT Houses (%)</th>
<th>Maximum Power Imported by Distribution Substation (kW)</th>
<th>Average Daily Household’s Cost ($)</th>
<th>Daily LDC’s Profit ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3960</td>
<td>7.04</td>
<td>7184</td>
</tr>
<tr>
<td>10</td>
<td>3930</td>
<td>6.20</td>
<td>7096</td>
</tr>
<tr>
<td>20</td>
<td>3900</td>
<td>6.20</td>
<td>7009</td>
</tr>
</tbody>
</table>

Four different locations (location-1, -18, -24, and -33) are selected in this study to demonstrate the effectiveness of the load management and conservation of IoT-based houses on the distribution substation and system loads. Figure 8 shows the power imported by the LDC through the distribution substation location-1, considering 20% penetration of houses with IoT-based load management, while the effects of load management from such houses on the total loads are presented at location-18 (Figure 9) and location-33 (Figure 10), both of which are far from the substation location, and location-24 (Figure 11), which has a high number of houses in the system. It is observed that, in the case of houses with IoT-based load management, the shape of the imported power (Figure 8) and the load profiles (Figures 9–11) remain the same but are reduced when compared to the profile of the base case of conventional houses.

**Figure 8.** Power imported though distribution substation considering 20% penetration of IoT-based houses.

**Figure 9.** System-load profiles at location-18, considering conventional houses and 20% penetration of IoT-based houses.
Figure 10. System load profiles at location-33, considering conventional houses and 20% penetration of IoT-based houses.

Figure 11. System load profiles at location-24, considering conventional houses and 20% penetration of IoT-based houses.

Figure 12 presents the daily energy supply reduction at location-1, considering conventional houses and 20% penetration of IoT-based houses. It is shown that, there is a reduction of 1705 kWh in the energy supply or energy imported by the distribution substation after integrating houses with IoT windows and occupant behavior. Such a reduction can enhance the system capacity of a distribution system and thereby defers the need for system upgrades. On the other hand, the daily energy demand reduction considering different locations and 20% penetration of IoT-based houses is shown in Figure 13. It is found that there are reductions of 30 kWh, 36 kWh, and 174 kWh in energy demand at location-33, -18 and -24, respectively. It is noted that the daily energy demand reduction is high at location-24 since it has a high number of houses in the system (Figure 7). It should be mentioned that the effectiveness of integrating houses with IoT windows and occupant on energy demand reduction and system capacity enhancement is notable when their penetration increases in the distribution system.
4.3. Compatibility of IoT-Based House Loads with a Rooftop Photovoltaic Generation

In order to assess the compatibility of IoT-based house loads with the power availability of the rooftop PV generation, different load profiles of conventional and IoT-based houses along with a power profile of the rooftop PV generation are presented in Figures 14–16. Although the load of IoT-based houses reduces when compared to the load of a conventional house, this load reduction does not coincide with the power availability of PV generation. IoT-based houses and PV generation are called compatible when the load of IoT-based houses increases with the high power availability of PV generation, while it reduces with the low or zero power availability of PV generation. This is not the case here, but in order to make them compatible, there is a need for an active action from the customer and/or the utility to coordinate the load of IoT-based houses with the power availability of the PV generation through a demand response program. This will definitely help increase the connectivity of PV-distributed generation in sustainable distribution systems.
Figure 14. Load profiles of conventional and IoT-based houses and power availability of 3 kW of PV generation at locations (2–6) and (19–25).

Figure 15. Load profiles of conventional and IoT-based houses and power availability of 10 kW PV generation at locations (26–33).

Figure 16. Load profiles of conventional and IoT-based houses and power availability of 10 kW PV generation at locations (7–18).

5. Conclusions

The paper presents a new framework that mathematically enables an IoT application in residential distribution systems by integrating IoT windows and occupant behavior with houses for load management and energy conservation. The proposed framework models residential loads considering the IoT concept, and thereafter a mathematical optimization model is developed to facilitate the integration of IoT-based houses into the residential distribution system. In order to demonstrate the performance of the proposed framework, different case studies are presented and analyzed. It is observed that the residential energy
consumption is reduced with houses with IoT-based load management in the distribution system. It is also noted that every 10% penetration of such houses reduces the maximum power imported through the distribution substation by 30 kW. The profit of LDC is slightly decreased when the penetration of IoT-based houses is increased due to the fact that the LDC has sold less energy to the households. In contrast, enabling an IoT application in the houses lowers their operation cost. Last but not least, there is a reduction of 1705 kWh in the energy supply or energy imported by the distribution substation when integrating the 20% penetration of IoT-based houses. Such a reduction can enhance the system capacity of a distribution system and thereby defers the need for system upgrades. Last but not least, the load of IoT-based houses would not likely be compatible with the power availability of a rooftop VP generation unless there is an action from the customer and/or the utility to deploy them together in the smart grid to ensure both environmental and economic benefits. This helps alleviate dependency on fossil fuels and also foster a greener and cleaner living environment.


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**Abbreviations**

- $i, j$: Buses, $i, j \in N$
- $h$: Hour, $h \in H$
- $su$: Substation location, $u \in U$
- $\gamma_{Htr}^{IoT}$: Penetration of houses integrated with IoT windows and occupant behavior
- $r_{Htr}^{TOU}$: Time-of-use electricity price, $$/kWh
- $\rho_{PlC}$: Peak load charge, $$/kW
- $\rho_{Grid}$: Main grid price, $$/kWh
- $n_d$: Number of days in a month
- $n_H$: Number of houses at bus $i$ in a distribution system
- $p_{Htr}$: Load of an IoT-based house, $pu$
- $PD$: Conventional load of a household, $pu$
- $P_{Sub}, Q_{Sub}$: Active and reactive power drawn, $pu$
- $PPK$: Daily peak load imported by substation, $pu$
- $P^f, Q^f$: Active and reactive power flow of the feeder, $pu$

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Sustainability 2023, 15, 15479


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