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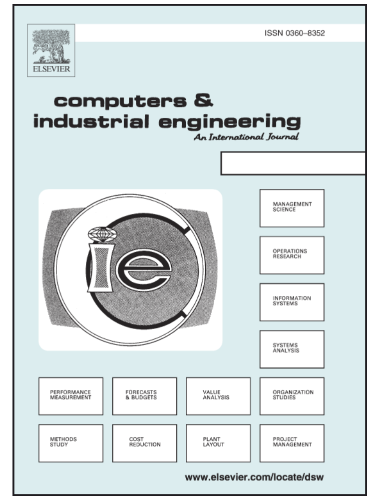

Optimal household appliances scheduling for smart energy management considering inclining block rate tariff and net-metering system

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Abstract

Smart grids that integrate household renewable energy sources and share information with households can help create and maintain a smarter data-driven environment. Within this environment, flexible home energy management policies that minimize household energy costs can be adopted. This paper considers a smart home with a renewable energy source that favors satisfying its energy needs at minimum cost. This is achievable by smartly scheduling the use of its domestic appliances to match a given energy grid tariff. Focusing on the case of Egypt in which an inclining block rate (IBR) tariff is imposed, this paper fills a gap in the literature regarding the load scheduling models aiming to minimize energy cost at the household level whenever such a tariff exists. A new mixed integer quadratic programming (MIQP) model is formulated for this scheduling problem, considering the adopted net metering system with installed domestic photovoltaic (PV) systems in Egypt. The model generates the optimal household load schedule and the optimal amounts of energy to exchange with the grid while considering all the system and consumer utility constraints. To assess the applicability of the proposed model, a survey is conducted to identify the diversity and characteristics of using the electrical appliances by the Egyptian households. Based on the collected survey results, the effectiveness of the proposed MIQP model is investigated. Results confirm the effectiveness of the proposed model to minimize energy cost for different categories of the Egyptian households.

Keywords: Smart Energy management; Household appliances scheduling; Mixed-integer quadratic programming; Inclining block rate tariff; Net-metering system; Egypt

1. Introduction

The main goal of a smart city is to optimize operational efficiency and improve its services and its residents' welfare. To achieve this goal, it is essential to upgrade traditional power grids to smart grids to increase the energy efficiency and improve service level (Dileep, 2020). The capacities of current traditional power grids are usually designed to support the peak-load which only lasts for short periods during the year. Such a peak-load-based design hinders the energy efficiency and increases the energy cost. Moreover, the traditional power grid limits the flexible and effective demand side management (DSM) which enables matching energy supply and demand without the need for expanding the capacity of the power grid. Furthermore, it does not allow the efficient utilization of distributed renewable energy systems whose power output is characterized by high fluctuations. Those inefficiencies are present in the generation, transmission, distribution, and demand side of the traditional grid. The adoption of smart grids would eliminate those inefficiencies and contribute to the realization of the objectives of emerging smart cities.

A smart grid is an integration of electric energy grid with bidirectional communication network system (Dileep, 2020). It integrates three major subsystems: smart infrastructure subsystem, smart energy management subsystem, and smart protection subsystem (Latifi et al., 2017; Shaban et al., 2021). Deploying intelligent grid systems that seamlessly integrate with residential renewable energy sources and communicate data with households can contribute to the establishment and sustenance of an intelligent data-centric ecosystem. Consequently, this enables the implementation of a flexible home energy management policy aimed at minimizing household energy costs (Forootani et al., 2022; Samuel et al., 2018). Substantial attention has been devoted to developing home energy management systems that facilitate the implementation of demand-side management programs at consumer premises (Huy et al., 2023; Samuel et al., 2018; Zhou et al., 2016). The home energy management systems can provide adequate solutions for the consumer to minimize energy cost, improve utilization of renewable energy sources, and ensure that consumer energy requirements and service levels are met. Smart load scheduling approaches are essential tools for home energy management to optimally manage the operation of the household appliances.

The smart load scheduling approaches necessitate the development of adequate load scheduling mathematical models that represent the characteristics of the smart homes and the associated load scheduling problems (Lu et al., 2018; Song et al., 2022). The literature has provided ample mathematical models that targets the smart scheduling of household appliances to minimize the energy cost paid by the consumer to the grid (Chai et al., 2015; Chavali et al., 2014; Shaban et al., 2021). Those models have considered different assumptions regarding the grid tariff, components of the home energy management system (Samuel et al., 2018; Song et al., 2022), the existence of renewable energy system (Hafeez et al., 2018), and the scheduling criteria (Shaban et al., 2021; Song et al., 2022). This has resulted in different mathematical models that represent different settings of the home energy management problem. Most of those scheduling models assume the presence of time varying tariff, and they aim to find the optimal load schedules that minimize the energy cost (Ahmad et al., 2017; Samuel et al., 2018). Those types of grid tariff are usually adopted in developed countries, while in developing countries, the inclining block rate tariff is imposed (Rahman et al., 2021; Rahman et al., 2017). Therefore, the existing household appliances scheduling models are not suitable for the application at the household level in developing countries.

Egypt is a developing country that has an ambitious plan to modernize its energy sector. The country has launched “Egypt Vision 2030” that targets increasing the renewable energy share in its energy mix and enhancing energy efficiency to match energy demand in a sustainable and cost-effective manner (Mondal et al., 2019). However, this sector is challenged by the ever-growing population that has increased by 1.6 million in 2022, bringing the total population to 104.4 million in December 2022 (CAPMAS, 2022). This has positioned the country as the most populous nation in the Middle East and the third most populous in Africa (Shaban et al., 2022) . Accordingly, the electricity demand is continuously increasing, necessitating the continuous expansion of the installed capacity of the power plants to cope with this ever-increasing demand. Although Egypt has recently installed many power plants whose capacity exceeds the peak load, the country has experienced power outages in the summer months due to the global economic crisis and the disruption in fuel supplies. Egypt relies heavily on fossil fuels for electricity generation, specifically natural gas and diesel, which account for about 89% of the total electricity generation in the country. In contrast, renewable energy sources and hydropower make up only 11% (EEHC Annual Report, 2022). Accordingly, the country needs to adopt smart energy management systems to match the energy supply with the demand efficiently and effectively. In addition, the consumers (residential, commercial, and industrial sectors) should be engaged in energy management initiatives. As such, they should be provided with adequate energy management tools that enable them to smartly manage their energy needs.

This research focuses on the residential sector which represents 86% of the total number of subscribers to electricity service, consuming approximately 38% of the total electricity generated. The residential sector is currently facing high prices of electrical energy and unstable power service, and the situation will get complicated after lifting the electricity subsidies. In this context, it is required to equip households with smart energy management tools that can allow them to adapt with those challenges. Motivated by that, this research is centered on the energy management problem facing the Egyptian households that are struggling to increase the efficiency of their energy usage and reduce their energy bills. There is a need to adopt home energy management systems that can contribute to achieving the goals of Egyptian households considering both the current tariff imposed on the residential sector in Egypt and the local regulations for integrating on-grid distributed renewable energy systems. In this context, the paper examines a smart household equipped with a renewable energy source (PV system), which aims to meet its energy requirements at the lowest possible cost. This is achieved by intelligently adjusting the usage schedule of its home appliances to align with a specified energy grid tariff (see Figure 1). Egypt adopts an inclining block rate (IBR) tariff that may adjust its pricing scheme to control the consumers' energy demand. The literature lacks load scheduling models that can be integrated with home energy management systems to minimize energy cost at the household level in Egypt. Therefore, there is a need to develop load scheduling models that suit the Egyptian conditions.

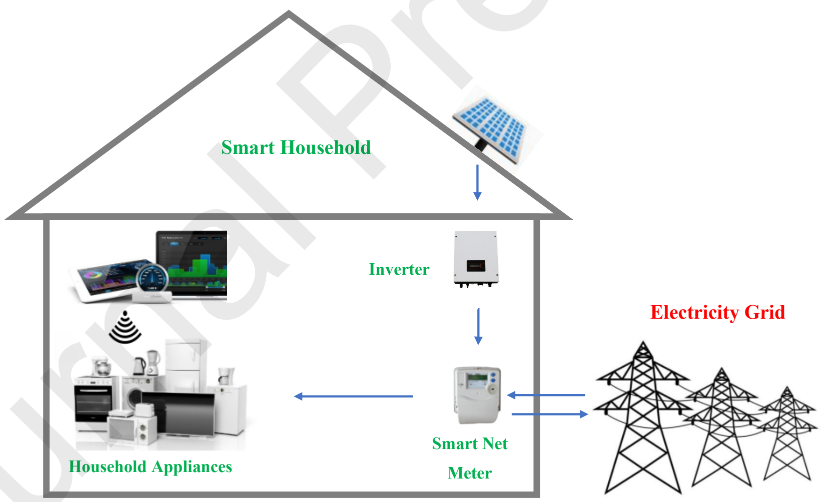

Figure 1: A smart household with on-grid PV system

This research aims to provide decision making tools that can help the Egyptian households to smartly schedule their appliances' usages. In this regard, a new mixed integer quadratic programming (MIQP) model is formulated for this load scheduling problem, considering the IBR tariff and the net metering system adopted with installed domestic PV systems in Egypt. The model is formulated to determine the optimal load schedule and the optimal amounts of energy to exchange with the grid that minimize the net daily cost, while considering the system and consumer utility constraints. The net daily cost represents the difference between the cost of the net energy consumed to run the household appliances and the expected daily revenue from the sold solar energy to the grid. The model also accounts for the preferred times and number of runs set by the consumer on the daily operation of the household appliances. It also accounts for the consumer's overall utility lower limit that need to be satisfied by the developed load schedule. To achieve this target, a survey has been conducted first to collect the essential information that characterizes the usage of electrical appliances in Egyptian households. The collected data has been utilized to investigate the effectiveness of the proposed MIQP model as a means of smart energy management at the household level in Egypt. The proposed MIQP model is applied to optimize the appliances schedules for different categories of the Egyptian households, considering the collected data from the survey. The investigated scenarios consider two categories of the Egyptian households (low and high living standards). Two different cases of each household category (with and without PV system) are investigated to analyze the impact of installed domestic PV systems on the energy cost. The results confirm the effectiveness of the proposed model to minimize energy cost for different categories of the Egyptian households.

This research contributes to the existing body of knowledge related to the energy management problem at the household level. It particularly provides a clear description of the load scheduling problem that faces the Egyptian households, reports significant data regarding the characteristics of the Egyptian households' appliances, and clarifies the energy management system in Egypt. Moreover, this research provides a new load scheduling optimization model that can be employed to smartly schedule the Egyptian household appliances considering both the IBR tariff and the PV net-metering system applied in Egypt. The model can determine the optimal household appliances schedule, and optimally integrate domestic PV systems with the grid in a way that minimizes the net energy cost incurred by the consumer. The effectiveness of the proposed load scheduling approach stems from its ability to generate optimal daily plans for the operation of household appliances that satisfy the household's energy requirements at minimum cost. It also considers the relative utilities of the household appliances, and therefore, it generates optimal schedules that satisfy the overall utility needed by the consumer. To the best of authors' knowledge, no previous research has attempted to develop smart load scheduling approaches for the Egyptian households, considering the usage characteristics of the Egyptian household appliances, net-metering systems applied for households with domestic PV systems, relative utilities of loads, overall utility required by the consumer, and the IBR tariff. In general, limited research has attempted the development of load-scheduling models that consider both the IBR tariff and net metering systems. In this regard, the proposed load scheduling model in this paper can be suitable for many other developing countries whose conditions are similar to Egypt. In addition, the model can be readily adapted to suit the conditions of other countries. Most importantly, this research proves that load scheduling models can be developed for the settings where non-time-varying tariffs exist. This research would trigger a new research direction related to the development of load scheduling models that consider non-time-varying tariffs such as the IBR tariff which is widely adopted in developing countries. Finally, the presented data and results in this research can be utilized in future relevant research and can be considered for validation and benchmarking purposes of relevant load scheduling models.

The rest of this paper is structured as follows. The literature review is provided in Section 2. The load scheduling problem that faces the Egyptian households is described in Section 3. The proposed MIQP model that can be employed to smartly schedule the Egyptian household appliances is presented in Section 4. The results of a survey conducted to collect information about the characteristics of the Egyptian households' appliance usages are presented in Section 5. The results of case studies conducted to demonstrate the model applicability are reported and analyzed in Section 6. The conclusions and future research directives are discussed in Section 7.

2. Literature review

This section summarizes and discusses the previous research related to the deployment of energy management systems, grid tariffs, and existing load scheduling approaches. It concludes by identifying the related research gap.

2.1. Energy management

The residential sector consumes a great amount of electric energy that reaches one third of the total consumption in USA and Europe, and 47% in Egypt (IRENA, 2018). This has triggered many initiatives and research studies directed towards the design of DSM programs that can help control the aggregate electricity demand by shaping individual consumers' consumption profiles. The aim of DSM is to incentivize the consumers to shift the operation of their electrical loads (household appliances) from peak periods to off-peak periods (Sedhom et al., 2021), and to promote effective integration of renewable energy systems with the grid (Sharda et al., 2021).

The engagement of consumers in DSM programs can be achieved through financial incentives and grid tariffs (Rahim et al., 2018). However, it is possible that the consumers are not able to achieve the acclaimed benefits from joining DSM programs due to the lack of proper energy management systems that can help the consumer to optimally plan the usages of household appliances (Shaban et al., 2021). Indeed, the development of home energy management systems can promote consumer's acceptance of the DSM programs (Beaudin & Zareipour, 2015; Zhou et al., 2016).

Liu et al. (2016) indicated that a smart home energy management system consists of five basic components: measuring devices, sensing devices, information and communications technology, smart appliances, and energy management system. Accordingly, extensive research has been devoted to proposing home energy management systems to enable and facilitate the implementation of DSM programs within the context of smart grids (Elazab et al., 2022; Song et al., 2022; Zhao et al., 2013; Zhou et al., 2016).

2.2. Grid tariffs

Several grid tariffs have been proposed and investigated for the purposes of DSM and smart energy management within the context of smart grids. The most investigated tariffs in the literature include time of use pricing (TOU), real time pricing (RTP), critical peak pricing (CPP), day ahead pricing (DAP), and inclining block rate pricing (IBR) (Dutta & Mitra, 2017; Rahim et al., 2018). The TOU tariff provides different prices for electricity at different times of the day where the pricing scheme of this tariff can be varied seasonally by the grid operator. The benefits of this tariff have been widely investigated for DSM in industrial, commercial, and residential sectors (Kusakana, 2018, 2019; Venizelou et al., 2018; Wang & Li, 2015; H. Yang et al., 2019). In the RTP tariff, the price of electricity per kilowatt-hour varies over time, approximately every hour (Conejo et al., 2010; Siano & Sarno, 2016). To reduce electricity consumption during critical peak times of the year, the CPP tariff is introduced (Li et al., 2018; Wang & Li, 2016). In the DAP tariff, the grid operator determines the value of the electricity price one day before it is sold to the consumers (Gomes et al., 2017; Heleno et al., 2016; Raziei et al., 2016; Vanthournout et al., 2015). The IBR tariff depends on the amount of electricity consumed by the consumer during a certain period, as the price of electricity increases whenever the consumer exceeds a specific amount of electricity consumption (Aurangzeb et al., 2021; S. Rahim et al., 2016).

Hybrid tariffs that combine one or more of the above-mentioned tariffs have also been investigated in the literature (Anees et al., 2018; Tantawy et al., 2022; Zhao et al., 2013). The implementation of the dynamic tariffs (e.g., TOU, RTP, CPP and DAP) needs the deployment of a smart grid and a smart metering infrastructure to allow information exchange between the grid and consumer. Therefore, these tariffs are more suited for current application in developed countries (Elazab et al., 2022; Rahim et al., 2016; Rahman et al., 2021). Most of the developing countries rely on the IBR tariff which can be designed to control the total monthly electricity consumption of consumers (Elazab et al., 2022; Rahman et al., 2021; Rahman et al., 2017).

2.3. Load scheduling models and approaches

In the literature, extensive research was conducted to develop load scheduling optimization approaches for smart energy management at the household level (Shaban et al., 2021). In this context, many mathematical models were formulated considering different scheduling criteria (objective functions) and various assumptions regarding the grid tariff, loads types and characteristics, existence of renewable energy systems, existence of storage system, and consumer preferences (Bastianetto et al., 2021; Lu et al., 2018). Most of the existing models were formulated to determine the optimal load schedules that minimize the energy cost paid by the consumer under a given grid tariff (Elazab et al., 2022; Yang et al., 2017). Other single objective load scheduling models were formulated to optimize the peak load, and peak-to-average ratio (PAR) (Perez et al., 2016). Moreover, different load scheduling models considered multiple objectives simultaneously such as energy cost minimization, peak load minimization, waiting time minimization, consumer comfort maximization (Silva & Han, 2019; Soares et al., 2014; Tantawy et al., 2022; Yahia & Pradhan, 2020). The electric loads were modeled differently, as they can be categorized as flexible or essential, shiftable or non-shiftable, interruptible or uninterruptable, and controllable or uncontrollable (Hassan et al., 2013; Jordehi, 2019; Paterakis et al., 2015).

Some of the existing models accounted for the presence of renewable energy and storage systems installed at the household (Hafeez et al., 2018; Samuel et al., 2018; Shaban et al., 2021). Most of the existing load scheduling models were mathematically formulated as mixed integer linear programming (MILP) (Elazab et al., 2022; Rad & Barforoushi, 2020; Shaban et al., 2021; Yang et al., 2017). Several other models were formulated as mixed integer nonlinear programming, nonlinear programming, and quadratic programming models (Setlhaolo & Xia, 2015; Silva & Han, 2019; Zhu et al., 2019). The solution approaches employed in the literature include exact methods (Ismail et al., 2021; Shaban et al., 2021), and approximate heuristics and metaheuristics (Della Croce et al., 2017; Soares et al., 2014).

Most of the existing load scheduling models and approaches were developed for specific grid tariffs, especially dynamic tariffs that provide different prices over time. Della Croce et al. (2017) addressed the problem of smartly scheduling household appliances within a given time horizon under the TOU tariff to minimize the overall energy cost while respecting the consumer preferences and other technical constraints. They formulated a single-objective MILP model for this scheduling problem and compared different solution approaches based on real datasets obtained from Telecom Italia (Italy). Bassinette et al. (2021) addressed the same load scheduling problem in Della Croce et al. (2017), and proposed a solution approach based on simulated annealing. Khalid et al. (2019) proposed a multi-objective load scheduling optimization approach that integrates fuzzy logic and heuristic optimization techniques for the simultaneous minimization of cost, energy consumption and PAR, considering the TOU and RTP tariffs. Fuzzy logic was employed to control the throttleable and interruptible appliances. Three heuristic methods were applied for solving the household appliances scheduling problem.

Zhu et al. (2019) proposed a non-linear multi-objective model for scheduling the operation of the household appliances with the objectives of maximizing consumer convenience, reducing costs and improving global energy efficiency. The proposed model was solved by a cooperative heuristic approach to achieve the closest optimal solution. Samuel et al. (2018) developed a load scheduling approach that minimizes energy cost and considers renewable energy systems, energy storage systems, and the TOU and CPP tariffs. Javaid et al. (2018) proposed a load scheduling approach with the objectives of simultaneously minimizing energy cost, the PAR and user satisfaction under day-ahead real time pricing (DA-RTP) and the CPP tariff. Several other load scheduling models were proposed while considering different dynamic tariffs (Chai et al., 2015; Hafeez et al., 2018; Jordehi, 2019; Samuel et al., 2018; Shakouri & Kazemi, 2017). It is noticeable that most of the existing load scheduling models have limited applicability to developing countries wherein the IBR tariff is mostly adopted.

For the case of Egypt, limited research addressed the development of smart load scheduling approaches for energy management at the household level. Shaban et al. (2021) studied the load scheduling problem that accounts for different criteria and considers the existence of shiftable loads, the TOU tariff, a distributed renewable energy system, and consumer preferences constraints. Their proposed load scheduling problem was formulated as a nonlinear optimization model, and a solution approach based on cuckoo search was developed. To validate the optimality of the developed approach, its results were compared to an equivalent MILP model which was formulated and solved with exact methods. Elazab et al. (2022) proposed a smart home energy management system to minimize energy cost for the Egyptian households. They formulated a MILP model that considers a smart home with the IBR tariff, a PV system, a battery storage, and a vehicle-to-home. Tantawy et al. (2022) proposed a nonlinear load scheduling optimization model that minimizes the weighted sum of the energy cost, PAR, and waiting time. The model assumes the existence of a PV source, battery storage units, and combined TOU and IBR tariffs. To determine the optimal load schedules for single and multiple homes, they evaluated the performance of different metaheuristics, such as genetic algorithm, particle swarm optimization, whale optimization algorithm and sine cosine algorithm. Ismail et al. (2021) developed a MILP model that considers the IBR tariff to maximize the fulfillment of the appliances' schedule with respect to a monthly budget limit. However, most of the developed load scheduling models that can be implemented in Egypt do not incorporate the key features that characterize the load scheduling problem faced by the Egyptian households.

2.4. Research gaps

Based on the conducted literature review, it can be concluded that most of the existing load scheduling optimization models, designed to facilitate smart energy management at the household level, are not well-suited for application in Egypt. These models primarily assume the presence of a dynamic tariff structure, which is suitable for developed countries. However, developing countries, like Egypt, often employ different tariff systems, such as the IBR tariff, and have distinct system characteristics. While there have been efforts to develop models that consider those tariffs, they are insufficient and do not fully address the unique conditions of these countries.

Another gap in the literature is the lack of models that account for the net-metering system, a common feature of on-grid PV systems. This system allows for measuring the difference between the electricity supplied by the PV system and the electricity consumed by the household. In countries like Egypt, where on-grid PV systems are prevalent, the absence of models that account for the net-metering system represents a significant gap in the literature.

These gaps motivated this research to develop a load scheduling model specifically designed for the Egyptian households. The aim is to create a model that can effectively minimize energy costs at the household level in Egypt, taking into account the specific tariffs, system characteristics, and the net-metering system prevalent in the country. Importantly, while our model is tailored to the Egyptian households, it is designed with adaptability in mind. This means that it can be easily modified for potential application in other countries with similar conditions. This comprehensive and adaptable approach will ensure a more realistic and efficient load scheduling process.

Our endeavor will contribute to the literature by filling the identified research gaps and providing a practical solution for energy management in Egyptian households, while also offering a model that can be adapted to similar contexts in other developing countries. This approach underscores the universal applicability and potential impact of our research.

3. Problem description

This section presents a description of the load scheduling problem that addresses the specific challenges faced by the Egyptian households. This description encompasses details about the types of household appliances, the applied IBR tariff in Egypt, and the net metering system utilized by households equipped with PV systems. The section concludes with a problem statement that delineates the diverse categories of the Egyptian households, offering a clear overview of the exact challenges and considerations within this context.

Egypt has a strategic goal to reduce the energy consumption through the adoption of energy efficiency measures and the deployment of energy management practices at the residential sector (Shaban et al., 2021). The operating behavior of the household appliances constitutes the energy demand of the residential sector, and therefore, the energy management problem that faces the Egyptian households should be clearly defined to address it adequately. In addition, the Egyptian households seek to satisfy their energy needs at the least possible cost.

The types of household appliances that can be found in the Egyptian households vary and depends on the income level of the respective families. Based on a conducted survey, whose results are detailed in Section 4, it was found that the most common appliances in the Egyptian households are nineteen electrical appliances. Those appliances can be divided into two main categories: regular use appliances (Daily Appliances), and irregular use appliances (Weekly Appliances). The regular use appliances are usually operated for a certain number of hours every day such as light bulbs, water heater, refrigerator, deep freezer, water pump, fans, air conditioner, television (TV), and computer. The second category includes irregular use appliances which are operated on a weekly basis, such as washing machine, steam iron, cleaner, cloth dryer, electric mixer, electric kettle, stove, microwave, coffee maker, and dish washer.

The Egyptian households have no restrictions on the operating behavior of their electrical appliances (loads). Each consumer may run as many loads as possible and without any restrictions on the running time (duration) of each load. The overall utility from the consumer perspective increases whenever many available appliances are operated for long periods during the preferred times for the consumers. Although the excessive running of the loads may satisfy the overall utility, it would exaggerate the electricity consumption leading to higher energy cost to be charged to the consumer. Therefore, the Egyptian households need to smartly operate their appliances in a way that satisfies the overall utility limit at the least possible cost.

Egypt adopts the IBR tariff for the residential sector. At the end of each month, the accumulated monthly electricity consumption by a residential customer is used as the basis for calculating the bill dues. The Egyptian IBR tariff includes seven consumption and pricing blocks that range from 0.48 EGP/kWh for the first block of monthly consumption up to 50 kWh, to 1.45 EGP/kWh for over 1000 kWh of consumption, as per the fiscal year 2022-2023 (see Table 1).

Table 1: The residential IBR tariff in Egypt for the fiscal year 2022-2023

Block (j)	Electricity Consumption (kWh/Month)	Price (EGP/kWh)
1	From 0 To 50	0.48
2	From 51 To 100	0.58
3	From 0 To 200	0.77
4	From 201 To 350	1.06
5	From 351 To 650	1.28
6	From 0 and lower than 1000	1.28
7	From 0 and more than 1000	1.45

The Egyptian government encourages households to install on-grid PV systems to meet their energy demand from renewable energy sources, and to reduce their energy bills paid to the grid. In addition, the households can achieve some revenue from the sold energy to the grid when the energy generated by the PV system exceeds the energy consumed by the household appliances. The country applies the net metering system for the households with installed domestic PV systems. Those households are obliged to change the traditional power meter into a net-metering power meter which allows the integration of installed PV systems with the national power grid (see Figure 1). The net-metering system accounts for the accumulated amount of energy generated by the PV system and accumulated energy consumption throughout the month. At the end of each month, the energy deficit is computed to determine the monthly electricity bill for the consumer. If the monthly energy deficit is positive, it means that the total energy consumption throughout the month has been satisfied from the energy generated by the PV system. The excess energy is injected into the national grid, and it is credited to the consumer's account to be utilized in the next months' consumption. However, if the energy deficit is negative at a certain month, it means that the total energy consumption has exceeded the generated energy, and the energy deficit has been imported and purchased from the grid. In this case, the IBR tariff is applied to determine the energy cost related to the negative energy deficit. Therefore, the installation of PV systems at households may help reduce the amount of their electricity bills as they will be charged lower pricing rates if they purchase small amounts of energy from the grid (see Table 1). At the end of the fiscal year, if the energy deficit is positive, the power grid purchases this remaining amount according to a certain purchasing price.

The objectives of the Egyptian households vary depending on income level and living standard which are broadly categorized into two consumer groups. The first group comprises low to middle-income households seeking to meet energy needs at the lowest cost. The second group includes high-income households prioritizing utility maximization within a budget limit. This research primarily focuses on addressing appliance scheduling challenges faced by the first group, aiming to devise an optimal schedule minimizing energy costs from the grid. This involves considerations of consumer energy requirements and other system constraints. A mathematical model is developed to address the household appliances scheduling problem faced by the Egyptian households. The next section provides the details of the developed model and its assumptions.

4. Mathematical model

In this paper, a novel mixed-integer quadratic programming (MIQP) model is developed to address the household appliances scheduling problem in Egypt. The formulated MIQP model considers the Egyptian IBR tariff and the net-metering system used with domestic PV systems. The model is formulated to determine an optimal household load schedule that minimizes the net daily cost, while adhering to all system and consumer utility constraints. Additionally, the model calculates the optimal amounts of energy to be exchanged with the grid.

A few assumptions are made to facilitate the formulation of the proposed load scheduling model. It is assumed that the scheduling time horizon is one day. It is considered that each day is partitioned into T time slots where each time slot t has a duration d_t, for $t = 1, \ldots, T$. It is assumed that all time slots have the same duration of one hour ($d_t = 1, \forall t$), and therefore, all the household appliances are assumed to operate for a number of runs such that the duration of each run is one hour. It is assumed that the consumer can provide the preferred times for running each load i. In other words, the consumer determines the possible times to run each load i, where $A_i^t = 1$ when the load i can be run at time slot t, and $A_i^t = 0$ when the time slot t is not preferred to run that load at time t. Each load i has lower and upper limits for the number of daily runs that should be respected in the load schedule. The relative importance of the loads varies where it is considered that a single run of each load i provides a utility of u_i for the consumer. The utility u_i can be measured as the relative importance index with respect to the consumer preferences. The load schedule should satisfy a lower limit of overall utility (UL).

The indexes, parameters, decision variables that are used to formulate the proposed MIQP model are defined as follows:

Model indices:

i	Load index, where $i = 1, .., I$.
t	Time slot index, where $t = 1, \ldots, T$ and $T = 24$.
j	Tariff block index, where $j = 1, \ldots, J$.

Model parameters:

BC_j	Price of grid electricity associated with consumption block j in EGP/kWh.
w_j	Upper limit of electricity consumption in block j.
a_j	Administrative cost associated with block j.
sp	Selling price of solar energy to the grid in EGP/kWh.
p_i	Rated power of household appliance i in kW.
A_i^t	Possible state of household appliance i at time slot t, where $A_i^t = 1$ means that household appliance i can be run at time slot t whereas A_i^t

	$= 0$ means that load i is not preferred to run at time slot t.
RL_i	Minimum number of runs for household appliance i.
RU_i	Maximum number of runs for household appliance i.
PW_t	Power limit at time slot t in kW.
S_t	Expected PV output at time slot t in kW.
u_i	Utility of running household appliance/load i for a single run.
UL	Lower limit of overall utility.
D	Days per month.
M	A big value.

Decision variables:

x_i^t	A binary decision variably, where $x_i^t = 1$ if a household appliance run is active at time slot t, $x_i^t = 0$, otherwise.
y_j	A binary decision variable, where $y_j = 1$ if the consumer's net energy consumption falls within the block j, $y_j = 0$, otherwise.
Z	A binary decision variable, where $Z = 1$ if the total daily energy consumption exceeds the total daily energy generated from the PV system, $Z = 0$, otherwise.

VC	The amount of daily solar energy utilized for satisfying the energy consumption.
VS	The amount of daily solar energy sold to the grid.
NE	The net amount of daily energy imported/purchased from the grid.
CP_j	The charged daily energy cost to the consumer related to block j.
U	The overall utility of a given load schedule.

The complete MIQP model is formulated as follows:

$$Minimize\ NC = \left[\sum_{j=1}^{J} CP_j - (sp.VS)\right] \tag{1}$$

Subject to:

$$\sum_{t=1}^{T} A_i^t.x_i^t \geq RL_i, \qquad \forall i \tag{2}$$

$$\sum_{t=1}^{T} A_i^t.x_i^t \leq RU_i, \qquad \forall i \tag{3}$$

$$x_i^t \leq A_i^t.x_i^t, \qquad \forall i,t \tag{4}$$

$$\sum_{i=1}^{I} p_i.x_i^t \leq PW_t, \qquad \forall t \tag{5}$$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} p_i.x_i^t - \sum_{t=1}^{T} S_t \leq M.Z \tag{6}$$

$$\sum_{t=1}^{T} S_t - \sum_{i=1}^{I}\sum_{t=1}^{T} p_i.x_i^t \leq M.(1-Z) \tag{7}$$

$$VC \leq \sum_{i=1}^{I}\sum_{t=1}^{T} p_i.x_i^t \tag{8}$$

$$VC \leq \sum_{t=1}^{T} S_t \tag{9}$$

$$VC \geq \sum_{t=1}^{T} S_t - M.(1-Z) \tag{10}$$

$$VC \geq \sum_{i=1}^{I}\sum_{t=1}^{T} p_i.x_i^t - M.Z \tag{11}$$

$$VS = \left(\sum_{t=1}^{T} S_t - VC \right) \tag{12}$$

$$D.CP_j = \left[\left(BC_j.D.NE \right) + a_j \right].y_j, \quad for\ j = 1 \tag{13}$$

$$D.CP_j = \left[\left(BC_{j-1}.W_{j-1} \right) + \left(BC_j.\left((D.NE) - W_{j-1} \right) \right) + a_j \right].y_j, \quad for\ j = 2 \tag{14}$$

$$D.CP_j = \left[\left(BC_j.D.NE \right) + a_j \right].y_j, \quad for\ j = 3 \tag{15}$$

$$D.CP_j = \left[\left(BC_{j-1}.W_{j-1} \right) + \left(BC_j.\left((D.NE) - W_{j-1} \right) \right) + a_j \right].y_j, \quad for\ j = 4 \tag{16}$$

$$D.CP_j = \left[\left(BC_{j-2}.W_{j-2} \right) + \left(BC_{j-1}.\left(W_{j-1} - W_{j-2} \right) \right) + \left(BC_j.\left((D.NE) - W_{j-1} \right) \right) + a_j \right].y_j, \quad for\ j = 5 \tag{17}$$

$$D.CP_j = \left[\left(BC_j.D.NE \right) + a_j \right].y_j, \quad for\ j = 6 \tag{18}$$

$$D.CP_j = \left[\left(BC_j.D.NE \right) + a_j \right].y_j, \quad for\ j = 7 \tag{19}$$

$$NE = \left(\sum_{i=1}^{I} \sum_{t=1}^{T} p_i . x_i^t - VC \right) \tag{20}$$

$$D.NE - W_j \leq M.\left(1 - y_j\right), \qquad \forall j \in \{1,\ldots,j-1\} \tag{21}$$

$$D.NE - W_j > M.\left(y_{j+1} - 1\right), \qquad \forall j \in \{1,\ldots,j-1\} \tag{22}$$

$$\sum_{j=1}^{J} y_j = 1 \tag{23}$$

$$U = \sum_{i=1}^{I} \sum_{t=1}^{T} u_i \times x_i^t \tag{24}$$

$$U \geq UL \tag{25}$$

$$x_i^t \in \{0,1\}, \qquad \forall i,t \tag{26}$$

$$y_j \in \{0,1\}, \qquad \forall j \tag{27}$$

$$Z \in \{0,1\} \tag{28}$$

$$CP_j \geq 0, \qquad \forall j \tag{29}$$

$$VC \geq 0, \quad VS \geq 0, \quad NE \geq 0, \quad U \geq 0 \tag{30}$$

The objective function (1) minimizes the net daily cost paid by the consumer to the grid. It represents the difference between the daily cost (CP_j) charged to the consumer's net daily energy consumption (NE) and the daily revenue from the sold solar energy to the grid (VS). The solar energy is sold to the grid at a price of sp. The cost of the net energy consumption (CP_j) is charged based on the IBR tariff applied in Egypt (see Table 1).

Constraints (2) ensure that each household appliance/load i must be operated for a minimum number of required daily runs (hours) of RL_i at the preferred time slots over the scheduling time horizon. Each load i is considered active (turned on) at preferred time slot t ($A_i^t = 1$) if $x_i^t = 1$, and it is considered turned off at preferred time slot t if $x_i^t = 0$. The model decides about the values of x_i^t considering the other problem constraints. Each load i cannot be turned on at non-preferred time slot t ($A_i^t = 0$) which leads to $x_i^t = 0$. Constraints (3) ensure that each load i does not exceed the maximum number of required daily runs (hours) of RU_i at the preferred time slots over the scheduling time horizon. Constraints (4) ensure that each load i can be run only at the allowed/preferred time slots for running this load over the scheduling time horizon, where the preferred time slots are determined by the consumer. Constraints (5) ensure that the total power consumption at each time slot t must not exceed the power limit PW_t. These constraints represent the power limit imposed due to the installed power meter. The power limit can also be set to ensure the safe operation of electricity in certain households. Constraints (6-11) calculate the amount of daily solar energy (VC) that can be utilized to satisfy the household's energy consumption. They compute the minimum of the available daily solar energy and the total daily energy consumption. Constraint (12) calculates the amount of daily solar energy that can be sold to the grid (VS).

Constraints (13-19) compute the charged daily energy cost to the consumer (CP_j) based on the consumer's net energy consumption and the grid's inclining block tariff rates. These seven constraints correspond to the seven consumption blocks associated with the Egyptian IBR tariff, as previously detailed in the problem description section. Each constraint calculates the electricity cost that would be charged to the consumer if the electricity consumption falls within a specific block j. Specifically, $CP_j \geq 0$ when $y_j = 1$, indicating that the consumer's net energy consumption is within the corresponding block j. Conversely, $CP_j = 0$ when $y_j = 0$, signifying that the consumer's net energy consumption is not within that block j. These constraints account for both fixed and variable costs associated with the total monthly consumption, providing a comprehensive representation of the charged energy cost based on the consumer's utilization pattern. The calculated costs by these constraints are intricately linked with the objective function. The objective function seeks to determine the optimal scheduling of household appliances, aiming to minimize the total cost incurred by the consumer. Constraint (20) calculates the net amount of daily energy imported from the grid. Constraints (21-23) determine the tariff block associated with the consumer's net energy consumption, considering the Egyptian IBR tariff.

Constraint (24) computes the overall utility (U) achieved from a given load schedule. Constraint (25) ensures that the lower limit of the overall utility is achieved. Constraints (26-30) define the domains of the decision variables.

5. Characteristics of the Egyptian household appliances' usages

In this research, a survey is conducted to identify the characteristics of using the electrical appliances by the Egyptian households. The collected data through the survey is utilized to perform a case study to demonstrate the applicability and effectiveness of the proposed MIQP model. A questionnaire is designed to perform the required survey through both online platforms and direct interviews. The questionnaire is designed to collect information regarding households, energy consumption, and monthly bills. Moreover, the questionnaire collects information about the characteristics of the household appliances.

A total of 160 respondents were approached, where the response rate has reached above 97% in the questionnaire items. The survey results indicate that 53% of the respondents are city residents while the remaining are living in villages. The results also indicate that the average number of family members is five, the average house area is 127 m^2, and the average number of rooms per house is four. The survey results indicate that 79% of the households have single-phase power meter while the remaining 21% of the sampled households have three-phase power meter. The households consume on average 350.2 kWh/Month in the summer months, and 269.3 kWh/Month in the winter months. The households are charged an average monthly electricity bill of 344.8 EGP/Month in the summer months and 254.1 EGP/Month in the winter months. The related descriptive statistics (average, standard deviation, minimum, first quartile (Q1), median (Q2), third quartile (Q3), and maximum) are provided in the appendix (see Table A.1)

An important section is designated in the questionnaire to collect information about the importance of the different households' appliances from the consumer perspective. The respondents were asked to determine the importance of each appliance considering the following choices: Not Important (NI), Low Importance (LI), Medium Importance (MI), High Importance (HI), and Very High Importance (VHI). These choices are equivalent to the numerical scores 1 (Not Important) through 5 (Very High Importance) on the Likert scale, respectively. The number of respondents is 160 and the response rate is 100%. Based on that, the relative importance index (RII) has been estimated for the different appliances using the following formula:

$$RII = \frac{\sum_{l=1}^{5} s_l . f_l}{\sum_{l=1}^{5} f_l} \quad (31)$$

where RII represents the relative importance index of a certain load which is equivalent to the utility index u_i indicated in the presented mathematical model, s_l represents the l^{th} point rating on the Likert scale, and f_l is the number of respondents who selected this rating. Based on the survey data, the relative importance index is estimated for the 20 household appliances that are commonly used in the Egyptian households. The results related to the relative importance index along with the rank of the different loads based on this index are reported in Table A.2. The results indicate that the refrigerator, washing machine, light bulbs, fans, and electric mixer are of the most importance to the Egyptian households. The coffee maker, dish washer, radio, stove, and microwave are of the least importance. The other appliances are of moderate importance.

Another section of the questionnaire is dedicated to collecting data about the number of times of using each electrical appliance per week (weekly frequency). The respondents were asked to determine the number of days they operate each electrical appliance from the list of appliances considered in the survey. The respondents select "zero times" for the household appliances that are not available at their homes. Therefore, the descriptive statistics have been computed for the number of usages that are greater than zero (see Table A.3). The results differentiate the household appliances that are used regularly on a daily basis, and the appliances that are used irregularly on a weekly basis.

The respondents were also asked to provide the number of operating hours for each household appliance. The related results to the number of operating hours for both the daily and weekly households' appliances are provided in Table A.4. The respondents were also asked to select the preferred time periods for running each household appliance and the related results are summarized in Table A.5. The respondents can select more than one period for each load for running it based on their preferences.

6. Results and analysis

A case study is conducted to demonstrate the applicability and the effectiveness of the proposed MIQP model for solving the Egyptian households' appliances scheduling problem. The case study applies the proposed MIQP model for different examples (cases) of this scheduling problem. The investigated cases are considered to represent two different categories of the Egyptian households in the summer months. The first category (Case1) represents a household of low standard of living that includes a small number of appliances and limited energy requirements. The second category (Case2) represents a household with a higher standard of living that has a larger number of household appliances and high energy requirements. Two variants of each case are considered to investigate the impact of installing a domestic PV system on the energy cost charged to the household. Therefore, the model is applied to determine the optimal load schedules for four different cases of the load scheduling problem: Case1, Case1+PV, Case2, and Case2+PV. The MIQP model is implemented in LINGO 18.0 on a laptop with Intel(R) Core (TM) i5-4200U CPU @ 1.60GHz 2.30 GHz, and 8.00 GB of RAM. The global solver of LINGO 18.0 is selected to solve the model for the different investigated cases. The optimal solution for the different cases is obtained in a fraction of a second.

6.1. Data collection

The required data for the investigated cases is mainly derived from the survey results. Other data sources are considered to complete the input data required for applying the proposed MIQP model to the investigated cases. The required input data for the model includes the electrical appliances/loads data, PV output data, IBR tariff data, selling price of solar energy, and power limit. The IBR tariff data has been obtained from the official sources (see Table 1).

The required loads data to collect include number and types of loads, rated power of each load, lower and upper limits for the number of required runs per day for each load, utility of running each load for a single run, and preferred time slots for running each load. The loads data for the two different categories of household (Case1 and Case2) are provided in Tables 2 and 3, respectively. The loads' data is obtained from the survey results. The load utility is taken directly from the survey results as reported in Table A.2. In the different cases, the refrigerator is considered to operate for 24 hours and therefore its rated power has been approximated to consider the cooling cycles of refrigerators. In other words, the rated power of the refrigerator has been adjusted to consider the assumption that the refrigerator is 24 hours connected to the electricity, and therefore, the associated energy cost due to its actual energy consumption can be computed accurately. Moreover, the weekly loads are considered where they are not running daily while they may be operated for several runs every week. It is assumed that the duration of each weekly load run is one hour. The proposed MIQP model is formulated to develop the optimal schedules for the daily operation of household appliances in a way that minimizes the daily energy cost. Therefore, the model assumes that all the appliances/loads are run daily. Nevertheless, an approximation can be made to consider the impact on the energy cost of the weekly appliances such as washing machines. The weekly loads can be considered by computing the equivalent values of the number of running hours per day and rated power consumption considering the actual rated power and the number of required runs per week. It is also assumed that the power limit in each time slot is unlimited for the different cases.

Table 2: The loads data for the first category of households (Case1 and Case1+PV)

Appliance (i)	**Rated Power** (Watt)	**Number of Daily Runs (Hours/day)**		**Appliance Utility (u_i)**	**Preferred Times**
		Lower Limit (RL_i)	Upper Limit (RU_i)		
Daily Loads					
Four 18-Watt Light Bulbs	72	6	18	4.16875	Noon, Evening, and Night

Appliance (i)	**Rated Power** (Watt)	**Number of Daily Runs (Hours/day)**		**Appliance Utility (u_i)**	**Preferred Times**
		Lower Limit (RL_i)	Upper Limit (RU_i)		
Refrigerator	220	24	24	4.39375	Morning, Noon, Evening, and Night
Water Pump	382	2	8	3.60625	Morning, and Noon
Two Fans	160	12	20	3.88125	Morning, Noon, Evening, and Night
TV	100	8	12	3.25	Noon, and Evening
Computer	100	6	9	3.1875	Noon, and Evening
Weekly Loads					
Washing Machine	50	3	5	4.1875	Morning, and Noon
Steam Iron	142.58714	2	4	3.4125	Morning, Noon, and Evening
Electric Mixer	71.42857	2	5	3.825	Morning, Noon, and Evening,

Table 3: The loads data for the second category of households (Case2 and Case2+PV)

Appliance (i)	Rated Power (Watt)	Number of Daily Runs (Hours/day)		Appliance Utility (u_i)	Preferred Times
		Lower limit (RL_i)	Upper limit (RU_i)		
Daily Loads					
Six Light Bulbs	108	6	18	4.16875	Noon, Evening, and Night
Water Heater	1500	2	4	2.450	Morning, and Evening
Refrigerator	220	24	24	4.39375	Morning, Noon, Evening, and Night
Deep Freezer	220	24	24	3.18125	Morning, Noon, Evening, and Night
Water Pump	382	2	8	3.60625	Morning, and Noon
Two Fans	160	12	20	3.88125	Morning, Noon, Evening, and Night
Air Conditioner	1500	8	10	2.1875	Noon, and Evening
TV	100	8	12	3.25	Noon, and Evening
Computer	100	6	9	3.1875	Noon, and Evening
Weekly Loads					
Washing Machine	50	3	5	4.1875	Morning, and Noon

Appliance (i)	Rated Power (Watt)	Number of Daily Runs (Hours/day)		Appliance Utility (u_i)	Preferred Times
		Lower limit (RL_i)	Upper limit (RU_i)		
Steam Iron	142.85714	2	4	3.4125	Morning, Noon, and Evening
Cleaner	107.14286	2	5	2.29375	Morning, and Noon
Cloth Dryer	50	3	4	1.8875	Morning, and Noon
Electric Mixer	71.42857	4	5	3.825	Morning, Noon, and Evening,
Electric Kettle	257.14286	2	7	2.0875	Morning, and Noon
Stove	257.14286	3	4	1.6875	Noon
Microwave	100	3	5	1.7375	Morning, Noon, and Evening,
Coffee Maker	142.85714	3	4	1.25625	Morning, Noon, and Evening,
Dish Washer	171.42857	3	5	1.29375	Morning, Noon, and Evening,

The PV output data has been collected from a real PV system installed at an academic building in Egypt. The real PV system has an installed capacity of 10 kW whereas it is assumed that the household in the investigated cases (Case1+PV and Case2+PV) has a PV system with an installed capacity of 2.5 kW. Therefore, the PV output data required for the investigated cases has been estimated at 25% of the average output of the actual PV system. The estimated PV output of the 2.5 kW PV system is depicted in Figure 2. The total daily energy generated from this PV system amounts to 13.0498 kWh. This amount can be utilized to satisfy the energy requirements of the household while the excess amount of solar energy can be sold to the grid at a price of 0.31492 EGP/kWh as per the solar energy prices for the fiscal year 2022-2023.

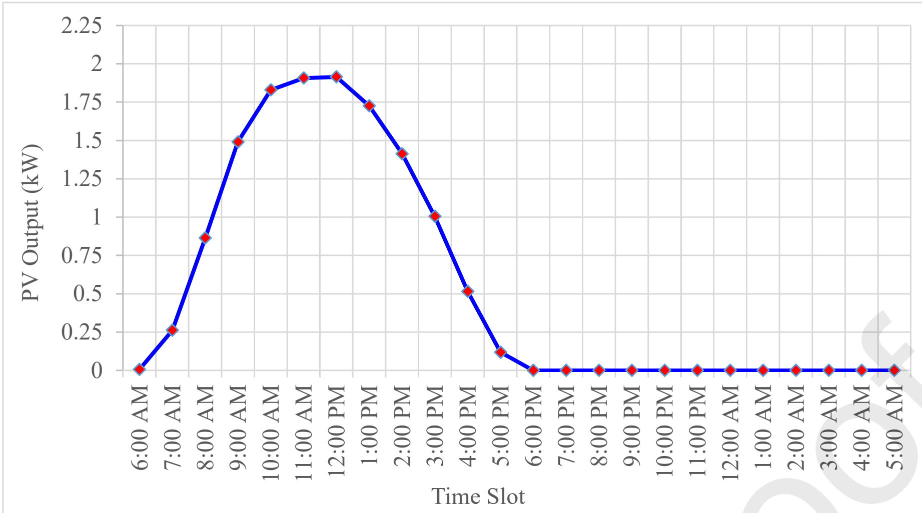

Figure 2: The estimated power output of a 2.5-kW PV system

6.2. First category of households

The first case considers a household with six electrical loads that are operated daily and three other electrical loads that are run weekly (see Table 2). A feasible solution for the base case (Case1) is to run each household appliance to the maximum number of runs per day at the respective preferred time slots. This solution ensures that both the household's energy requirements and the overall utility are satisfied. The related load schedule for this feasible solution requires a total amount of energy of 12.15 kWh/day, and therefore, the total monthly consumption will be about 364.5 kWh which falls within the fifth block of the Egyptian IBR tariff. The energy unit cost related to the fifth consumption block is 1.28 EGP/kWh for the fiscal year 2022-2023 (see Table 1). As a result, the household will be charged a monthly electricity bill of 346.5 EGP (11.55 EGP/day).

However, applying the proposed MIQP model can provide a better solution that satisfies the energy requirements and the other constraints of the household at the least possible cost. The optimal solutions for the two variant cases related to the low living standard household (Case1 and Case1+PV) are provided in Table 4. The optimization results for the base case (Case1) show that the household can satisfy its energy requirements at a minimum cost of 6.69 EGP/day (201 EGP/Month). This solution saves about 163.5 EGP/Month for the household compared to the feasible solution of running each load to the maximum number of runs per day. The optimization results also indicate that the optimal load schedule for this case consumes a net amount of energy of 7.79 kWh/day (234 kWh/Month). This amount of electricity consumption falls within the fourth consumption block, and therefore, the household is charged the monthly electricity bill at a cost rate of 1.06 EGP/kWh. The optimal schedule of the household appliances is depicted in Figure 3 where it shows the preferred time slots for running the different loads and the selected time slots for running these loads. This load schedule provides an overall utility of 253.70. In Figure 3, the model's scheduling decisions, such as keeping lights on during days and off during nights, are contingent upon the input data reflecting user preferences, emphasizing the adaptability of the model to diverse user scenarios.

Table 4: The optimal solution for the two cases related to the low living standard household.

Decision Variable/Output	Model Symbol (Unit)	Household without PV (Case1)	Household with PV (Case1+PV)
Net Energy Cost	*NC* (EGP/day)	6.69	-1.62
Net Energy Consumed	*NE* (kWh/day)	7.79	0.00
Overall Utility	*U*	253.70	253.70
Solar Energy Utilized	*VC* (kWh/day)	0	7.79
Solar Energy Sold	*VS* (kWh/day)	0	5.26

The optimal load schedule for the case of the household with PV (Case1+PV) remains the same as the obtained optimal load schedule for the base case (Case1). However, the optimal solution for this case indicates that the household will not be required to purchase electricity from the grid since the daily energy requirements are totally satisfied from the generated solar energy. Moreover, there is an excess amount of generated solar energy that will be sold to the grid, and this would achieve a net daily profit of 1.62 EGP (48.70 EGP/Month) for the respective household.

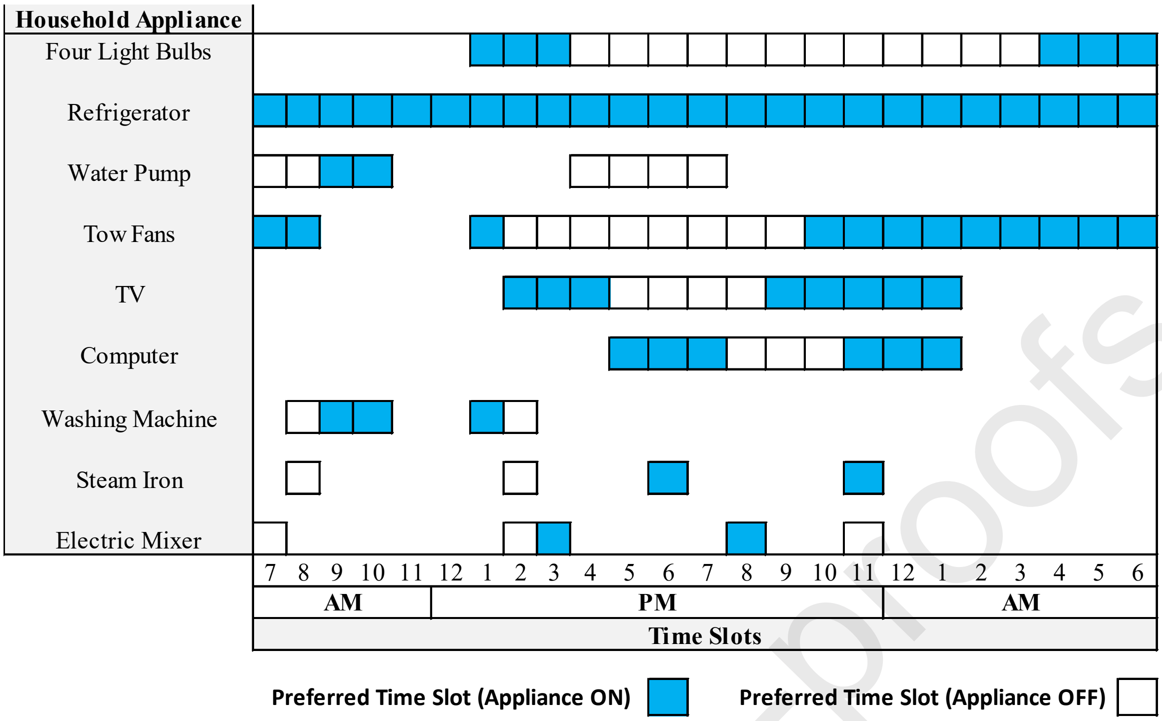

Figure 3: The optimal load schedule for the two cases related to the low living standard household (Case1 and Case1+PV)

6.3. Second category of households

The related load data for the second category of households that includes many household appliances is presented in Table 3. In this case, the household is considered to include nine daily electrical loads and ten weekly electrical loads. The feasible solution of running all the loads to their maximum number of runs per day will require a total amount of energy of 40.4 kWh to be purchased from the grid. This means that the total monthly consumption for the respective household will be about 1212 kWh which falls within the seventh consumption block at a cost rate of 1.45 EGP/kWh. Accordingly, the household will pay about 1797 EGP/Month (59.4 EGP/day).

Applying the proposed MIQP model for the base case (Case2) results in an optimal load schedule that requires a total amount of energy of 28.14 kWh/day (844.2 kWh/Month). The detailed optimization results ae provided in Table 5. Therefore, the total monthly energy consumption for the household falls within the sixth consumption block at a cost rate of 1.28 EGP/kWh. As a result, the household will be charged a monthly bill of 1105.719 EGP (36.86 EGP/day). The optimal load schedule for this case is provided in Figure 4. The load schedule depicts the optimal number of runs for each household appliance and the selected time slots for those runs at the preferred time slots for running the appliance.

Further cost savings can be achieved if the household has an installed PV system. For the case of the household with PV (Case2+PV), the optimal solution indicates that the household will partially satisfy its energy requirements from the energy generated from the 2.5 kW PV system. The optimal load schedule requires 28.04 kWh/day where the household utilizes 13.05 kWh/day from the generated solar energy and purchases 15.09 kWh/day from the grid to satisfy this energy demand (see Table 5). The total monthly energy consumption for the respective household will be 452.82 kWh which falls within the fifth consumption block at a cost rate of 1.28 EGP/kWh (see Table 1). Accordingly, the household will be charged a minimum monthly electricity bill of 459.61 EGP (15.32 EGP/day). The results indicate that the household has not been benefited from the decrease in the tariff block since the cost rates for the fifth and sixth blocks are the same (1.28 EGP/kWh) in the IBR tariff of the fiscal year 2022-2023.

Table5: The optimal solution for the two cases related to the high living standard household.

Decision Variable/Output	**Symbol (Unit)**	**Household without PV (Case2)**	**Household with PV (Case2+PV)**
Net Energy Cost	*NC* (EGP/day)	36.86	15.32
Net Energy Consumed	*NE* (kWh/day)	28.14	15.09
Overall Utility	U	346.19	346.19
Solar Energy Utilized	*VC* (kWh/day)	0	13.05
Solar Energy Sold	*VS* (kWh/day)	0	0

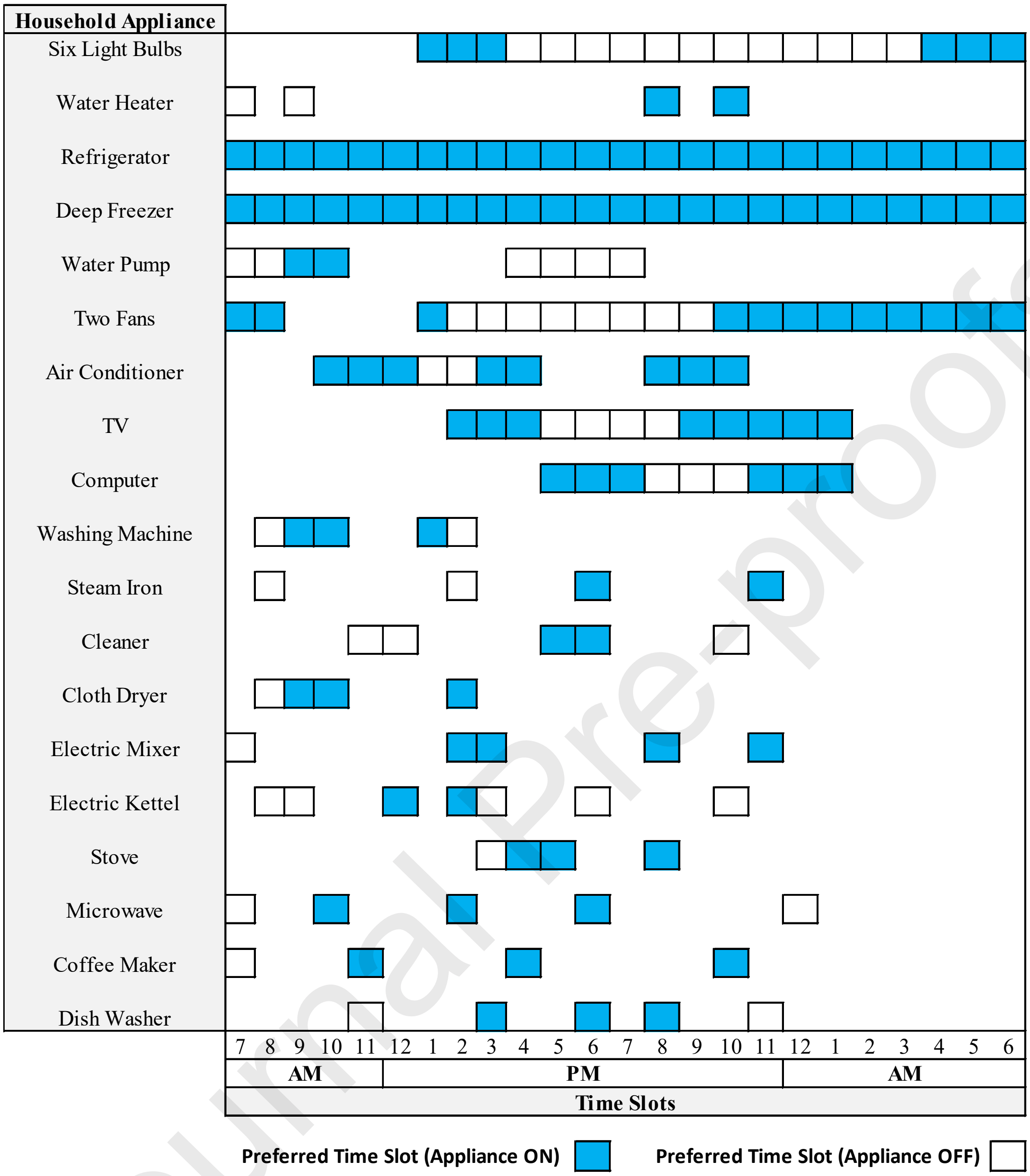

Figure 4: The optimal load schedule for the two cases related to the high living standard household (Case2 and Case2+PV)

6.4. Sensitivity analysis

The purpose of the sensitivity analysis is to investigate the effect of changing the overall utility limit on the net daily cost and the optimal load schedule. The developed MIQP model is solved at different levels of the overall utility limit within its possible range. Meanwhile, the data used for the investigated cases in the previous section remains fixed.

The results for this analysis are reported in Figures 5 and 6. The results indicate that the net daily cos is sensitive to the overall utility limit. The increase in the overall utility limit will lead to a higher net daily cost regardless of the household category (see Figures 5 and 6). This can be attributed to the increase in the number of loads' runs to satisfy the utility requirements, and therefore, the energy consumption increases leading to higher energy costs. Most importantly, the results indicate that the net daily cost will be highly sensitive to the overall utility limit in the cases in which the household is not connected to a PV system (Case1 and Case2). On the other hand, the net daily cost is less sensitive to the overall utility limit in the cases of households with PV (Cas1+PV and Case2+PV). The results show that the case of a household with PV can achieve the possible maximum overall utility without purchasing any energy amounts from the grid. However, in either case, a sharp increase in the net daily cost is observed as the overall utility limit is increased to its possible maximum value. The results imply that the utility achieved for the consumer has a cost and this cost increases as the utility requirements increases. The existence of installed PV systems at the household could reduce the net daily cost to the overall utility limit.

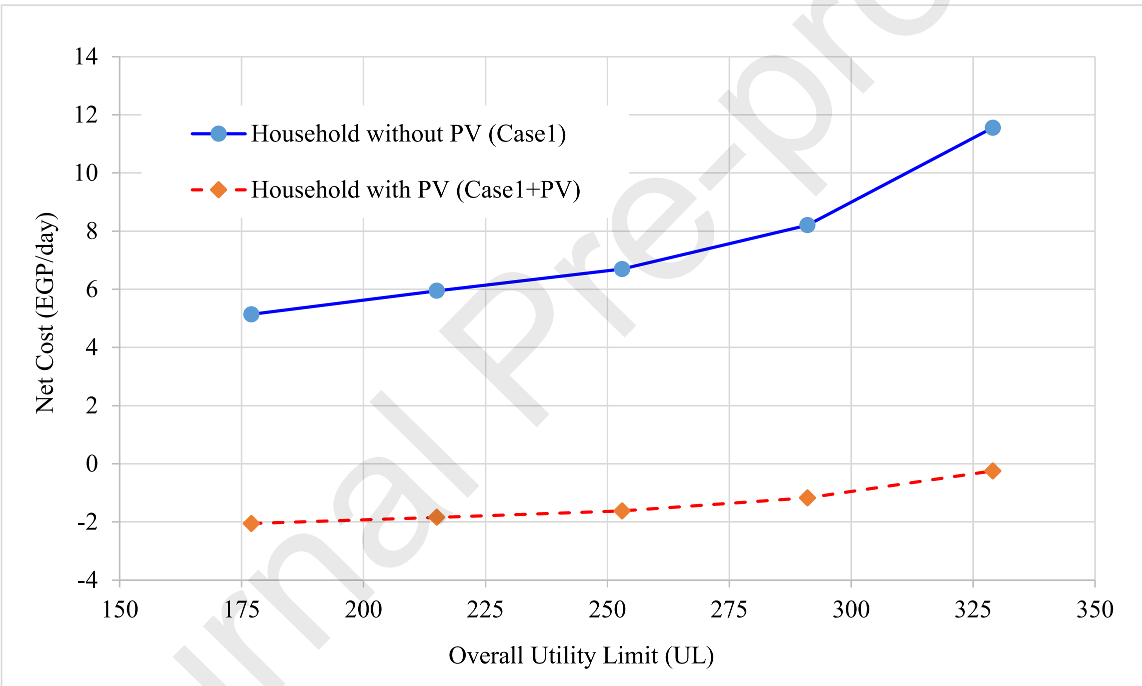

Figure 5: The impact of the utility limit on the net daily cost for the two cases related to the low living standard household.

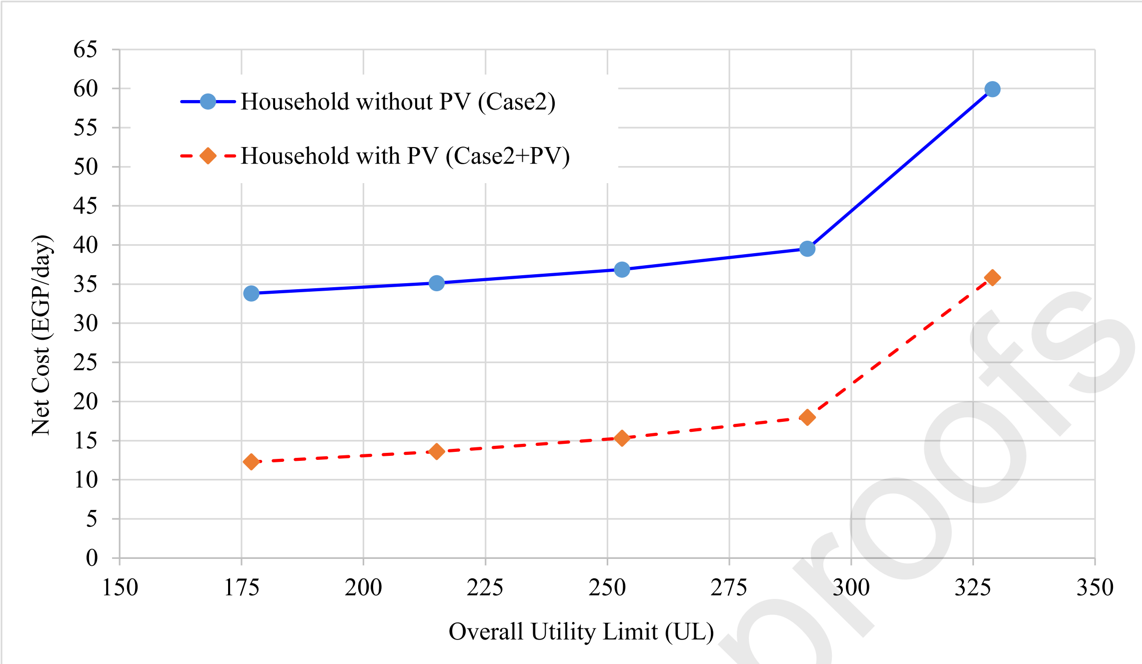

Figure 6: The impact of the utility limit on the net daily cost for the two cases related to the high living standard household.

7. Discussion and Managerial Implications

The global landscape demands urgent solutions for effective energy management, accommodating consumers across both developing and developed countries. These solutions must align with diverse consumer goals, whether it is minimizing energy costs for household loads or maximizing utility/benefits within specified budget constraints.

Existing research has predominantly focused on methods for scheduling household loads, often assuming the prevalence of a time-of-use tariff. This assumption caters well to developed countries but falls short in addressing the prevalent IBR tariff in developing countries. This paper focuses on the Egyptian case, providing an in-depth exploration of the household appliances scheduling problem faced by Egyptian households. It highlights the goals, outlines the IBR tariff employed in Egypt, and introduces the net metering system needed for linking PV systems to the national grid in Egypt.

A crucial outcome of this research is the formulation of a mathematical model tailored to optimize electrical load operations, meeting consumer requirements in terms of preferred operating times at minimum costs. The model allows for determining the significance of various household appliances, establishing minimum utility thresholds, considering energy generated by PV systems, and identifying preferred load operation times, all based on user inputs. The ensuing optimal load operating schedule is developed to meet the energy needs of the Egyptian families efficiently and cost-effectively.

The research contributes innovative ideas for resolving household appliances scheduling challenges, particularly in countries with IBR tariffs. The findings underscore that the presence of PV systems, coupled with the proposed mathematical model, can significantly reduce electricity bills under an IBR tariff. The proposed model can support the determination of the suitable size of domestic PV systems in case the household is going to employ the proposed model for energy management.

For widespread application and accessibility within Egyptian households, a user-friendly interface is envisioned. Developing programs, computer applications, or websites could empower users to input household electrical load data and obtain customized operating schedules. Collaborations with electricity companies or entities specializing in smart energy management are recommended for the implementation of such energy scheduling tools.

The mathematical model serves as a valuable tool for optimizing the operation of household appliances across diverse categories of the Egyptian households. Achieving this optimization involves conducting surveys to comprehend distinct categories, their approaches to operating household appliances, and the varying importance of these appliances. The data gleaned from these surveys becomes instrumental in generating tailored results through the mathematical model. Consequently, these results offer specific and direct solutions applicable to different categories of the Egyptian households, empowering each household to adopt a solution aligning with its unique circumstances.

In essence, the research not only provides a tailored solution to the specific challenges faced by the Egyptian households but also envisions a user-friendly and widely applicable tool that can revolutionize electrical load management practices, aligning with broader goals of sustainability and cost-effectiveness in energy consumption.

8. Conclusions

This research addressed the load scheduling problem that faces the Egyptian households and provided a smart load scheduling approach to minimize energy cost. In this regard, a clear description of the load scheduling problem was presented and an MIQP load scheduling model was formulated. The proposed MIQP model can be employed to smartly schedule the usages of the Egyptian household appliances considering the Egyptian IBR tariff and the net metering system with installed domestic PV systems, which is applied in Egypt. The smartness of the proposed load scheduling approach lies in its ability to generate optimal load schedules that meet the energy requirements of households at the lowest possible cost. It considers the relative utilities of household appliances and produces optimal schedules that fulfill the overall utility constraint.

A survey was conducted to understand the diversity and characteristics of electrical appliance usage among Egyptian households. The results of the survey provided estimates for the relative utilities of household appliances. Additionally, it offered valuable insights into the operating characteristics of the appliances used in the Egyptian households. These survey results were then utilized in a case study to demonstrate the applicability and effectiveness of the proposed MIQP model as a tool for smart energy management at the household level in Egypt.

Several cases representing two different categories of households based on their living standards were investigated. Additionally, two variants of each case were considered to examine the impact of installed PV systems on energy costs. The results confirm the effectiveness of the proposed MIQP model in minimizing energy costs for different categories of the Egyptian households. For instance, a household with a low living standard can meet its daily energy requirements at a minimum cost of 6.7 EGP/day without a PV system, and achieve a daily return of 1.62 EGP/day with a 2.5 kW PV system installed. A household with a high living standard can meet its energy requirement at a minimum cost of 36.86 EGP/day, which decreases by 58% with a 2.5 kW PV system installed.

Furthermore, a sensitivity analysis was conducted using the MIQP model to investigate the impact of the overall utility limit on the optimal net daily cost. The results show that an increase in the overall utility limit leads to a higher net daily cost, regardless of the household category. This implies that the utility achieved for the consumer has a cost that increases as the utility requirements increase. However, the model can be utilized to achieve the required overall utility limit at the lowest possible cost.

Future research will involve the development of a new household appliance scheduling model that maximizes overall utility while adhering to a household's budget limit. This model could be beneficial for households aiming to maximize the utility derived from their electrical appliances without exceeding a consumer-set budget limit. In this case, the model will determine the optimal schedule for household appliances that maximizes utility without exceeding the budget limit. Additionally, an experimental design approach could be used in future research to investigate the factors impacting the objective functions in both models, providing heuristics to assist consumers in easily scheduling their appliances.

Appendix A

Table A.1: Descriptive statistics for the collected data on households' general information and electricity consumption

Item	Sample Size	Response Rate (%)	Descriptive Statistics						
			Average	Standard deviation	Min	Q1	Q2	Q3	Max
General Information									
Number of Family Members	160	97.5	5	1.663	1	4	5	6	12
House Area (m^2)	160	96.88	127	56.415	29	90	120	150	500
Number of Rooms	160	97.5	4	1.609	2	3	4	5	16
Electricity Consumption in Summer and Winter (kWh/Month)									
Summer Electricity Consumption (kWh/Month)	160	75.63	350.2	294.4	75.5	150.5	275.5	500.5	1500
Winter Electricity Consumption (kWh/Month)	160	75.63	269.3	254.6	75.5	150.5	150.5	275.5	1500
Electricity Bill in Summer and Winter (EGP/Month)									
Summer Electricity Bill (EGP/Month)	160	96.25	344.8	248	50	225	250	425	1500

Winter Electricity Bill (EGP/Month)	160	95	254.1	190.5	30	150	250	350	1500

Table A.2: The estimated relative importance index for the Egyptian households' appliances

Appliance (Load i)	Ratings Frequency					$RII\ (u_i)$	Rank
	NI (1)	LI (2)	MI (3)	HI (4)	VHI (5)		
Light Bulbs	0	7	26	60	67	4.16875	3
Water Heater	69	14	28	34	15	2.45000	11
Refrigerator	0	0	11	75	74	4.39375	1
Deep Freezer	26	25	32	48	29	3.18125	10
Water Pump	17	12	28	63	40	3.60625	6
Fan	1	11	34	74	40	3.88125	4
Air Conditioner	77	26	25	14	18	2.18750	13
TV	7	34	50	50	19	3.25000	8
Radio	104	31	16	4	5	1.59375	18
Computer	32	22	27	42	37	3.18750	9
Washing Machine	2	4	18	74	62	4.18750	2
Steam Iron	13	18	45	58	26	3.41250	7
Cleaner	63	24	42	25	6	2.29375	12
Cloth Dryer	95	20	23	12	10	1.88750	15

Appliance (Load i)	Ratings Frequency					$RII\ (u_i)$	Rank
	NI (1)	LI (2)	MI (3)	HI (4)	VHI (5)		
Electric Mixer	4	9	35	75	37	3.82500	5
Electric Kettle	76	30	29	14	11	2.08750	14
Stove	101	28	16	10	5	1.68750	17
Microwave	100	21	24	11	4	1.73750	16
Coffee Maker	133	17	7	2	1	1.25625	20
Dish Washer	130	20	5	3	2	1.29375	19

Table A.3: The estimated weekly frequency of using the Egyptian households' appliance.

Appliance (Load i)	Sample Size*	Descriptive Statistics						
		Average	Standard deviation	Min	Q1	Q2	Q3	Max
Light Bulbs	160	6.031	1.761	2	7	7	7	7
Water Heater	89	4.326	2.141	1	3	4	7	7
Refrigerator	160	6.006	1.821	1	7	7	7	7
Deep Freezer	124	5.613	2.140	1	3	7	7	7
Water Pump	138	5.486	2.152	1	3	7	7	7
Fan	158	5.722	1.954	1	4	7	7	7
Air condition	70	4.286	2.341	1	2	4.5	7	7
TV	151	5.053	2.202	1	3	7	7	7
Radio	56	3.429	2.239	1	2	3	5.75	7
Computer	131	4.237	2.259	1	2	4	7	7
Washing Machine	147	3.204	1.887	1	2	3	5	7
Steam Iron	142	3.148	1.822	1	2	3	4	7
Cleaner	86	2.988	2.095	1	1	2	5	7
Cloth Dryer	60	2.683	1.827	1	1	2	4	7

Appliance (Load i)	Sample Size*	Descriptive Statistics						
		Average	Standard deviation	Min	Q1	Q2	Q3	Max
Electric Mixer	157	3.834	1.934	1	2	3	5	7
Electric Kettle	68	4.103	2.364	1	2	4	7	7
Stove	46	3.174	2.090	1	1	2.5	4.25	7
Microwave	44	3.227	2.044	1	1.25	2.5	5	7
Coffee Maker	20	2.75	1.585	1	1.25	2.5	4	7
Dish Washer	22	3.364	2.216	1	1	3	5.25	7

* Number of respondents with positive number of usages

Table A.4: The estimated number of running hours of the Egyptian households' appliances.

Appliance (Load i)	Sample Size*	Average	Standard Deviation	Min	Q1	Q2	Q3	Max
Daily Households Appliances								
Light Bulbs	160	12.956	6.186	1	8	12	18	24
Water Heater	87	4.276	5.466	0.5	1	2	4	24
Refrigerator	160	22.331	4.616	3	24	24	24	24
Deep Freezer	127	21.457	6.227	1	24	24	24	24
Water Pump	138	5.486	4.166	0.5	2	5	8	18
Fan	160	14.169	6.879	1	8	12	20	24
Air condition	70	7.643	5.413	1	3	7	10.3	24
TV	149	8.651	6.111	1	4	6	12	24
Radio	46	6.17	6.86	1	1	3	7.25	24
Computer	129	6.632	5.533	0.5	2.3	5	9	24
Weekly Households Appliances								
Washing Machine	151	1.5563	0.8766	1	1	1	2	5
Steam iron	142	1.3592	0.8940	1	1	1	1	8

Appliance (Load i)	Sample Size*	Average	Standard Deviation	Min	Q1	Q2	Q3	Max
Cleaner	75	1.4	0.93	1	1	1	1	5
Cloth Dryer	54	1.3333	0.6729	1	1	1	1.25	4
electric mixer	153	1.5425	0.7779	1	1	1	2	5
Electric Kettle	65	2.723	2.736	1	1	2	3	15
Stove	42	1.429	0.966	1	1	1	1.25	5
Microwave	42	1.881	1.365	1	1	1	2.25	5
Coffee Maker	21	1.429	0.978	1	1	1	1	4
Dish Washer	19	1.368	0.684	1	1	1	2	3

* Number of respondents with positive number of usages

Table A.5: The preferred time periods for running the Egyptian households' appliances.

Appliance (Load *i*)	Morning (%)	Noon (%)	Evening (%)	Night (%)
Light Bulbs	14.375	33.125	85	36.875
Water Heater	23.75	18.125	23.125	9.375
Refrigerator	81.875	83.125	83.125	67.5
Deep Freezer	59.375	58.75	59.375	49.375
Water Pump	53.75	60	46.875	24.375
Fan	54.375	82.5	69.375	46.25
Air Conditioner	13.75	25	18.75	15
TV	32.5	58.75	67.5	21.25
Radio	21.25	13.125	10	6.875
Computer	30	40.625	53.125	21.25
Washing Machine	44.375	36.25	30	14.375
Steam Iron	42.5	35	24.375	3.125
Cleaner	25.625	27.5	12.5	3.125
Cloth Dryer	20	16.25	8.125	3.75
Electric Mixer	30	71.875	30	1.875

Appliance (Load *i*)	Morning (%)	Noon (%)	Evening (%)	Night (%)
Electric Kettle	23.75	25.625	19.375	4.375
Stove	14.375	18.125	9.375	1.875
Microwave	11.875	13.75	11.875	2.5
Coffee Maker	8.75	3.125	5	1.25
Dish Washer	6.25	6.875	6.25	0

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- The appliances' scheduling problem facing the Egyptian households is addressed
- A new mixed integer quadratic programming (MIQP) model is presented
- The MIQP model considers load scheduling under the IBR tariff applied in Egypt
- A survey is conducted to identify the characteristics of appliances' usage in Egypt
- Significant reductions in energy consumption and costs can be achieved

Optimal Household Appliances Scheduling for Smart Energy Management Considering Inclining Block Rate Tariff and Net-Metering System

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