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A sustainable user-centered application for residential energy consumption saving

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Abstract. Being a significant contributor to energy consumption, residential buildings are now in crucial need to reduce and schedule their energy usage. It was found that the previous research on energy management have focused on the technological solutions without considering the users' needs and requirements. To address this gap, user's involvement is considered as cornerstone in developing a solution. For this purpose, a survey was designed and answered by 410 participants. Statistical analysis was used to identify the significant factors affecting the users' willingness to use a mobile application to manage their energy consumption. Fuzzy AHP was used to analyze users' preferences and behaviors, then K-means clustering was used to rank the various home appliances' priorities according to the users' preferences. Finally, a mobile application framework was proposed to enable a user-friendly tool to schedule home appliances operations. It was found that 70% of the users are willing to use such application as it can save money through managing their energy consumption while considering their preferences at the same time while having a positive environmental impact. Such approaches can change the utility-customer relationship from supplier-buyer relation to an efficient and sustainable partnership with an expected energy saving up to 15%.

Highlights:

- A socio-technical approach is adopted to deal with residential energy management
- A framework was developed for a mobile application based on a survey of 410 users
- Fuzzy analytic hierarchy process and K-means clustering were used for analysis
- The proposed solution enables customers to control their electricity consumption
- Up to 70% expressed their willingness to use such application

Keywords:

Information and communication technology; Residential energy consumption; Smart grids; Dynamic pricing; Mobile application; Sustainable solutions

Nomenclature

ICT	information and communication technology
HVAC	heating, ventilation and air conditioning
IoT	Internet of Things
FAHP	fuzzy analytical hierarchy process
MCDM	multi-criteria decision making
DNI	Direct numerical input scaling
TFN	transformed fuzzy number
GF-AHP	generic fuzzy analytical hierarchy process model
CCI	centric consistency index
GCI	Geometric consistency index
CH criterion	Calinski-Harabasz criterion
B2C	Business-to-Customer
SDGs	Sustainable Development Goals

1. Introduction

Energy management includes several activities that were traditionally performed relatively straightforward based on marginal profit and cost considerations. Many power utilities have started to use advanced tools, such as dynamic pricing, to motivate the customers to change their consumption patterns. Residential buildings are significant contributors to energy consumption. Household appliances consume around 30% of the electricity usage [1]; these appliances include refrigerators, washing machines, dishwashers, microwaves, dryers, electrical ovens, and water heaters. According to [2], architecture should be established to enable distributed and autonomous control, where the energy is considered as a product defined only by its price, whereas citizens are seen as agents and value creators in the energy sector. The main challenge for power grids here is the high variability in demand and peak loading that leads to transmission congestion, higher emissions, and the worst nightmare 'power outage'. Meanwhile, the demand on energy is increasing by an average of 1.4% per year until 2035 [3]; with this increase, complex management challenges were raised in the design, implementation, control, and maintenance of these systems. All these aspects are the concern of industrial engineering and systems management; from industrial engineering point of view, an electrical power system is a traditional system that has several resources that should be optimized to reach the desired outputs. Hence, the decisions made in such systems are not just related to the technical aspects of power generation and transmission, but also related to the managerial and economic aspects. Over the past two decades, several approaches were used to address energy management and scheduling issues; some works were mathematically driven [4], while other works were technologically-driven [5].

With the massive technological leap due to the advances in communications and the increasing number of the 'digital users', the scope of this work is the integration of information and communication technology (ICT) into the electrical power networks to enable efficient resource utilization and agile energy consumption. Using computers for energy management has started at the 1980s [6], nevertheless, modern ICT methods offer much broader opportunities in the electric networks, especially smart grids. ICT enables connecting all parts of the grid such as by facilitating network communications between machines and humans. ICT applications in smart grids may include sensors for remote measuring, grid systems modeling and simulation, chips and controllers, smart switches, load analysis software, automated load maintenance, and automated dispatch [7, 8]. Accordingly, ICT can play a key role in adding smartness and efficiency to power systems besides providing more viability to energy management at both macro and micro levels [9]. ICT-based technologies enable the optimization of resource usage which influences the 'supply-demand' in energy management. The current successful ICT-based practices include control and monitoring of heating, ventilation and air conditioning (HVAC) systems, ICT-based lighting and sensing control, electrical and automated drivers in industrial equipment, smart metering and smart grids in power stations, energy conversion and utilization of energy resources [10, 11]. However, the current energy planning still suffers from the inefficient data support and the load overestimation [12]. To support such decisions, complex data models should be developed and used efficiently. In that sense, smart solutions are needed to connect the transmission, storage, and distribution infrastructure from real-time forecasting of intermittent energy outputs to energy usage points [13]. However, Price-driven demand response is a recent concept in the energy sector, where the price is used as a control signal that affects consumers' consumption [14].

The authors of this work believe that ICT applications for energy management should be not only innovative, but also sustainable. Accordingly, the economic, environmental, and social aspects should be accounted for [15, 16]. To reach this goal, two-way communications that utilize wireless and wired communication protocols are considered [17]. Environmental assessment should be considered dynamically with high response and accuracy to achieve more energy efficiency and conservation [18]. Successful implementations of smart energy systems require a strong customer-centric focus, with a market model that underpins customer participation and engagement [5]. Therefore, the major contribution of this paper is to propose an ICT-based application to manage the residential energy consumption based on users' preferences and desires, and to improve user's experience. The proposed approach will result in a transition in the relationship between the power utility and the customer from supplier-buyer relation to an efficient and sustainable partnership.

The paper is organized as follows: Section 2 gives a literature review on the previous works using ICT in energy management and their assessment in terms of sustainability; following that, the research gap is explored, and the research contribution is highlighted in Section 3. The endeavor of Section 4 is to understand the user cognition, desires, and interactions on energy management, and suggesting research questions to be explored along with presenting the research framework. Section 5 presents an empirical study based on a survey for different users, and Section 6 gives the results and insights of the study. The objective of Section 6 is to propose a mobile application framework that makes use of the concepts of dynamic pricing of electricity. Finally, conclusions, novelty, limitations, and future research directions are presented in Section 7.

2. Literature review

To have an overview of the role of ICT applications in energy utilities, a review on recent works was performed. In [10], two potential applications of ICT in the renewable energy sector have been surveyed; energy production and production supporting, with the aim of enhancing the safety and efficiency while focusing on rural areas. According to [19], ICT, as a key element of smart grids, consists of two main layers: (i) computing platforms and operation systems layer; and (ii) business applications and services layer. In general, the main requirements of energy management affected by the advances in ICT are capacity, regulation, and power quality [20, 21]. In [22], it was suggested that the key concepts of energy Internet are consumer, micro grid, virtual power plant, smart grid, and smart energy. The business perspective of that work has five aspects; strategic, data, behavioral, regulatory, and security issues.

With the advances in communication and data storage capacities, other works that used newer techniques were reviewed. For example, data mining technology was addressed in [23] and [24] to dig the load profiles of the residential electricity consumption. Unsupervised machine learning was used in [25] to assign customers to predefined set of clusters. Other recent technologies were proposed by researchers in the context of energy management, such as applying the Internet of Things (IoT) in smart grids [26, 27, 28], wireless sensor networks [29], and using Arduino microcontrollers for residential energy management [30]. In [31], the role of smart sensor networks in smart grids applications was explored for demand management and power monitoring. Some recent works have used several mathematical methods for the energy pricing; in [32], a genetic algorithm was proposed to find the optimal supply with a real-time pricing strategy for a smart grid with multiple utility companies and users. In [33], a reasoning multi-agent approach has been used to identify human activities in smart homes.

To provide a sustainable solution, the economic, environmental, and social dimensions should be considered. Table 1 compares recent works on energy management from this point of view, to assess their covering of the three sustainability dimensions.

Table 1 Comparison between the works in literature according to the sustainability dimensions addressed

Ref no.	Authors	Sustainability dimensions		
		Economic	Environmental	Social
[10]	Stallo, Sanctis, Ruggieri, Bisio, & Marchese (2010)	✓	✓	
[19]	Al-Omar, Al-Ali, Ahmed, & Landolsi (2012)		✓	
[21]	Hejazi & Rad (2018)	✓		
[11]	Masood, Baih, & Raza (2013)	✓		
[20]	Foles et al. (2020)	✓		✓
[22]	Zhou, Yang, & Shao (2016)	✓		✓
[23]	Kuo, Lin, & Lee (2018)	✓		✓
[24]	Fana, Xiao, Li, & Wan (2018)		✓	✓
[29]	Huang, Chang, Chen, & Kuo (2011)	✓		✓
[30]	Abubakar, Khalid, Mustafa, Mustapha, & Shareef (2018)	✓		
[31]	Jaradat, Jarrah, Bousselham, Jararweh, & Al-Ayyoub (2015)	✓	✓	✓
[34]	Vasilica Oprea, Bâra, Ifrim (2018)	✓		
[36]	Lang & Okwelum (2015)	✓	✓	✓
[18]	Santos, Matias, Abreu, & Reis (2018)	✓	✓	
[38]	Vasilica Oprea, Bâra, Ifrim, & Coroianu (2019)	✓		✓
[39]	Tua, Hea, Shuaia, & Jiang (2017)	✓	✓	
[40]	Gouveia, Seixas, Shiming, Bilo, & Valentim (2015)	✓		✓
[33]	Jarraya, Bouzeghoub, Borgi, & Arour (2020)	✓		✓
[35]	Della Croce, Garraffa, Salassa, Borean, Bella, & Grasso (2017)	✓		
[32]	Tao, Gao, Zhu, & Liu (2019)	✓		✓
[5]	Zorilla & Ibrain, (2019)	✓	✓	✓
[41]	Sadeeq & Zeebaree (2021)	✓	✓	
[42]	Hasankhani & Hakimi (2021)	✓	✓	
[43]	Mostafa et al. (2022)	✓	✓	

The mentioned works were thoroughly studied to get insights on their outcomes as well as putting hands on the current research gaps and further research directions as discussed in Section 3.

3. Research gap and contributions

3.1 Research gap

From the literature review, it was found that there are two main categories for the residential energy management programs: incentive-based programs and price-based programs. Incentive-based programs can be used by the power utility to access the home appliances and flatten the demand during peak loads, and as a reward, discount rates are provided for the consumers [34, 35]. The main drawback of this program is its violation of the consumer's privacy by controlling the operation of his/her home appliances [36]. Price-based programs have the same objective but with a different process; the customers voluntarily change their electricity consumption according to the prices announced by the power utility that may vary through the day [37]. Recent applications such as smart meters and smart switches can be utilized for both programs by providing two-way communication between the power utility and the customers to minimize peak consumption [38]. Yet, both methods still need more research to enable efficient implementation. The first method collides with the privacy of the consumers while the second method lacks the social aspect that takes into consideration the needs and behavior of the customers.

From Table 1, it can be seen that the economic dimension related to cost and profit was the major concern of most of the works, fewer works sought to address the other two dimensions. Only three works addressed the three sustainability dimensions; however, both works gave general review and discussion. The work in [31], while insightful, does not implement the suggested ideas. In [36], a specific model was proposed for controlling the consumption of air conditioners in curtailment days. In [5], a conceptual smart real-time system was proposed to forecast the energy prices and provide the users with information on their consumption. However, the three works have not considered user needs or preferences in an interactive way. In [39], the economic and environmental urges were addressed to shift towards a sensor-embedded smart grid that can support efficient energy scheduling for household users. From another perspective, in [40], the socio-economic aspect was addressed by collecting surveys to understand the relation between energy consumption and the standard of living. This paper was inspired by these works to cover the current research gap by involving the users into developing the solution that is aspired to be sustainable by addressing the three dimensions.

3.2 Research contribution

Recently, most of the literature research works on using ICT devices for energy have focused on smart meters, smart appliances, and IoT. Although these technologies are very important, a key part of the ICT revolution is missing; that is

‘Smart phones’. The number of smartphone users was 2.5 billion in 2016 and has increased to about 3.6 billion users by 2020 with millions of sold and downloaded applications, the number is expected to increase to be 4.3 billion by 2023 [44]. This technology can be used in the context of energy management to support personalized services. Some utility companies use mobile solutions to enable customers to access some information such as bill statements/payments. However, the use of mobile apps for more advanced interaction is still very limited in terms of consumption control and pricing. Fig.1 gives a generic framework of using mobile application in the context of smart grids and smart homes energy management. The framework starts from the smart grid which is provided with smart meters and a demand response management system to measure and analyze the power consumption of the users. The home appliances are controlled through smart switches which are controlled by a mobile application through gateway. The data of the consumption and usage patterns are collected by data aggregation unit and processed through a meter data management system to be fed into the demand response management system.

The main problem is that current ICT-based applications, while making use of the technological advances, have fairly considered how those applications could actually support the human requirements. From a design perspective, getting the users engaged in the design lead to a more sustainable performance than providing just high non-interactive technology. Besides the review on using ICT in energy management and smart grids, the contribution of this paper is to provide an adequate framework of how people could reinforce effective energy management attitude through a user-friendly ICT application that is both socially and technically driven with involving the users’ needs and preferences. That will lead to economic and environmental benefits through electricity consumption saving.

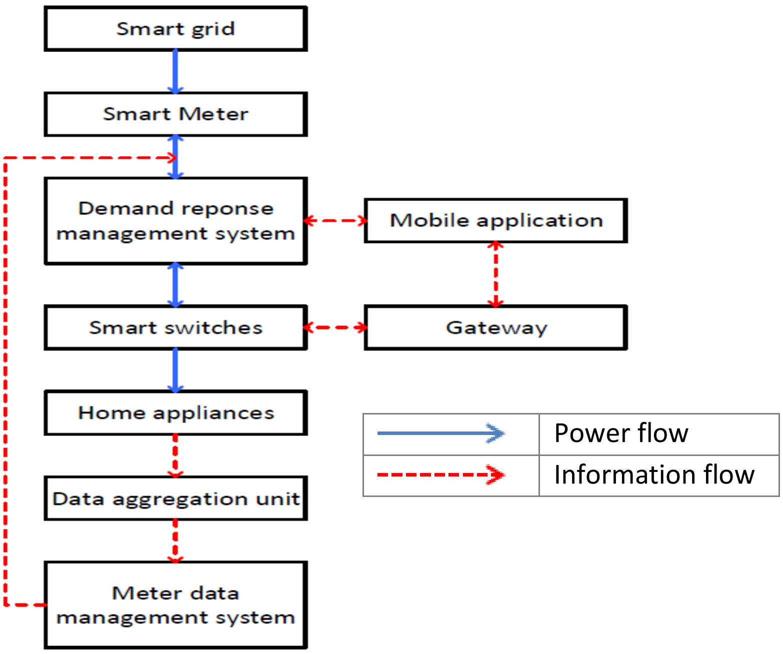

Fig. 1. A generic framework for the proposed system

4. Methodology and research framework

According to [45], significant efforts are requested by governments and research institutes to support users' behavior at the household level with the objective of energy saving. In this work, views of Giddens' social structuration theory [46] and constructionism [47] are taken to study how individual users could adopt constructed ICT-based applications. Constructionism is based on the evoking idea of learning-by-making [48]; the term 'construct' here means 'build or design' in a broader manner as it starts from the conceptual level and ends by the implementation level. Through assessment and evaluation, the solution may need to be 'reconstructed' either for the system itself or the design features [49]. The challenge is to grasp the social actors' latent behavior patterns and aspects of "*why*" and "*how*" they view their energy consumption. Looking at the previously established applications, it was observed that the adoption of user-centered approaches is rare, and it should be reconfigured in grasping more desirable requirements in energy management. The authors believe that the proposed approach will open the path for this user-centered approach to be incorporated in the features and functions of ICT-based energy applications in a society. With this theoretical view, a socio-technical approach is adopted to deal with energy management, focusing on user requirements to synthesize a direction for developing *user-friendly* ICT-based applications. Fig. 2 presents the proposed model of user-friendly ICT-based application for residential energy management.

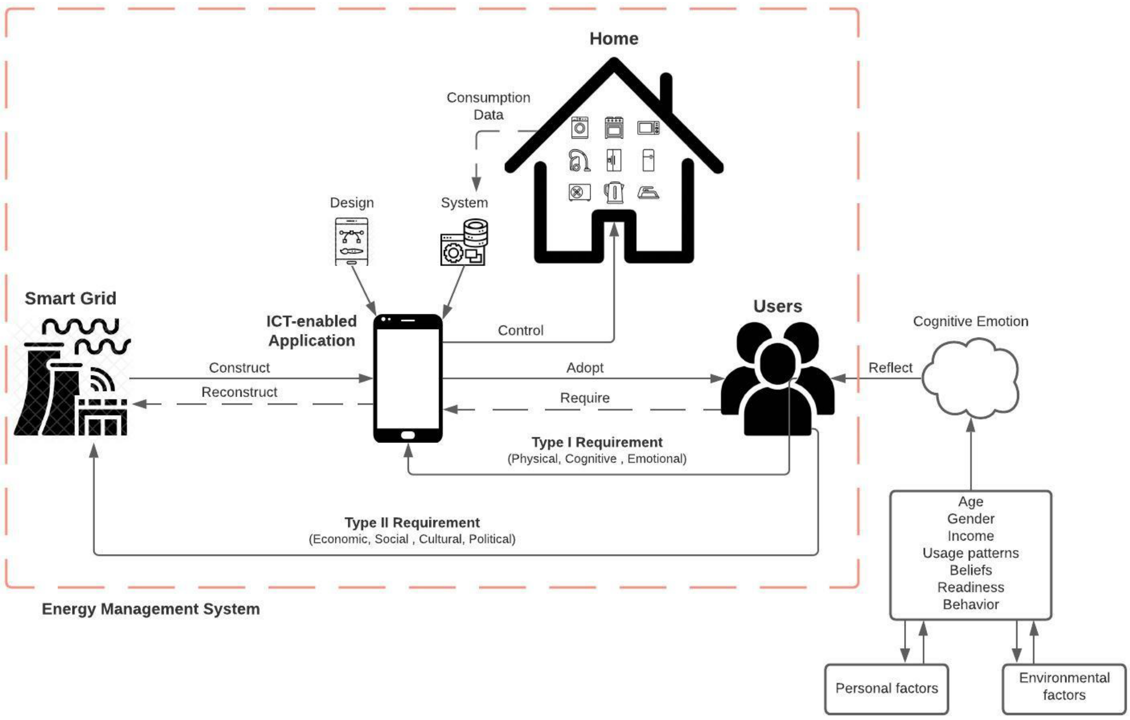

Fig. 2. A proposed model of user-friendly ICT-based applications for residential energy management

In this way, the individual users could generate multiple requirements, concerning economic, social, environmental, cultural, and political aspects for reconstructing the given ICT-based applications in a society. Based on this view, the proposed socio-technical model can be applied in the context of residential energy management to explore two research questions:

1) ***How can an established ICT application support individuals' energy management in residential areas?***
2) ***How can individual users generate multiple types of requirements to identify user-friendly experience and desirable applications?***

An empirical study, based on a survey, was used to collect information that can provide insights on users' preferences and use them to propose a novel mobile application. Fig. 3 shows the research framework of the paper. The numbers shown on the framework refer to four steps of the user-centered design process as defined by the International Organization for Standardization [50]. The process has four steps: (1) Understand and specify the context of use, (2) Specify the user requirements, (3) Produce design solutions to meet these requirements, and (4) Evaluate the designs against requirements. In addition, the framework complies with the design science research cycles proposed in [51], that consists of three cycles; the relevance cycle in which the users are identified, and their needs and requirements are analyzed. The next cycle is the design cycle, in which the ideation is performed to design a model based on the users' needs. The third cycle is the rigor cycle, in which the proposed model is communicated to add to the body of research.

5. Empirical study

5.1 Study framework

In general, a flat utility consumption curve is desired to optimize energy management. Considering both financial and technical challenges of storing the energy generated by renewable sources, flattening the electricity consumption has become a vital goal. Several studies adopted classifying the day to peak and off-peak hours [34], besides grouping appliances into categories according to their consumption [52]. The purpose of this work is to propose an application that can be used by customers to identify the inlet-controlled devices (heater, cooker, etc.) on the web server. For each device, the user defines the possibility to be switched off at the premium pricing time. For a better user experience, the user is asked to define three casual levels of control for each device: red, yellow, and green. The red devices are kept on all time, the green devices are switched off with any increase at the nominal electricity prices, and the yellow devices are partially switched off/on based on the premium charges.

To create a user profile that can be used for controlling the devices, such framework was proposed:

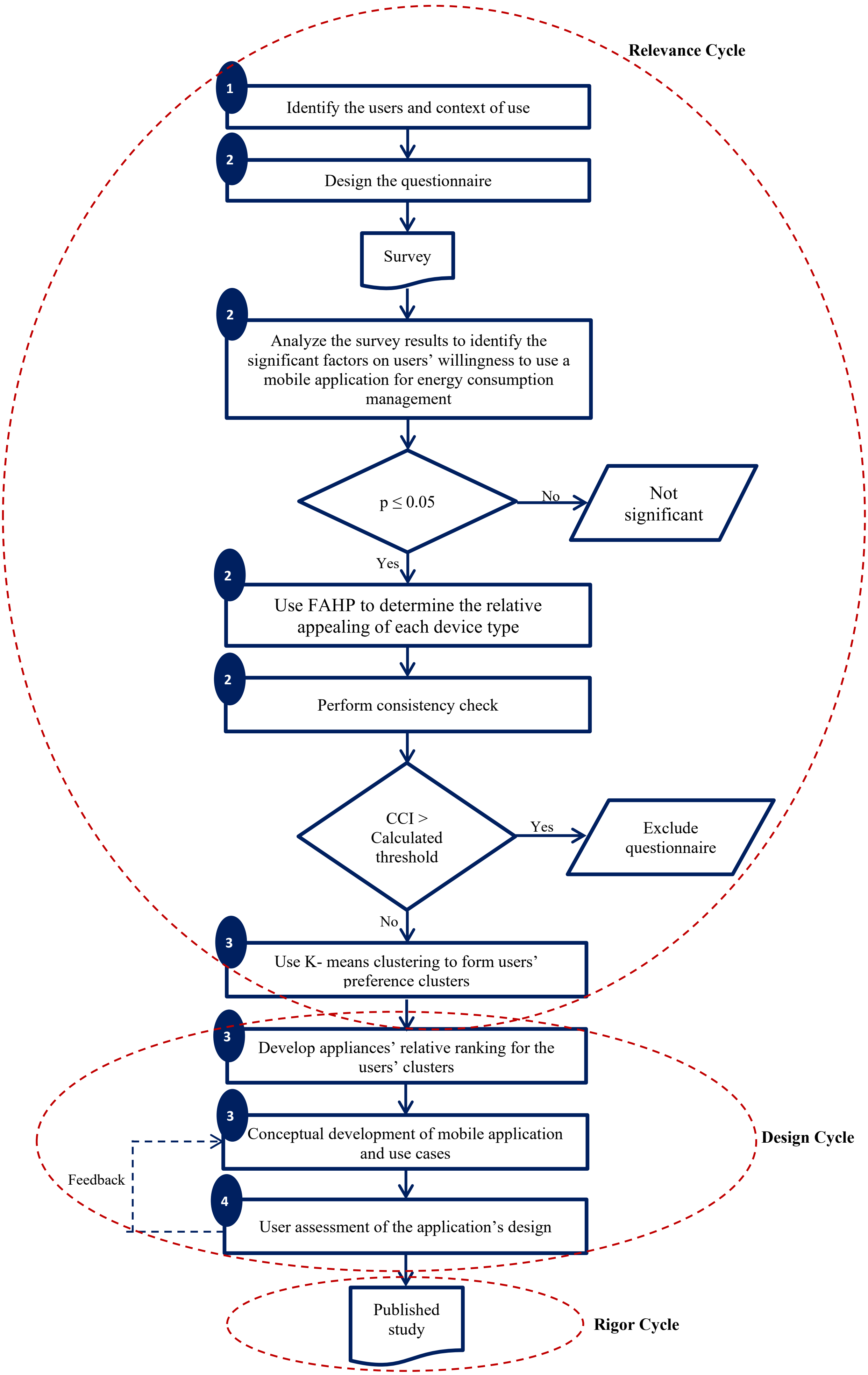

Fig. 3. Research framework

- A sample representing the customers is surveyed by using a designed questionnaire, then fuzzy analytical hierarchy process (FAHP) approach is used for formally determining the relative appealing of each device type to be switched off during the premium charges time.
- The obtained FAHP weights of each customer are clustered by using a K-means algorithm to obtain a reasonable number of customers' profiles.
- Customer's selection of green, yellow, and red devices is to create customer's profile is based on the similarity weighted average of the clustered profiles.

5.2 Results and discussion

A survey was conducted to acquire the user relative ranking of seven categories of home devices. The questionnaire was answered by 410 respondents from Egypt. The respondents include 260 males (63.4%) and 150 females (36.6%). The age of the survey subjects and the percentage of electricity bill as a percentage of their total income are categorized in Fig. 4 (a) and (b), respectively.

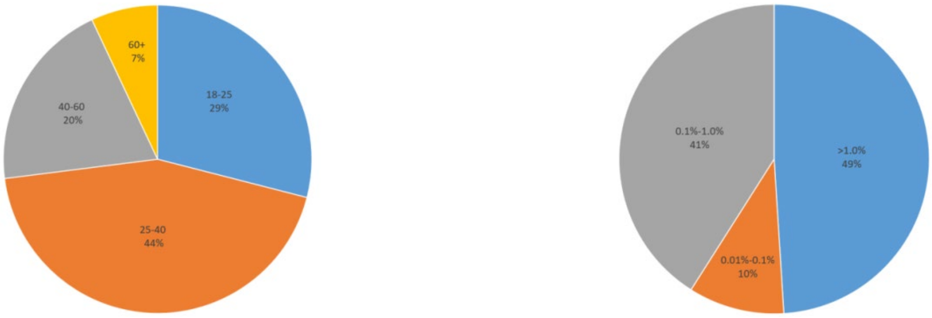

Fig. 4.
(a) the age of the survey subjects (b) the percentage of electricity bill compared to the survey subject's total income

5.2.1 Application attractiveness survey

Each survey respondent was asked to rank his/her willingness to use a mobile application to reduce his/her electricity bill on Likert scale of 5, where a 5 means that he/she will use it for sure. The average answer was 4.2, revealing that the application idea is quite attractive. Table 2 shows the mobile application attractiveness for the 410 respondents grouped by different criteria.

The data was studied to get insights on the significant factors affecting the users' willingness to use a mobile application to control their consumption. Four factors were considered and the null hypothesis is that there is no difference between the different groups for each factor. Table 3 gives P-value and t-test for each factor to check its significance. The asterisk denotes a significant difference for this factor.

Table 2 The summary of the mobile application attractiveness grouped by different criteria

Criteria	Groups	Number of respondents	Mean	Variance
Utility bill % of total income	>1.0%	200	4.0000	2.1053
	<1.0%	210	4.4286	0.6571
Respondents' age	18-40	300	4.5000	0.7414
	40+	110	3.4545	2.4727
Other mobile application usage	Seldom usage or only for social networking	190	3.7368	1.9825
	Navigation, rides or whenever possible	220	4.6364	0.5281
Belief about the impact of electricity saving on the environment	1	10	1.0000	1.0000
	2	30	2.0000	1.0000
	3	40	3.2500	1.5833
	4	90	4.4444	0.5278
	5	240	4.7083	0.3895
Belief about how expensive are the electricity prices	1	10	1.0000	1.0000
	2	30	2.0000	1.0000
	3	40	3.2500	1.5833
	4	90	4.4444	0.5278
	5	240	4.7083	0.3895

Table 3 Statistical measures for different factors

Factor	p-value	t-test
Utility bill % of total income	0.37	1.17
Respondent's gender	0.15	1.49
Respondent's age	<0.05*	2.72
Other mobile application usage	<0.05*	2.62

From Table 3, it was found that the respondents' utilities/income percentage has no significant difference on their willingness to use the application. The t-test for the application attractiveness for the two groups: the one who reported that their utility bills represent more than 1% of their income (49% of the respondents) and the group who reported that it represents less than 1% (51% of the respondents) shows that there is no significant difference (at 95% confidence level) between the two groups (t = 1.17). In addition, there is no significant difference (at 95% confidence level) of the application attractiveness based on the respondents' gender (t = 1.49). The mean analysis shows that the elder respondents are less attracted to use the application compared to the younger ones (t = 2.72). The results have showed that the average answer of the younger respondents is 4.5, while it is only 3.5 for the elder group. Moreover, the respondents, who reported that they seldom use mobile applications or only using it for social networking, answered with an average of 3.7 about their intention to use the proposed mobile application; while more advanced technology attracted respondents answered with an average of 4.6. The mean t-test confirms that such difference is significant at 95% confidence level (t = 2.62). Correlation coefficient was calculated between the respondents' belief about the impact of electricity saving on the environment and their application attractiveness; it was found to be 0.77 which denotes a positive correlation. Similarly, there is a correlation between the respondents' belief about how expensive are the electricity prices and their willingness to use the mobile application to control their consumption (R= 0.95 for non-intersection model), which denotes a strong positive correlation.

5.2.2 Using FAHP for survey analysis

FAHP is a multi-criteria decision making (MCDM) method that can be utilized for many applications such as resource management and energy planning [53]. FAHP is a simple and adaptable method that is based on hierarchical structure that enables each criterion to be focused and transparent. Several works have utilized AHP for energy applications [54]. According to [55], AHP and FAHP methods have been used more than other tools and approaches in energy applications. Their main advantage is the ability to handle ‘intangibles’ that can be related to the ‘latent patterns addressed in Section 3. Fuzzy AHP is used as an extension of conventional AHP to handle uncertainty and to capture the subjective preferences [56].

To get insights into the users’ preferences and lifestyles, each respondent was asked to rank the relative easiness of two appliances’ categories to be rescheduled when the electricity is priced higher than its nominal level, as shown in Table 4. To differentiate the left-side answer from the right-side one, the left hand side number is represented by its reciprocal as shown in Table 4. Fuzzy logic uses the membership function to describe data in a more similar way to common language. Table 5 gives the transformed fuzzy numbers according to the fuzzy number of linguistic variable set [57]. However, the linguistic answer of (A^1: Almost the same) is handled as a crisp value due to the easiness of judging that both categories are almost the same.

Table 4 Example of the AHP questionnaire

Climate control (air-conditions and heater)					Washing machines			
For sure is easier 9	Greatly easier 7	Probably easier 5	Slightly easier 3	Almost the same 1	Slightly easier 3	Probably easier 5	Greatly easier 7	For sure is easier 9
AHP reciprocal representation								
For sure is easier 1/9	Greatly easier 1/7	Probably easier 1/5	Slightly easier 1/3	Almost the same 1	Slightly easier 3	Probably easier 5	Greatly easier 7	For sure is easier 9

Table 5 Direct numerical input scaling (DNI) into transformed fuzzy number (TFN)

Fuzzy number	Linguistic answer	Transformed Fuzzy Number TFN (a_L, a_M, a_U)
A^{-9}	For sure is easier 1/9	(1/9, 1/9, 1/7)
A^{-7}	Greatly easier 1/7	(1/9, 1/7, 1/5)
A^{-5}	Probably easier 1/5	(1/7, 1/5, 1/3)
A^{-3}	Slightly easier 1/3	(1/5, 1/3, 1)
A^{1}	Almost the same 1	(1, 1, 1)
A^{+3}	Slightly easier 3	(1, 3, 5)
A^{+5}	Probably easier 5	(3, 5, 7)
A^{+7}	Greatly easier 7	(5, 7, 9)
A^{+9}	For sure is easier 9	(7, 9, 9)

The FAHP model uses the entropy concepts to calculate fuzzy aggregate weights that have been widely applied in many domains and applications [58]. Despite including the consistency check as part of the original Saaty's AHP model [59, 60], many of the FAHP researchers ignored conducting such checks due to the complexity of the FAHP calculations and the expected fuzziness of the results. This problem was addressed in [61] through introducing a generic FAHP model (GF-AHP) with a control procedure for decision matrix consistency through centric consistency index (CCI) which is an extended version of the geometric consistency index (GCI) [62]. The advantage of CCI is that it can control the individual consistency of pairwise matrix. From [61], the CCI is claculated as per equation (1) and the questionnaire is acccepted if its value is less than 0.37 if the number of categories is more than 4. To be able to calcaute the CCI, the TFNs are obtained from the DNI as per Table 5, then the fuzzy eigenvalues are calcaluted and used to calaculate the fuzzy weights (W_{Lj}, W_{Mj}, W_{Uj}) based on the model propsed in [63].

$$CCI(A) = \frac{2}{(n-1)(n-2)} \sum_{i<j} \left[\log\left(\frac{a_{Lij}+a_{Mij}+a_{Uij}}{3}\right) - \log\left(\frac{W_{Li}+W_{Mi}+W_{Ui}}{3}\right) + \log\left(\frac{W_{Lj}+W_{Mj}+W_{Uj}}{3}\right)\right]^2 \qquad (1)$$

After checking the consistency of the obtained 410 questionnaires, 80 questionnaires were excluded from further analysis because their calculated CCIs were more than the 0.37 threshold [64]. The fuzzy weights of the remaining consistent 330 questionnaires were de-fuzzified by using equation (2) to obtain the crisp weights of each category for each respondent (Table A1 in Appendix).

$$W_i = [(W_{Ui} - W_{Li}) + (W_{Mi} - W_{Li})]/3 + W_{Li} \qquad (2)$$

To generate a limited number of user profiles that can be used by the mobile application to automatically switch off the devices during the premium prices times, K-means clustering is used to cluster the respondents' preferences into a limited number of preference clusters. The parameters input for the K-means clustering algorithm are 330 respondents' preferences; 7 attributes; 2,310 instances; 1-30 clusters. In order to find a stable model, a random number of clusters were tested. The analyses yielded six clusters. They were characterized by a descriptive analysis of the most important variables and based on the preferences and energy awareness of the respondents. One thousand iterations were conducted by using Matlab™ for each different value of K by using the K-means function. Fig. 5 shows the flowchart of the used K-means clustering algorithm, and Fig. 6 shows the minimum, the average, and the maximum error, which is calculated as the summation of the Euclidian distance from the cluster centroid, for each number of clusters (K). Considering the naïve number of clusters of $K = \sqrt{n} \approx 6$ and using the elbow method, the suggested number of clusters is marked by the rectangle in Fig. 6; that is between 2 and 10. The Calinski-Harabasz (CH) criterion was calculated for K=2:10 and the cluster (k=4) is obtained at the maximum value [65]. The final ranking of the four user clusters is shown in Table 6. The red marked categories are the appliances that should be kept on for these clusters of customers, while the green marked categories can be easily switched off when the premium prices are charged by the utility company. The yellow categories are that one which should be adaptively controlled by the application based on the level of the premium price.

6. Mobile application prototype

The expectations of consumers are increasing, including reduced electricity bills, increased reliability and more comfort. ICT can be used in this regard to enable the consumers to check their bills and respond to real-time prices. Demand management through dynamic pricing is a strategic tool to achieve customer participation and satisfaction [32]. Hence, a successful mobile application that responds to dynamic pricing strategy requires three components:

- Timely and economic tool to communicate such dynamic prices to the customers.
- A persuasive message to convince the customers to decide to actively respond to the price fluctuations.
- A usable and convenient tool to execute the decisions.

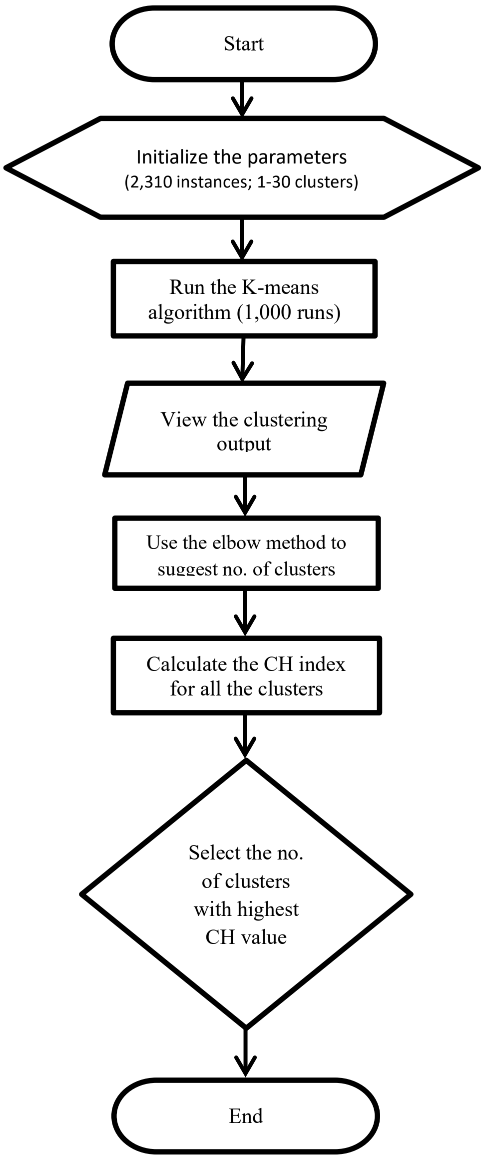

Fig. 5. Flowchart of the used K-means clustering algorithm

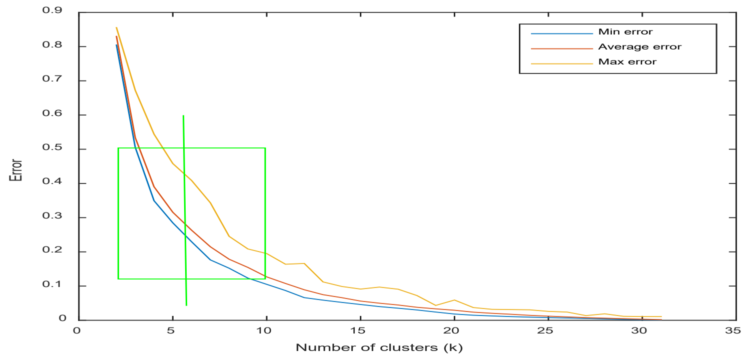

Fig. 6. The clustering error

Table 6 The relative ranking of different categories for the four clusters of customers

No.	Climate Control	Washing Machine	Water Heater	Refrigerators	Lighting	Cooker	IT
1	0.204	0.207	0.089	0.208	0.188	0.053	0.053
2	0.126	0.193	0.101	0.393	0.048	0.08	0.061
3	0.173	0.016	0.037	0.052	0.149	0.253	0.328
4	0.086	0.088	0.130	0.287	0.127	0.061	0.226

To address the first component, a mobile application is proposed to be sponsored by the utility companies. The use case diagram of the application is shown in Fig. 7 and the use cases are summarized in Table 7. The application allows the utility companies to effortlessly segment their users, as described in Case 3.1; and instantaneously notify their customers about the premium values and/or the timely limited offers, as described in Case 3.3.

To accomplish the second component, the application displays the possible hourly customer's energy saving by keeping the switch-off devices dimmed through the premium rate compared to the nominal rate, as described in case 3.4. Moreover, it displays the additional saving the customer may achieve by switching off another suggested set of devices selected from the user's yellow list based on the user profile.

To achieve the third component, the application is connected through a gateway to a set of Wi-Fi enabled On/Off switches with ammeters (smart switches). A prototype of the smart switches was developed in which the plugs are connected through ZigBee wireless communication and URLs to the servers at the utility. The switches measure the electricity consumption by measuring the current voltage and control the devices with an electromechanical relays in the slave socket [29]. The slave circuit developed in [66] is used in the proposed mobile application. The output voltage of the proposed circuit is used to measure and record the power consumption and to switch the loads on and off. The ZigBee transceiver is used to communicate with other transceivers that are connected to the servers.

Each of the smart switches is connected at the power inlet of one or more of the electricity consuming devices and transmitted to the company server the power consumed by this device and allows the application to switch the device on and off based on the communicated dynamic utility prices, as described in Case 3.2. When the utility company announces a premium price, the system checks the user profile to decide which device to switch off temporarily to reduce the power consumption at the premium rate. Using such applications is expected to increase customer satisfaction and provide more communication to the stakeholders [67].

Table 7 Summary of use cases of the proposed mobile application

Case ID	Case Name	Primary actor	Other actors	Precondition /Triger	Description
1.1	Generate users' clusters	The utility company	Sample of its clients (server actor)	N/A	**A-** Send the questionnaire to its sample of the clients **B-** Calculate the weights of each category for each respondent **C-** Use the K-mean to generate the users' clusters based on the FAHP calcauted weights
1.2	Set the electricity prices dynamically	The utility company	The application server (receiver actor)	Utility supply demand mismatch	**A-** Increase the utility prices when the supply is less than the demand **B-** Reduce back the prices when the supply covers the noticed demand
2.1	Join the community	The utility customer	The application server (receiver actor)	Installing the mobile app and installing at least five Wi-Fi on/off switches	**A-** Define the type of each smart controlled device (heater, washing machine, etc…) **B-** Assign a control level to each device (red, yellow, green)
2.2	Add a new device	The utility customer	The application server (receiver actor)	Installing a Wi-Fi on/off switch to the device	**A-** Define the type the device (heater, washing machine, etc…) **B-** Assign a control level to it (red, yellow, green)
2.3	Override the system control	The utility customer	The application server (receiver actor) The Wi-Fi enables switch (receiver actor)	The user urgently needs to operate the device The user wants to save more than the suggest by the server	**A-** Manually switch on a device that switched off by the system **B-** Manually switch off a device that system did not switch off but suggest the saving obtained if by switching it off
3.1	Assign a user to the nearest cluster	The application server	The utility company (receiver actor)	N/A	Based on the clusters generated in step 1.1.
3.2	Switch on-off devices based on utility prices	The application server	The Wi-Fi enables switch (receiver actor)	Utility supply demand mismatch	**A-** The server sends on/off signal to the registered switches **B-** The switches perform the
3.3	Inform the user about the current utility prices	The application server	The mobile app (receiver actor The utility customer, (receiver actor)	Utility supply demand mismatch	**A-** The server pushes notification to the app of the price change **B-** The app display how is the current prices different from the previous one
3.4	Suggest saving/cost for user manual decisions	The application server	The mobile app (receiver actor The utility customer, (receiver actor)	Utility supply demand mismatch	**A-** The server pushes notification to the app of the suggestions **B-** The app display graphically the suggestions to the user **C-**The user decide however to follow or not the suggestions

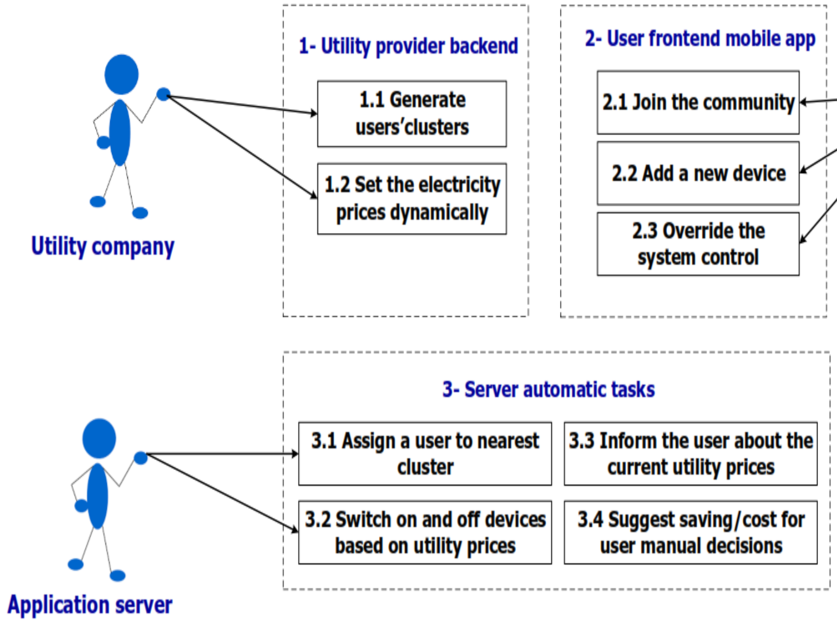

Fig. 7. Use case diagram of the proposed mobile application

A preliminary user study was conducted to assess the proposed solution and its suitability from the users' point of view. A questionnaire was designed and distributed to a focus diverse group in sense of age and jobs. One of the authors illustrated about the application and its functions, then the participants were asked to rate the usefulness, functionality, ease of use, satisfaction, and willingness to use. Fig. 8 represents the result of the users rating for the proposed application based on a five-point Likert scale, where scale 1 represents strongly disagree and scale 5 represents strongly agree.

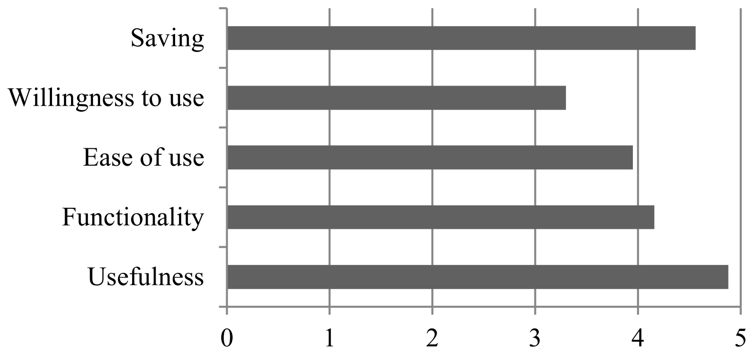

Fig. 8. Mean of the users' feedback on the proposed application on Likert scale from 1 to 5

From Fig. 8 the users think that the proposed solution can be useful, functional and easy to use. Most of them (~70%) are willing to use it as it can save money through managing their energy consumption. This research paves the way for further studies in the use of optimization algorithms for energy consumption management.

7. Conclusions, novelty, limitations, and future work

Most of the existing works on using ICT applications for residential energy consumption management focus primarily on the technological advances that can be utilized to achieve economic and environmental advantages. However, the social aspect is of paramount importance since the energy consumption is significantly affected by users' behavior, and hence has an impact on the relation between a utility company and its customers/users. Therefore, this study adopts a social construction theory by a view of socio-technical perspective rather an institutional one in arguing the importance of user's requirements (e.g. latent behavior patterns, emotions, and desires beyond manifest usage behaviors in energy consumption) for constructing newly defined ICT-enabled energy applications and reconstructing ones. As a result, this study will open a feasible direction of how users' requirements could be incorporated in designing applications associated with energy consumptions. To develop a sustainable solution, the three aspects; economic, social, and environmental should be taken into consideration. In this paper, we present a framework for a user-friendly mobile application based on a survey that is designed to assess users' needs, cognition, and interaction. A mathematical technique (Fuzzy analytic hierarchy process), a statistical method (p-value), and a data mining technique (K-means clustering) were used to analyze and derive ratio scales from paired comparisons. It was found that the most significant factors that have an impact on the application attractiveness from the users' point of view are the respondents' age, the respondents' usage of other mobile applications, the respondents' belief about the impact of electricity saving on the environment, and the respondents' belief about the electricity prices.

This paper aims at providing two contributions; first, it presents a study on an important energy-related topic by targeting the use of information and communication technology for energy management in smart grids and residential demand. Second, it proposes a user friendly ICT-based solution for Business-to-Customer (B2C) situations for utility companies that enables customers to control their electricity consumption through a mobile application. Using such mobile application is a win-win situation for the companies and the users. It helps the users to control their electricity bills, reduces the demand during peak times, supports energy saving that has positive environmental impact, and enables a better social life and comfort for the users. Providing the consumers with detailed and immediate information about their energy consumption can save from 5 to 15% [68]. ICT-based approaches and the digital revolution provide an efficient opportunity to enable this paradigm shift by helping the consumers to control their energy consumption and save money. In this context, the authors provide several recommendations for the utility companies: (i) Data should be collected to analyze the relationship between the users' preferences and the power consumption; (ii) The utilization of technology should be based on a socio-technical perspective in order to develop a sustainable relationship with the users; (iii) Having insights about the flexibility in service expectations can improve the estimation of the demand-side energy management; and (iv) User-centered design should be adopted to grasp more desirable requirements in the established ICT applications for energy management.

The novelty of the paper is the integration between the social aspects, represented through the users' survey and the technical aspects of designing a mobile application framework that enables mutual energy management between the utility company and the user with considering users' needs and preferences. That will lead to economic and environmental benefits through electricity consumption saving. Hence, it can be deducted that the proposed framework would provide a sustainable solution that addresses the three dimensions of sustainability; namely, economic, social, and environmental. Recent works in [69, 70] emphasized the increasing need for such solutions to collaborate in achieving sustainable development goals (SDGs).

From this socio-technical study, the authors believe that such research can provide a better understanding of the residential energy consumption and users' preferences and add more awareness towards energy consumption management. Having better quality and more comprehensive information about users will help the utility companies to improve their load supply management especially for intermittent renewable energy. The limitations of this work are the lack of actual feedback from the potential users on the proposed mobile application since the mobile app development requires a distinct process which was out of the scope of this paper. In addition, building such mobile app requires building a real model with the power utility network which is not feasible currently. Future work can be performed towards revenue management and dynamic pricing to provide the companies with tools that facilitates calculating and offering of different prices at different demand levels. Also, the proposed framework can be compared with similar applications for residential energy management to assess its points of strength and weakness.

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Appendix

Table A1. The crisp relative ranking of different categories for the consistent questionnaires

No.	CCI	Climate Control	Wash Machine	Water Heater	Refrigerators	Lighting	Cooker	IT
1	0.144	0.173	0.016	0.037	0.052	0.149	0.253	0.328
3	0.173	0.275	0.233	0.032	0.155	0.221	0.071	0.016
4	0.346	0.113	0.302	0.030	0.223	0.171	0.078	0.085
5	0.171	0.090	0.335	0.021	0.215	0.196	0.021	0.123
7	0.239	0.103	0.149	0.091	0.289	0.274	0.040	0.055
8	0.361	0.040	0.122	0.153	0.177	0.230	0.058	0.220
9	0.182	0.155	0.213	0.066	0.277	0.240	0.033	0.019
10	0.336	0.067	0.033	0.061	0.302	0.200	0.076	0.270
11	0.128	0.228	0.234	0.084	0.181	0.225	0.029	0.027
12	0.257	0.232	0.250	0.152	0.140	0.180	0.033	0.018
13	0.163	0.260	0.234	0.068	0.175	0.208	0.040	0.029
14	0.257	0.139	0.224	0.123	0.218	0.228	0.040	0.028
15	0.152	0.185	0.167	0.083	0.263	0.250	0.036	0.021
16	0.12	0.191	0.273	0.088	0.217	0.175	0.042	0.022
17	0.173	0.254	0.193	0.072	0.219	0.219	0.029	0.016
18	0.115	0.237	0.121	0.047	0.184	0.184	0.020	0.207
19	0.218	0.135	0.247	0.109	0.216	0.216	0.059	0.022
21	0.108	0.234	0.021	0.066	0.236	0.207	0.131	0.104
23	0.317	0.064	0.298	0.308	0.137	0.104	0.057	0.045
26	0.139	0.116	0.242	0.075	0.331	0.026	0.149	0.062
27	0.204	0.313	0.160	0.081	0.217	0.024	0.151	0.062
29	0.117	0.182	0.173	0.117	0.420	0.022	0.052	0.038
30	0.212	0.020	0.245	0.151	0.379	0.060	0.102	0.050
31	0.367	0.478	0.076	0.085	0.189	0.066	0.056	0.073
32	0.12	0.237	0.019	0.152	0.244	0.158	0.033	0.159
33	0.132	0.179	0.028	0.233	0.319	0.086	0.022	0.134
34	0.11	0.028	0.158	0.099	0.275	0.095	0.090	0.260
35	0.271	0.106	0.115	0.090	0.425	0.033	0.097	0.135
36	0.356	0.102	0.132	0.079	0.458	0.083	0.035	0.113
38	0.249	0.024	0.092	0.095	0.391	0.058	0.123	0.222
39	0.136	0.158	0.252	0.077	0.338	0.066	0.098	0.016
40	0.301	0.024	0.167	0.114	0.299	0.059	0.027	0.318
41	0.213	0.197	0.193	0.120	0.397	0.046	0.035	0.014