International Journal of Computing and Digital Systems
ISSN (2210-142X)
Int. J. Com. Dig. Sys. 5, No.4 (July-2016)

http://dx.doi.org/10.12785/ijcds/050405

Design and Implementation of a Residential Energy Monitoring System Prototype Tailored to Meet Local Needs

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Received 30 Nov. 2015, Revised 23 May 2016, Accepted 15 Jun. 2016, Published 1 July 2016

Abstract: The Kingdom of Saudi Arabia, like many other Gulf Council Countries, is lately experiencing a very rapid population and industrial growth, which results in an increasing demand for energy. To meet this growing demand, the GCC too is transitioning towards a smarter electricity grid with increased penetration of renewable sources. However, all agree that the success of such a shift in paradigm also depends on demand side management, most of energy demands coming for residential area. Providing residents with real-time feedback on their energy consumption is a promising way to promote energy saving behavior through an increased awareness. This paper outlines the design and development phases of a residential energy monitoring system that has been tailored to meet local needs, that is to say a non-intrusive system with a user friendly interface available both in English and Arabic endowed with an alert system providing real-time consumption information, as well as energy saving and awareness tips.

Keywords: home energy management system; energy monitoring system; wireless sensor network; KSA; GCC

1. Introduction

The Kingdom of Saudi Arabia (KSA) is fortunate to have the world's largest proven oil reserves, and the world's fourth largest proven gas reserves. It is also the world's 20th largest producer and consumer of electricity [1, 2]. As stated in [3], on a per capita rate, Saudi Arabia has very high electricity consumption, mainly due to the improvement in living standards. Also, KSA is experiencing both population and industrial growth, causing a huge demand for power and especially electricity. Combined with these two local factors, the very high emission rate of CO_2 in the region makes it a National priority to reduce energy consumption. All agree that society needs to use existing electrical power more efficiently [4]. One way of making that happen in residential area is to inform the consumer about their energy usage. In fact, several experiments on energy monitoring systems shows that the visualization of power consumption could reduce the entire energy consumption of residential areas by 10–30 % [5]. Currently, people only know their total monthly consumption, but a real-time load monitoring does not exist.

This study outlines the design, development, and implementation phases of a residential energy monitoring system, the iTrack system, that has been tailored to meet local needs, that is to say:

- an enhanced visualization system providing real-time consumption information (e.g. total house consumption, or room / appliance consumption) through a user-friendly interface available both in English and in Arabic;
- an educating interface, increasing energy awareness of users or simple visitors through a set of energy saving and awareness tips;
- an interactive solution with a warning mechanism where it is possible to set up thresholds on monitored parameters to help detect alarming situations and alert the user through an alarm message (e.g., sms, e-mail);
- an adaptive system that can work with any type of building, and corresponding billing rates;
- a non-intrusive solution that does not necessitate construction / hard-wiring;

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- an efficient processing of past data to enable comparison of past and current consumption, besides comparison of various sensors current consumption;
- an accessible system, reachable from anywhere, from any device (e.g. smartphone, PC);
- a highly secure system, with various actors having various privileges;
- a low-cost system itself consuming low power.

2. System Overview

A. General Description

The iTrack system consists of software and a hardware components. The hardware component encloses a non-intrusive wireless sensor network, which measures current and voltage in particular points of the electrical circuit, and a router that transfers measurements to the iTrack system database located remotely. The software component examines the received data and generates a visual form of the home electricity consumption. The software component is an accessible interface in a form of web-based application. For accurate calculations of energy consumption, the system communicates with the Saudi Electricity Company (SEC) database to acquire the consumption segment information. This information is important because KSA electricity charges not only based on the consumption amount but also on the building type (e.g. residential, commercial) [6]. The system user have the option of setting a maximum limit for either the whole house, or specific room / appliances. The iTrack system alerts the user whenever the current consumption is close to the limit over a mobile messaging service. The projected users for the system are everyone; however, the Saudi population of all ages and capabilities are especially intended. Hence, iTrack offers both Arabic and English interfaces, throughout English phrases to Arabic automatic translation. Figure 1 displays the system context diagram with the external units contributing to its operation.

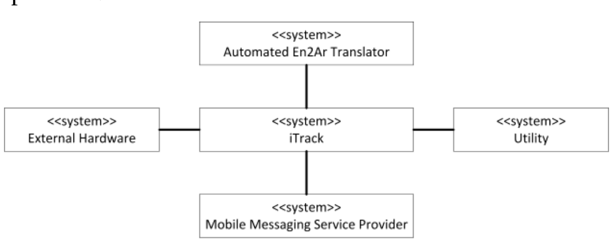

Figure 1. Context Diagram for the iTrack System

B. Use case diagrams

The iTrack system provides functionalities for three types of users: admin, home-resident, and guest. The admin have the privilege of adding, deleting and/or editing on the features of his/her home. In addition, the admin can set the consumption limit to assist regulating the energy consumption. The home-resident privilege is restricted to viewing functionalities; this user can view accurate measurement of energy consumption and calculation of user electricity bill, or viewing consumption limits (Figure 2). Finally, the guest privilege include only browsing the website, discovering its functionality and signing up into the website. Figure 3 shows the use case diagram established for each actor.

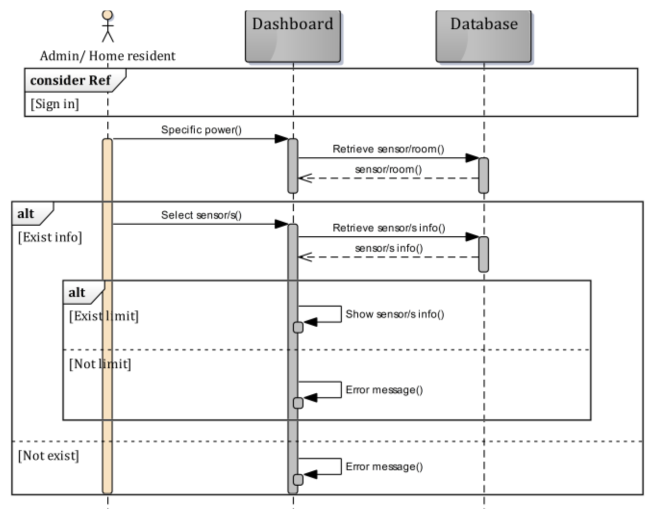

Figure 2. View Consumption Limit (Each) Sequence Diagram

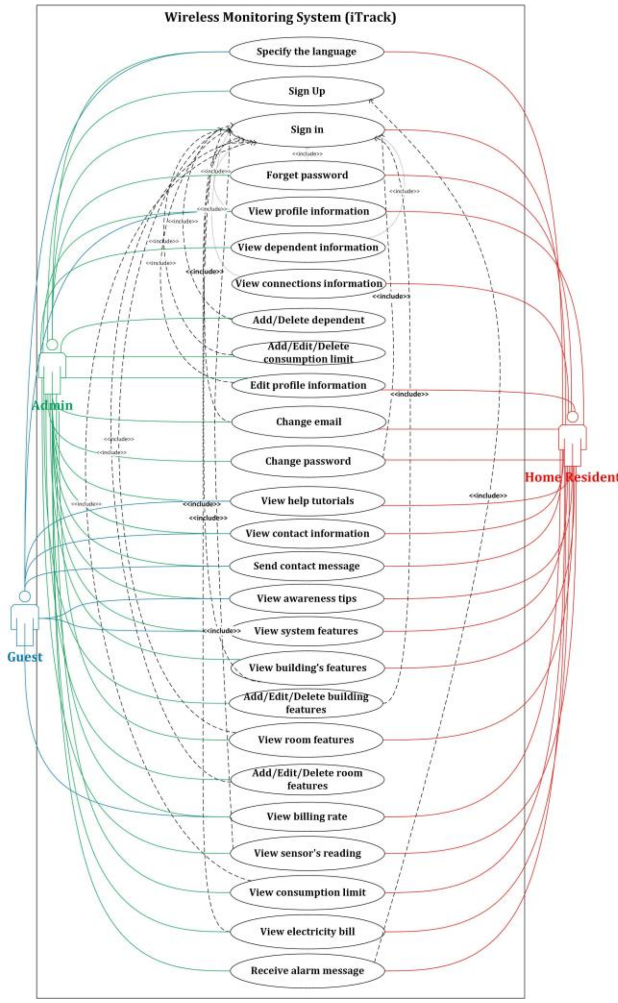

Figure 3. Use Case Diagram

3. PROPOSED SYSTEM ARCHITECTURE

To develop a web-based system, there are multiple web-based architectures choices (e.g. layered architecture, message bus architecture, N-tier architecture, object-oriented architecture, service-oriented architecture) [7]. For the development of iTrack, client-server and N-tier architectures was the preference.

Client-server architecture is a computing model where one or more computers act as a clients and one computer acts like server, and all clients request services from the server [8]. The server hosts both the software system and the system database. Users in different locations can access the server through various kinds of devices simultaneously. Additionally, the security of the client-server system is high because of the information storage in a centralized database.

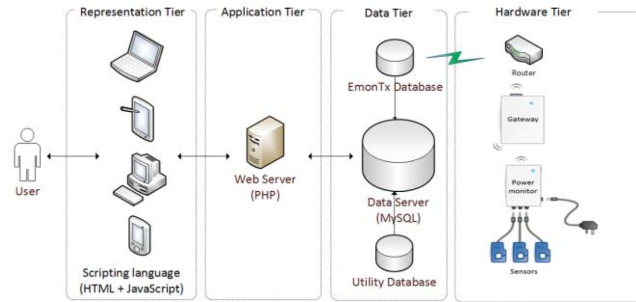

Figure 4. Architectural Design of the iTrack System

Figure 4 illustrates the architecture of iTrack. iTrack system architecture is made of 4-tiers: representation tier, application tier, data tier, and hardware tier. The first tire (representation) is the system interface, website, accessed using the user device's web browser. The second tire (application) is the actual system website hosted in a web server. The third tire (data) is system database stored in a data server. Finally, the forth tire (hardware) is the hardware sensor network which provides to the previous data tier the needed data for power consumption calculation.

A. Hardware architecture

The iTrack hardware architecture is constructed of three main components: sensor nodes, gateway, and regular home router. The sensor nodes are places in the electricity circuit using a non-invasive clip for the CT current sensors and an AC-AC Voltage adaptor for the voltage signal. These sensor nodes communicate with the gateway using a wireless adapter. The gateway itself is a link that transmits the data units to the iTrack database with the help of the home router. The home router connects the gateway to the Internet that is the transfer medium of iTrack data.

B. Database architecture

iTrack database as shown in Figure 5 is made of eight entities, eight binary relationships; called binary because each relationship is associated with two entities only, and the associated attributes with each one of them (each entity and each relationship) which are illustrated by oval shape. The primary attributes (the primary keys) of these entities are indicated by underlying these attributes. The entities themselves are marked by rectangular shape, that are (Account, User, Role, Building Type, Building, Consumption Range, Room, and Room Power). Additionally, all the relationships between the entities are marked diamond shape, which are (four 'Has' relationships, "Contain", "Create", "Own", and "billing rate "relationships). The cardinality, the numbers in the lines connecting the entities, specifies the number of instances each entity can have of the other entity. For example, the cardinality of the user and account entities under the has relationship is one to one; each user has only one account and each account has only one user. Likewise, Figure 6, show that each building type has one to many consumption ranges with the corresponding price for that range while each consumption range is for one to many buildings. Each consumption range has an ID a start range and an end range.

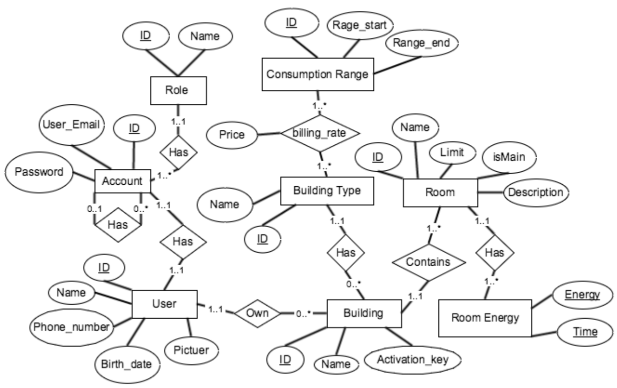

Figure 5. ER Diagram of the System's Database

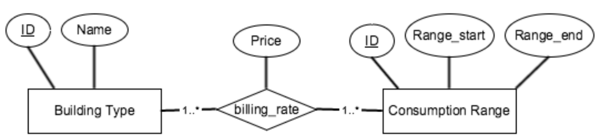

Figure 6. ER diagram of the External Database

C. Software architecture

iTrack software is created in the form of Model View Controller (MVC) architecture. The Model part of the architecture is presented by classes that hold and encapsulate the information received from iTrack database. These model classes use simplifies the transfer and use of data objects. The model classes is designed to match the database mapping presented in section 3B. Figure 7 displays the model classes of iTrack. The control part of the architecture is the heart of iTrack. The control is presented by classes where all the functionalities and implementations are placed. This part is the house of logic and data flow control between and from the view interfaces. The view part is simply the user interface. The choice of MVC pattern as software architecture promote maintainability. For instance, the modification of a user profile functionality can be done easily through the modification of a function in the profile control class.

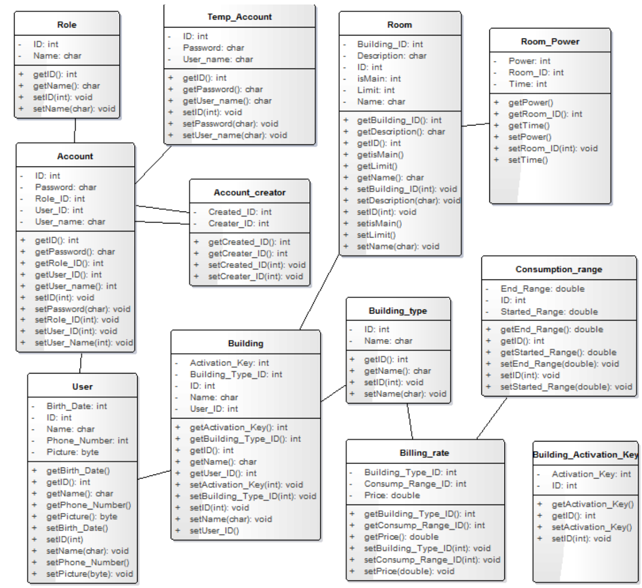

Figure 7. Model Classes Diagram

For demonstration reason, Figure 8 presents the internal structure for the individual Dashboard control class.

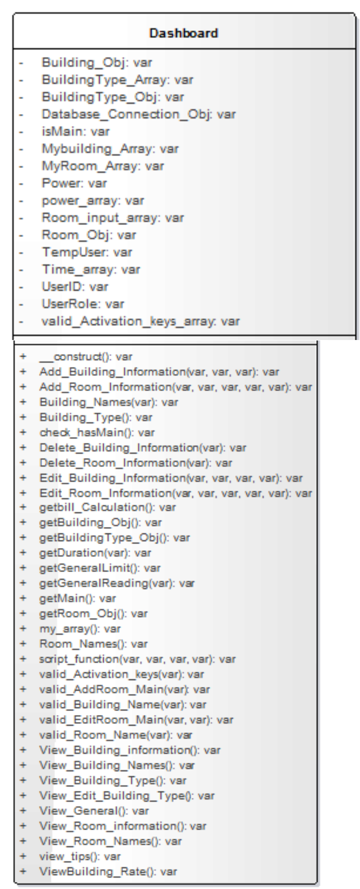

Figure 8. Dashboard Control Class Diagram

D. Interfaces architecture and design

iTrack system interfaces are clear, user-friendly and attractive. The interfaces fulfill these qualities because they are based on the following eight golden rules:

- Strive for consistency: all the interfaces components like colors, fonts, layout, menus, should be consistent.
- Cater to universal usability: recognize the user characteristic of iTrack system like novice or expert, education and age range.
- Offer informative feedback: provide a system feedback after each interaction between the iTrack users and the system.
- Design dialogs to yield closure: give an indication about user action if it is completed or failed.
- Prevent errors: design the system in a way that users should not be able to make major error by minimizing the typing input and making the user to choose from menu, gray out the unneeded field, give clear messages and instructions.
- Permit easy reversal of actions: give the user the ability of undoing actions.
- Support internal locus of control: design the system in a way that makes the user feels like he/she is controlling the action.
- Reduce short-term memory load: design the system in a way that does not require the user to recall information from previous interface.

The iTrack system interfaces are: home, about, awareness tips, change email, continue registration, dashboard, forget password, help tutorial, profile, reset password, system features, and verify email. The functionalities provided by these interfaces varies depending on the user type (Admin, home resident and Guest).

For all system user:

- The users can navigate from the home interface ton any other interfaces. Additionally, the users can see the home interface advertisement area.
- The users can browse iTrack team members contact information on the about interface.
- The users can communicate with iTrack website by sending email on the about interface.
- The users can read the informative safety and saving energy tips on the awareness tips interface.
- The users can discover iTrack features on the system feature interface.
- The users can watch help videos of how to use iTrack system on the help tutorial interface.
- The users can keep track of the consumption range coming from the utility database on the dashboard interface (electricity bill tab)

For the guest of iTrack website:

- The guest can see dummy dashboard that demonstrates the provided information for him/her if he/she decide to join iTrack.

For the admin of iTrack website:

- The admin can sign up to iTrack system using the sign up interface.
- The admin can manage his/her profile by:
  - Viewing his/her profile information
  - Adding/deleting his/her dependent accounts
  - Modifying his/her data like: profile picture, full name, birth date, phone number, change password and change email.
- The admin can manage his/her building information on the dashboard interface by:
  - Adding/editing/deleting a building information (building type, name and activation key).
  - Adding/editing/deleting room information (room name, room description, room limit and main sensor).
- The admin can view consumption information (graph that show the consumption habit, the percentage of the consumed limit, bill calculation).

For the home resident:

- The home resident can continue the registration process, which is initiated by his/her admin, on the continue registration interface.
- The home resident can manage his/her profile by:
  - Viewing his/her profile information
  - Adding/deleting his/her dependent accounts
  - Modifying his/her data like: profile picture, full name, birth date, phone number, change password and change email.
- The home resident can view consumption information (graph that show the consumption habit, the percentage of the consumed limit, bill calculation).

4. Implementation, Testing, and Deployment Details

A. Sensor Network

iTrack hardware prototype was created by utilizing an open source monitoring product produced by openenergymonitor.com (Figure 9). This product cost is relatively low and the product itself does not consume a lot of power.

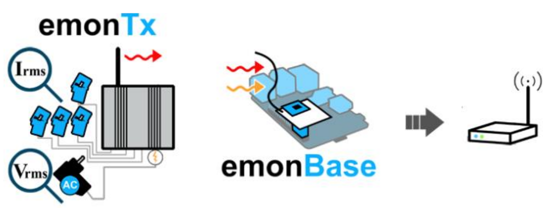

Figure 9. Hardware Architecture of the iTrack Prototype

The main two components of iTrack system hardware are EmonTx (wireless sensor nodes) and Raspberry Pi (gateway).

The EmonTx monitors AC electrical power on up to four separate house circuits through non-invasive clip to measure current and voltage (Figure 10). EmonTx utilize wireless energy monitoring nodes to monitor full real power data; EmonTx senses and sends these data as frequently as every 10 seconds. The different real power data monitored by EmonTx V3 are Real Power, Apparent Power, Power Factor, Root Mean Square Voltage, and current [9].

Figure 10. EmonTx; Power Monitor

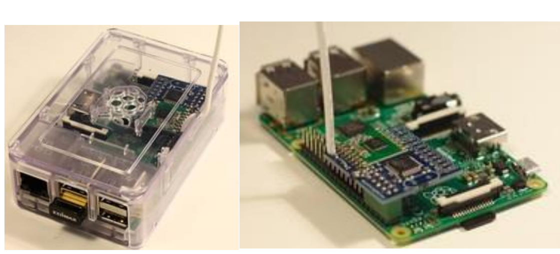

Figure 11. Raspberry Pi; EmonBase

The gateway used in iTrack sensor network shown in Figure 11 is Raspberry Pi (RPi). RPi is a "credit-card sized Linux computer developed by the Raspberry Pi Foundation. The device has many applications both in the developed and the developing world" [10].

B. Data Saving

The Raspberry Pi functions as a base-station for data logging of locally received information from EmonTx. The Raspberry Pi has RFM12Pi wireless adaptor board that forward through the Internet the data to a remote unit [11]. The remote unit saves the data on a MySQL database for future visualization, post-processing, and alerting. iTrack software synchronize the utility database and the iTrack database using a background process that runs automatically in the server. The background processes is configured to run using Crone jobs.

C. Visualization, and Alerting

As mentioned earlier, iTrack system model is MVC architecture. Hence, iTrack has three categories of files; the view files enclose the code of all interfaces (HTML, CSS, JavaScript, jQuery); the controllers file houses the code that communicate the interfaces with the Model classes (PHP); the Model files comprises classes that hold data coming from the system database. The selection of this model is based on the need for rapidity, interoperability and ergonomic criteria. In Fig.12, the page show the user electricity consumption, including the real-time calculated bill, and the ratio of consumption compared to the total consumption in a percentage form. The function of alert when approaching the consumption limit is implemented as a process that runs daily. The process compares the total energy consumption with the set limit, and sends alert message in case the consumption approached 75% of the limit.

D. Security

To increase iTrack website security multiple security mechanisms are used. For instance, the user password is encrypted using md5 technique. The user of the system is ensured to be a human not a machine using captcha code method. Also, messages are sent to the user email for verification whenever he/she signs up, adds dependent or changes his/her email. In case of user attempt to hack the system using this link sent in these messages, the system had the ability to detect that. Therefore, the iTrack system is robust against hackers whom attempt to acquire the privileges of other user.

5. Conclusion

This study outlined the design, development, and implementation phases of a residential energy monitoring system that has been tailored to meet local needs, that is to say a non-intrusive system with a user friendly interface available both in English and Arabic endowed with an alert system, and also providing energy saving and awareness tips. The iTrack system has been fully deployed, and is currently hosted on a VPS managed through a CPanel listen. The prototype hardware is also currently used on-campus to monitor electricity consumption of appliances in faculty office area.

Future enhancement are planned through implementation of new useful functionalities, such as the incorporation of fault detection techniques utilizing already available sensor measurements, for a system robust to sensor failures, or an automated setting of the sensors by providing a visual blueprint of the house instead of manually inserting the building information.

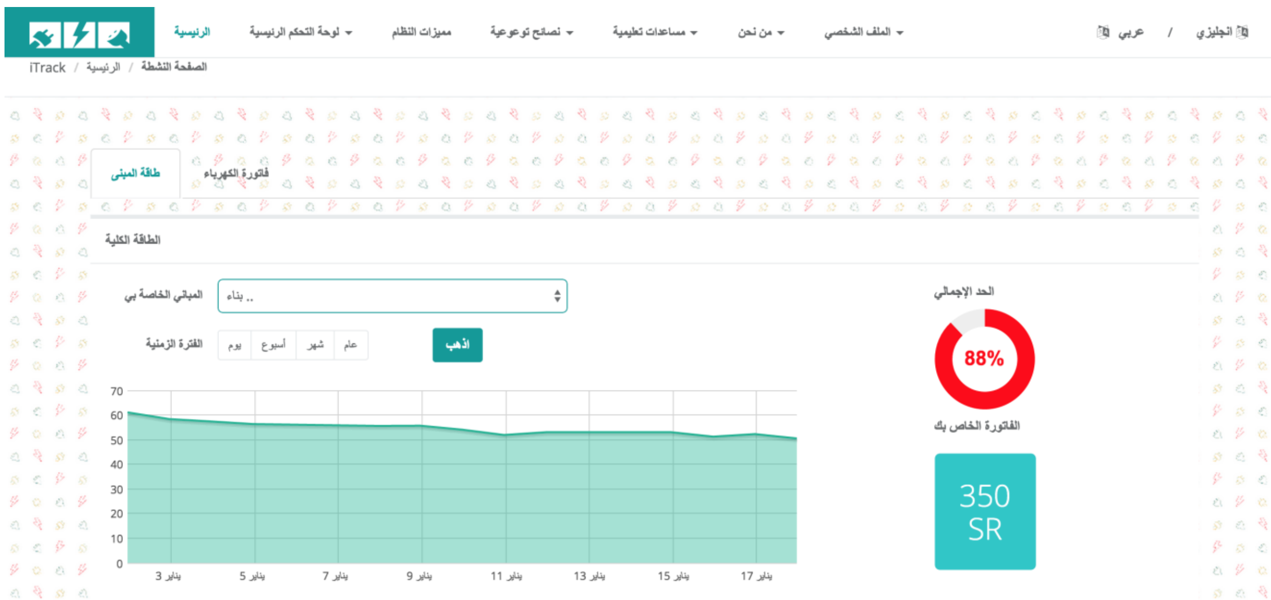

Figure 12. Building Power (General Power) Interface

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