Energy-Efficient User Interaction with an Off-Grid Building

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Abstract: This paper describes the design of energy-efficient wide spectrum mechanisms and protocols to capture context information and employ actuation to close the feedback loop. The project described in this article focuses on harvesting energy from the environment through as many ways as possible, and efficiently using the harvested energy in off-grid buildings, dynamically adapting the consumption to currently available energy levels. The main energy sources to be used for harvesting are: solar energy, wind energy, wasted wireless communication energy and hydro energy. Through its web and Android interfaces, the project offers functionalities such as analyzing energy harvesting efficiency, monitoring building-wide energy consumption, setting up profiles and managing consumers individually.

1. INTRODUCTION

The growing importance of context-awareness as an enabler for more intelligent, invisible and autonomous applications and services has highlighted the need for a greater integration of the physical with the digital world. Energy in particular is becoming an increasingly important topic in our lives. As we become more aware of the limitations and the costs of the energy we consume in our daily life and in our personal environment, we look on technology to give us aid in optimizing our efficiency.

2. MOTIVATION AND SCENARIOS

Our goal is to design highly efficient energy mechanisms and protocols to capture and actuate context information. The target application is an off-grid house which can employ energy harvesting, storage and management in order to become self-sufficient [1], [2], [3], [4].

The project uses technologies such as Wireless Sensor Networks, WiFi, Ethernet and an efficient energy harvesting implementation to value solar energy, wind energy and wasted wireless energy. We designed a complete hardware and software solution to optimize energy consumption and match energy usage with available energy sources in an off-grid implementation. The proposed system offers the average user the ability to obtain detailed statistics of both harvesters and consumers in its home and to easily take action in order to optimize energy consumption.

There are two ways a consumer can register to the system: as pluggable or as dimmer devices. The user can connect to these devices through a web interface or a smartphone and apply individual settings or system-wide energy profiles.

Before actual implementation, we described the functionality of our system through a series of use-case scenarios. This helped in defining the system architecture and iron-out eventual problems or design faults. There are a total of three scenarios, described below:

- When leaving the apartment for just a couple of hours or for a holiday, Jane can simply select the according profile and her house will enter a standby mode: the lights go out and the appliances and the heating system are turned off. A couple of hours before coming back home, Jane can remotely connect to the Eneco system, using a username and password, and can turn on the heating system, to have the same comfort in a eco friendly way.
- In a remote village school, with off-grid, alternative energy harvesters, the school administrator, concerned with the lack of sunlight in the last few autumn days, checks the battery levels in the Eneco system and switches to the energy saver profile, powering off three of the four computers in the school and dimming out the lights, thus maximizing energy for the electric heating system.
- In his office, Mark thinks about the eco policy his company is trying to promote and logs in the Eneco system using his Android device. Using a quick menu configuration, he switches to the eco profile. This will disable the plugs for all non-essential consumers in Marks's office, while maintaining functionality for all essential systems. However, Mark decides the profile is too strict and wants to power up the plug for his sound system, so he activates the custom profile by enabling that plug.

3. PROJECT DESCRIPTION

The project focuses on harvesting energy from the environment through as many ways as possible, and efficiently using the harvested energy in an off-grid building, adapting the consumption to the currently available energy levels. The main energy sources to be used for harvesting are:

- solar energy;

- wind energy;
- waste wireless communication energy;
- hydro energy.

Through its web and Android interfaces, the project offers functionalities such as analyzing harvesting efficiency, energy consumption throughout the building, setting up profiles and managing consumers individually. The system can switch AC sockets on or off and can turn light dimmers down or up in order to adjust consumption to the current energy levels in the system.

The system has a hierarchical architecture (Fig. 1), with a System Server as a central node acting as a gateway between the user interfaces, harvesters and consumers in the system. The System Server gathers data from energy harvesters, wireless smart energy meters installed on standard AC sockets and light dimmers. Data is published to the user through the use of a web interface and mobile devices. The system is universal in a sense that any electrical consumer that can be plugged in a standard AC socket or connected through a light dimmer can be part of this system.

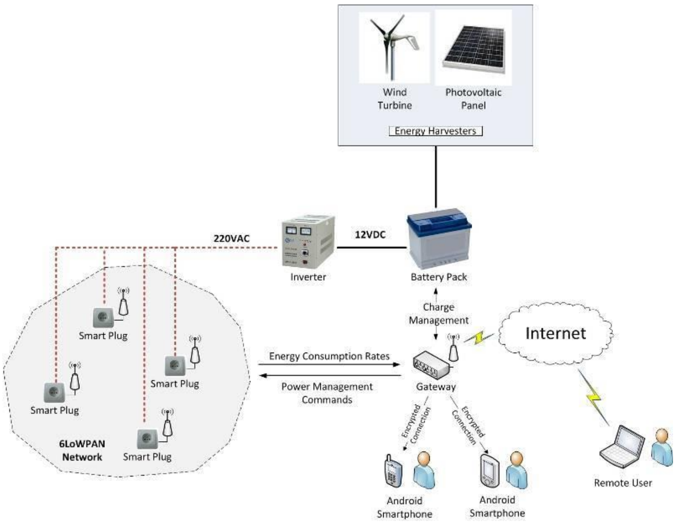

Fig. 1. System Diagram

- **System Server:** this is the central part of our system. It is an embedded device, based on the OM11042 kit (Element14, n.d.). Its role is to monitor the harvesters, communicate with the nodes on the consumers, store data and publish it both on a web interface and on the smartphones.

- **Harvesters:** we have designed and built several alternative energy harvesters: solar energy, wind energy, hydro energy and wasted wireless energy. These are pumping energy in a 12V motorcycle battery, whose energy level is permanently monitored and is directly available to the user. Of course, in practice, even greater alternative energy harvesters are available.

- **Wireless Nodes:** the nodes are connected to each consumer in the system. They have a double purpose: reading consumption data, which is forwarded to the system server and performing actions such as switching off a plug or dimming down the lights.

- **Interface Devices:** the system server connects with a Wireless router through its Ethernet interface. Users can access data and perform actions by connecting with their username and password to this router. Two methods are supported: a web interface accessible from any browser, and an Android application.

Various types of communication and protocols are used: the server uses SPI to communicate with an SD card which holds the data, connects through 802.15.4 with the nodes and using Ethernet with a router. The router sits on the edge of the system and waits for both wired and wireless internet connections with user computers or mobile devices.

4. HARDWARE DESIGN AND IMPLEMENTATION

In order to implement the complex heterogeneous system described in the previous chapter, we needed to use a mix of commercial off the shelf components and custom-built hardware. The hardware side of the project can be split into several independent modules which are described below.

4.1 System Server

The heart of the system is the NXP LPC1768 [5]. It acts as a gateway between the user and the hardware, and, therefore, performs 3 essential functions: it measures the voltage intake from the harvesters and battery level using its 6 built-in ADC inputs, computes current and power consumption and logs the data on the SD Card and fulfils user requests, providing real-time measurement data and issuing commands to the consumers. The communication with the user is conducted over Ethernet and the sensors and actuators are contacted via a wireless 802.15.4 link.

The System Server is an assembly of 2 PCB boards:

- the peripheral board interconnects the LPC to a SD Card, Ethernet port and a wireless ZigBit module.

- the voltage measurement board uses the LPC's 6 ADC inputs, some shunt resistors and resistive dividers to measure the individual voltages generated by the harvesters.

4.2 Harvesters

Energy Harvesting is the process by which energy from the surrounding environment is captured and stored. In recent years the term has been applied mainly to sensor networks, where autonomous sensor nodes employ this process to replenish their energy resources. When applied to our architecture, energy harvesting increases the robustness and availability of the system, making it energy-independent.

In our implementation, the harvesters charge a 12V motorcycle battery, which is the central energy storage of our system. The battery is connected to an inverter to provide power to the 220V AC sockets and lights.

For our implementation, we planned on using four alternative energy sources: *solar energy, wind energy, hydro energy and wasted wireless energy*.

Due to time constraints, we were not able to build very efficient harvesters for each of them. Even so, the Eneco system is completely autonomous – the system server, nodes, wireless router and actuators draw power from the central battery.

Solar cells (Fig.2) offer the best efficiency while, at the same time, are an environmentally-friendly power source. The purpose of the system is to combine solar energy with other available energy sources and. In case the energy sources are have a low production level for a period of time, the system will signal the user and take appropriate measures to prioritize energy consumption.

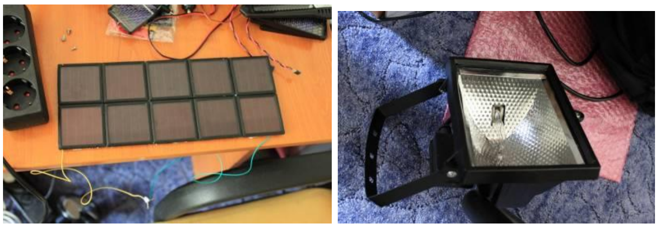

Fig. 2. Solar energy: (a) solar energy harvester using photovoltaic cells; (b) 500W spotlight to simulate external light conditions.

The most common energy scavenging technique is the use of photovoltaic cells to obtain power from ambient light, usually sunlight. For locations in which the availability of light to network nodes can be guaranteed to a sufficient degree, and for which mains and primary battery supply is impractical, this can be an excellent energy source.

The electrical power that can be extracted from a photovoltaic cell is proportional to the area of the cell and the intensity of the incident light. The terminal voltage of the cell resembles that of a semiconductor diode and is relatively insensitive to changes in light intensity, while the output current is directly proportional to light intensity.

The efficiency of wind energy harvesting is also non-negligible, although it suffers from the drawback of not being always available. However, locations such as coastal areas and large open fields benefit from a constant breeze most of the year and, in the absence of wind power, solar energy can be reliably used as a complement.

Fig. 3. Wind energy: (a) wind energy harvester based on a common fan; (b) dismembered hair drier to simulate wind.

For wind energy harvesting we are using a common fan (Fig. 3) with its DC motor used in reverse, as an electric dynamo. After rectifying the AC current generated by the motor, we managed to get a high enough voltage to charge the battery.

In order to simulate wind, we have also dismembered a hair drier.

Typically, wireless sensors are designed to observe environments in a more flexible way than wired ones can, but sensor's power supply is the most confounding problem. In solving this problem, engineers dusted a decades-old idea: radio-frequency energy recycling, be it from strategically placed transmitters or from the ambient energy emitted by cellphone towers and television stations. The concept was once dismissed as unfeasible because of the rapid dissipation of electromagnetic waves as they travel from their source. However, in our system even microwatts, if trickled into a battery or supercapacitor, can be enough to power a wireless sensor node for a limited amount of time. This is where the idea of a rectifying antenna, or rectenna comes in.

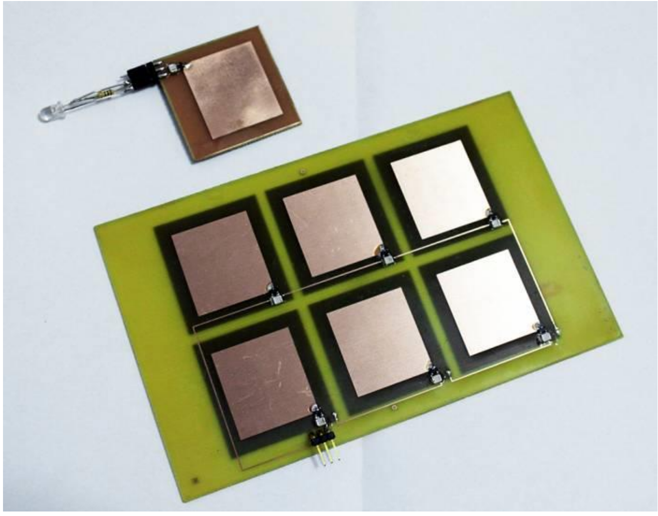

Fig. 4. Special antenna used for harvesting wasted wireless energy.

A rectenna is a special type of antenna that is used to directly convert microwave energy into DC electricity. A simple rectenna element consists of a dipole antenna with a Schottky diode placed across the dipole elements. The diode rectifies the AC current induced in the antenna by the microwaves, to produce DC power. Schottky diodes are used because they have the lowest voltage drop and highest speed and therefore waste the least amount of power due to conduction and switching. Large rectennas consist of an array of many such dipole elements.

The idea of using rectennas for our design was chosen because, as opposed to the more well-known energy harvesting methods, it is a novel approach of getting power from the environment and it has remarkable efficiency (over 80% of captured microwave energy is converted to DC).

Also, the fact that any modern living urban environment like a home or an office building is flooded with WiFi networks, GSM cellphones, repeaters and towers and even radio stations offers a strong incentive for implementing this type of energy harvesting.

There is only one drawback to this solution: one harvester is tuned to a very narrow frequency band and, if one wants to convert a wide band signal, multiple individual harvesters must be used, each tuned to a different frequency so that the whole spectrum is covered. However, all WiFi, Bluetooth and Zigbee networks operate in a narrow band around 2.4GHz and GSM networks around 900MHz. These are the types of networks most regularly found in a living environment, so designing harvesters for these two frequencies would yield close to optimal results.

Another good thing about rectennas is that they can be cheap to build and need very little additional components. The antenna part of the rectenna is a common patch, tuned for 2.4GHz and etched on a regular FR4 printed circuit board.

The rectifier (RF to DC conversion) circuits were designed using discrete Schottky barrier diodes. Two Agilent zero-bias diode pairs, HSMS-2852, were employed in a voltage doubler rectifier circuit. The HSMS-2852 diode was chosen as its performance is optimized for the chosen operating frequency band (2.4 GHz ISM band), and further, no external bias is required. The diodes appear in parallel to RF signals, but are in series for the DC circuit, as such the voltage output is doubled. To generate even higher voltages, additional voltage-doubler stages can be connected to the top of the aforementioned stage.

4.3 Energy Savers

As part of the functionalities our system proposes, it incorporates some mechanisms for saving power, such as smart plugs and light dimmers. The Eneco system automatically uses them in order to adjust energy consumption according to the user preferences and available energy.

We achieved this using a set of remote control smart plugs (Fig.5).

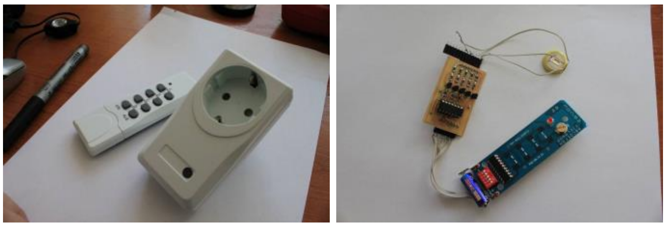

Fig. 5. Remote control smart plugs.

After reverse-engineering a set of standard plugs, we have engineered and manufactured a couple of extension boards for the System Server. Using the extension boards, the System Server can now switch off the AC socket, according to user preferences.

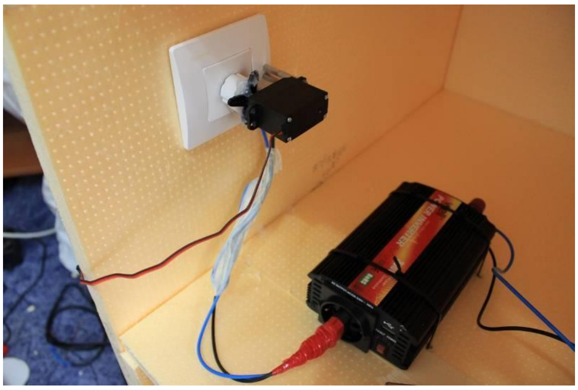

Fig. 6. Custom light dimmers.

We have attached to a series of light dimmers a servomotor (Fig.6), which enables the system server to automatically dim the lights up or down. We could have done it electronically, but due to time and safety constraints we thought it would be better to approach the matter this way.

Power is supplied into the light dimmer by an inverter, which is connected to our system's energy storage (i.e. 12V motorcycle battery). The servomotors are controlled by custom made nodes.

4.4 Energy Metering

For our smart building idea, we use a single phase energy meter that can measure mains voltage and current and give an estimate of the active power if a standard 220V appliance is plugged in.

The heart of the meter is an AVR ATmega16 microcontroller. All measurements are carried out in the digital domain and measurement results are available on a USART interface.

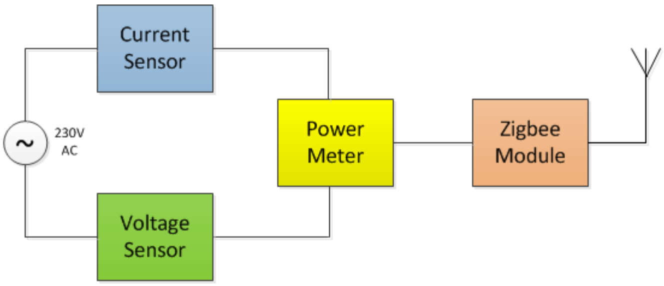

Fig. 7. Custom light dimmers.

To further integrate it with our project we attached a 802.15.4 radio transceiver and made the measured data accessible to users via wireless in the same manner as with the other sensor notes. In other words, we transformed a standard power extension cord into a wireless power metering device.

The energy meter hardware consists of a power supply, an analog front end, a microcontroller section, and an interface section with the radio transceiver. The power supply connects the nodes directly to the central battery, thus enabling the whole system to be completely off-grid.

5. SOFTWARE ENGINEERING.

The software side of the project is comprised of three major components: the server software, the firmware for the sensor nodes and the mobile application.

5.1 Server Software

The System Server is the central point of the Eneco system, acting as a gateway between the user interfaces (web, smartphone) and the inner part of the system (energy storage, harvesters, consumers etc.).

Careful consideration need to be put into programming the NXP LPC1768, in order for it to run the large series of tasks the system needs to properly function:

- use the ADC to sample power production and consumption data from the system;
- connect through UART with the wireless sensor network coordinator;
- send commands to the smart plugs and to the light dimmers;
- reply to HTTP requests from the web interface and from the Android application.

Each of the harvesters is connected to the ADC pins of the microcontroller, which in turn samples for voltage, current and power.

The System Server connects through UART with the coordinator node of the wireless sensor network. Each sensor node in the wireless network is uniquely identified by its IPv6 address and can serve as a source for a wide variety of measured data, such as light intensity, temperature, humidity, AC voltage and current or average power consumption., All the smart plugs in the system can be remotely switched on or off by the microcontroller using a simple device selection protocol. The smart dimmers in the system are controlled using PWM, which allows a smooth control of the light intensity for each dimmer. In this way, the System Server is able to switch the smart plugs on or off and dim the lights up or down, ensuring an optimum power consumption according to the user's needs.

HTTP requests and specially formed URL's are used for both browser interaction and control from the Android application. Data can be viewed directly in a browser, or sent to the Android client, so that users have a more powerful and user-friendly interface.

For a real time performance, an interval of about 5 seconds is expected between HTTP requests from the web interface and from the Android application. In the same manner, the browser page refreshes itself at the same interval, offering a close-to-real-time feedback.

The website has a minimalistic design, in order to save computation time and communication bandwidth. Though it is partly constructed dynamically, the data shown is mainly given in numbers and in easy to compute bar charts.

The requests from the Android application only require the current values, as data is stored on the phone app to compute a graph for a longer period of time.

5.2 Server Node Firmware

In our system, wireless nodes are split into two categories: sensor nodes and coordinator nodes. Sensor nodes have a simple architecture, meant only for sensor data collection and low-level actuation. Coordinator nodes act as an edge router for the wireless sensor network. It acts as a sensor data sink and as a command entity for the entire sensor network island. Data flow is routed by the coordinator to the embedded System Server through a simple UART interface.

The main characteristics of the sensor node firmware are:

- **security:** the data transmitted is secured with a simple encryption method that uses a pre-shared key with size equal to the packets being sent over the air, thus making it secure against eavesdropping.
- **fault-tolerance:** he sensor gateway is tolerant to the disappearance of nodes in the network by implementing a graceful degradation of the provided service. This is accomplished by pushing data from the other sensors to the coordinator node. Once a node disappears, the data it already sent is still kept on the gateway and can be accessed via the mobile interface or directly on the gateway display. The reappearance of the node is transparent, new data is gathered and kept on the embedded gateway.
- **scalability:** The operating system used, Contiki offers an implementation of IPv6 tailored for wireless sensor networks (more specifically 802.15.4 networks), uIPv6. The size of the network is bounded by geographical disposition of the sensors and by saturation of the radio frequencies for 802.15.4
- **standardized:** the nodes use a mainstream wireless sensor network operating system, which allows for heterogeneous networks. Also, all nodes run IPv6, enabling the possibility of remote access from outside the network.

5.3 Android Interface

The Android interface in our project needs to be able to both display rich information such as graphs and tables and to take in user action through forms.

The user interface maps the main scenarios and is divided into four main sections:

- **Harvesters:** allows the user to read information about the harvesters available in the system, with a comparison of their total efficiency. Each of the harvesters has also a detailed view, which gives additional information about their current voltage, current and power.
- **Consumers:** allows the user to read information about the consumers connected in the system. Each of the consumers has also a detailed view, which gives

additional information about their current consumption and also allows the user to perform actions on individual plugs or dimmers, such as switching off or dimming down.

- **Profiles:** easily enables the users to specify a setting for all the consumers in the system.
- **Management:** enables the user individual access to each of the consumers, thus activating the custom profile.

Name: Slider
Type: Light Dimmer
Profile: Normal
Battery: 13%
Temperature: 24.0 C
Light: 20

Fig. 8. The Android application interface.

All charts are plotted using AChartEngine, a free software library for Android applications.

Graphs are available for both harvesters and consumers. Graphs can display individual devices or all of them:

- all harvesters: there is a separate graph for voltage, current, power and energy; the energy graph is a pie chart showing relative performance of the harvesters in the system;
- one harvester: if the user chooses only one harvester, its graph will show three separately coloured lines corresponding to voltage, current and power;
- all consumers: there is a separate graph for voltage, current, power and energy; the energy graph is a pie chart showing which are the biggest consumers in the system;
- one consumer: if the user chooses only one consumer, its graph will show three separately coloured lines corresponding to voltage, current and power;

On each of the consumers, the user can set a state, depending on its type. For example, consumers that plug into sockets can be switched on or off by the user and the illumination can be set at a specific level. The Eneco system can also manage automatically all consumers according to the profile that the user set.

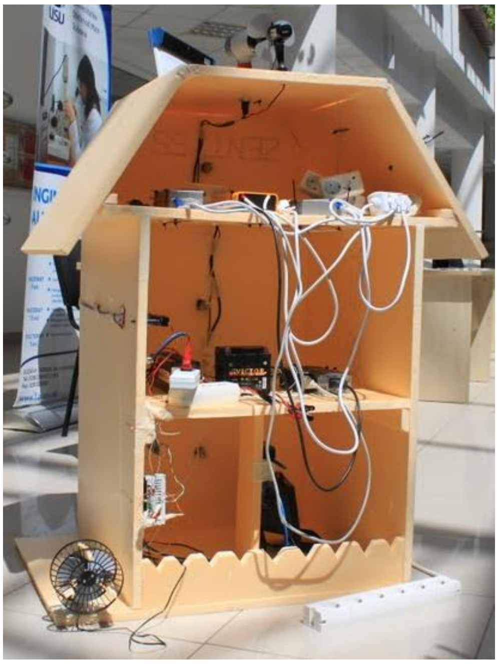

Fig. 9. The final system mock-up.

7. CONCLUSIONS

We designed and built a concept of an autonomous off-grid building that employs different energy harvesting and dynamic power management techniques to adapt to varying energy production and consumption rates. The system offers a high level of flexibility through its interfaces and offers multiple functionalities, such as analyzing energy harvesting efficiency, monitoring building-wide energy consumption, setting up profiles and managing consumers individually.

The outcome of the project development was a demo mock-up off-grid house (Fig. 9), with full functionality in all the four areas: system server, harvesters, wireless nodes and interface devices.

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