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WoT (Web of Things) for Energy Management in a Smart Grid-Connected Home

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Abstract

This paper considers a case study of a smart grid-connected home in Australia that has solar photo-voltaic panels for distributed electricity generation and batteries for local energy storage. With a focus on Web of Things (WoT), this paper explores a strategy to facilitate management of electrical energy in the context of the emerging smart grid ideas that are consistent with sustainability practices. The strategy considers a cyber-physical software system that incorporates web-enabled physical devices and RESTful APIs to enable monitoring, integrating and controlling electrical appliances in a household. A dynamic adaptation is considered of the energies flowing between the smart grid, local solar panels and local storage batteries for powering the house with a view to reduce costs and greenhouse emissions.

Keywords: Web of Things (WoT), Smart Grid, web technology, sustainability, distributed energy, RESTful API

Introduction

Increases in recent times in electricity costs and in associated emissions of greenhouse gases are having an impact on societies to adopt business and lifestyle strategies based on sustainability practices. The emergence of the smart grid (Xinghuo et al., 2011) facilitates both suppliers and consumers of electricity in reducing carbon footprint and improving the reliability and efficiency of electricity generation, distribution and utilization. The smart grid unifies recent developments in the electrical power area with those in information and communication technologies (ICT) to bring to bear changes to business practices and life styles of consumers. The smart grid recognizes the distributed nature of electricity industry and the unifying power of the ICT.

Traditional power grids consist of (i) large-scale electricity generators that are located within easy reach of energy resources, (ii) high-voltage transmission lines to bring bulk electricity to load centres that are close to loads, such as industries, cities, townships etc., and (iii) lower voltage distribution networks which in turn distribute electrical power to smaller consumers of electricity. Unlike such traditional power grids, smart grids have distributed energy generation that encompasses both centrally-located large-scale generators with ratings of 100's of megawatts (MWs) and many geographically distributed smaller generators of widely varying sizes from 10's of MWs that use fossil fuels and renewables to a few kilo watts (kW) that may be solar photo voltaic (PV) panels mounted on the roof of a small house.

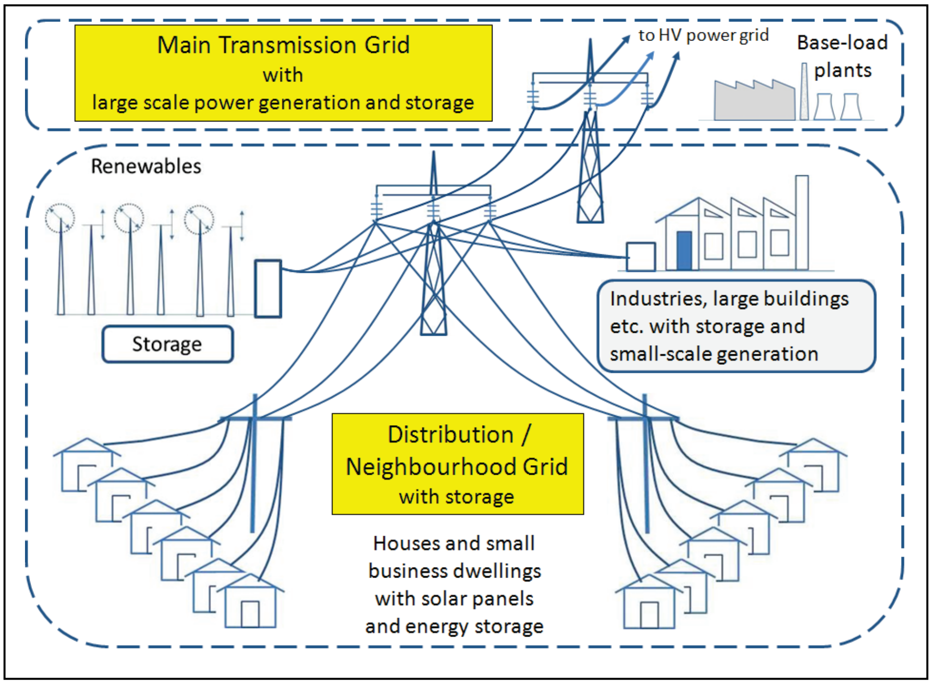


Figure 1 A Smart Grid integrating generators, distributors and consumers of electricity

Several geographically distributed power generators need to be integrated into the smart grid, recognizing the varying capacities, characteristics and technologies associated with generators (Figure 1). Electricity generated using renewable energy sources, such as photovoltaic (PV) solar panels and wind turbines, is variable depending upon the season, weather conditions and the period of any given day. This variability has a strong influence on the delivery of reliable power to consumers. Storage of electrical energy to dampen the effects of variability in the power from renewables is therefore an important aspect of the smart grid. Various types of energy storage: pumped hydro storage, batteries, fuel cells, flywheels etc. need to be integrated into a smart grid. Such distributed energy storages in the grid may serve different networks within the grid so that they continue to operate as self-powered islands during outages resulting from natural causes or system faults (Nourai & Keane, 2010).

The electricity generated by solar PV panels and by some wind generators is in the form of direct current (DC). This DC power must be converted (or inverted) to make alternating current (AC) power to enable connection to an AC smart grid. Smart grids need smart inverters with controls to maximise renewable power utilization, and to supply power to either the local load and/or the grid (Xinghuo et al., 2011).

The smart grid needs to integrate the action of generators, energy suppliers and customers. The smart grid must provide suitable multi-way communication of relevant information between various business actors associated with the grid. The smart grid includes even a small household as a business actor into its business model because a household contributes towards sustainable business outcomes.

There are many research papers on smart grids with a focus on large power systems (Brown, 2008; Ipakchi & Albuyeh, 2009; and Farhangi, 2010) that emphasize the importance of pervasive control and monitoring requirements in a smart grid. They point out the convergence of ICT with power system engineering. There are also many publications (Guinard, 2011; Kamilaris, et al., 2011) that deal with energy management at household levels using the ICT strategy, such as Web of things. Some other publications stress the need for a level of smartness from systems to deliver proper intuitive assistance (Schmidt, 2000; Langley et al., 2006; and Zaki & Forbrig, 2011) to users of the system.

However, there appears to be very limited publications on the informing strategy that is essential to provide relevant information that empowers electricity users at a household level to derive both economic and environmental benefits from a smart grid. Power utilities and governments take into account the economic and political benefits of using ICT in smart grids for optimized utilization of infrastructure at reduced operational costs. They also attempt to provide real-time information to commercial and residential customers of their electricity usage and engage in suggesting ways to reduce their costs, energy usage and greenhouse emissions to reap economic and social benefits. Such informing developments are essential to assist a householder – also a business actor – to participate in the smart grid business by adopting appropriate electricity management schedules. An informing strategy forms the basis of this paper.

Integration of the management of electricity in a household to a smart grid is the research addressed in this paper. The paper describes both the physical aspects of integration of several electrical systems and appliances as well as seamless integration of information to facilitate electricity management at the household level. Crucial research issues for a household to be a part of a smart grid are: (i) data collection from physical devices in the house hold, (ii) integration of collected data from the household and other relevant information available elsewhere, (iii) provide appropriate information to the householder in a user friendly way to make considered decisions in line with their lifestyle option, and (iv) enable the householder to control physical systems and appliances in the household. Our paper addresses some of such issues by describing a practical web strategy to provide useful energy information to the household customer. Given the broad nature of the research issues involved, a descriptive case study is presented here as the most appropriate approach to provide a systematic way for data collection, information analysis and reporting of results. We also illustrate a few issues that are important to develop suitable decision support for energy management at the household level.

The household considered in the paper has (i) several loads that consume electricity, (ii) local electricity production using solar panels, (iii) battery storage and (iv) a smart inverter that controls power flow between electrical power units. The house is connected to a smart grid via a smart meter. The paper is structured as follows: The next section outlines recent developments in integrating physical devices to Web of Things (WoT) in the context of smart grids. Section 3 discusses the physical electrical system in a house that is connected to a smart grid via a smart energy meter. In Section 4, we discuss the architecture of the proposed information system. A case study of home energy management is considered in Section 5 using measured values of power profiles over a day and a few scenarios for reducing cost and/or greenhouse emission. Section 6 provides some conclusions.

Web of Things for Smart Grids

Information and communications technologies (ICT) are essential for a house that is connected to a smart grid for efficient and effective energy management (Xinghuo et al., 2011). It has been argued by Santacana et al. 2010 that the very distributed nature of a smart grid, in which even a small household is a supplier of electricity to the grid, and hence a business actor, information flow is much more ubiquitous than in a traditional grid. Some new ICT technologies that are considered for smart grid applications are smart meters, low-power wireless personal area networks (WPAN) and other telecommunication technologies for real-time monitoring and controlling the network.

Web of Things (WoT) enables customers use the internet and make informed decisions about their energy use, and thus change their lifestyle by managing their energy consumption. Also smart grids must enable actors in the grid to operate under industry standards to accommodate its wide and varied customer base, abide by local political, economic and social policy settings. The web is a very effective, user-centric, scalable, distributed platform with underlying technologies such as TCP/IP, HTTP, HTML/XML, JSON etc. This success has now been extended to incorporate real world objects into WWW using web technologies, known as the Web of Things (WoT). Such developments are eminently suitable for application to the development of smart grids.

Integration of Physical Devices

In recent years, Automated Metering and Reading (AMR) has enabled power utilities to measure and read the power consumption of customers remotely to facilitate demand-side load management. However, AMR is a one-way communication between the meter in a household and the utility. AMR does not allow multi-way communication between many actors of a smart grid to enable pervasive control. The emerging Automated Metering Infrastructure (AMI) enables a two-way communication between the meter at a household and the utility. AMI thus supports reading of the meter as well as facilitating changes to the electricity usage by a customer.

Until recently, the complexity of communication standards, protocols and services meant that integration of physical devices into the internet was possible only with high-power consuming embedded sensing and control devices. The emerging IEEE 802.15.4 is a low-power wireless personal area network (WPAN) standard. The 6LoWPAN standard makes this latest Internet protocol (IPv6) available to even the most minimal embedded devices over low-rate wireless networks, and is well suited for embedding into home appliances in the internet of things paradigm (Shelby & Bowman, 2009). Since typical households have cable Ethernet connections and Wi-Fi as the backbone network, extension via 6LoWPAN is possible without laying additional cables. Seamless integration to the internet is the attractive feature available with IPv6 over the other standards. IPv6 connectivity of smart appliances integrates these appliances to the internet network layer. The system architecture discussed in this paper achieves web integration of household appliances (application layer) via web servers.

Internet of Things (IoT) and Web of Things (WoT)

The Internet of things (IoT) deals with principles and technologies that enable the internet to get into the real-world of physical objects. IoT gives every device an IP address and lets it plug into the internet. In IoT, everyday devices and objects that contain an embedded device are connected by integrating these into the web. Examples of smart devices are sensor networks, household appliances etc. Web of Things (WoT) is an extension to IoT (Zeng, Guo & Cheng, 2011), and reuses the web standards and builds on the success of web 2.0. Well-established web standards and blueprints such as HTTP, REST, URI etc. are used in WoT to ensure ease of development with existing web frameworks in accessing the functionality of smart objects. In WoT, real-world objects, for example consumer appliances, are integrated into the WWW by representing them as web resources, which can be accessed using lightweight APIs based on REST principles. In WoT, real-world objects including their sensors and actuators are exposed as URLS. End users are able to create physical mash-ups by composing personalized services based on physical resources. In

WoT, HTTP is used as an application protocol rather than as a transport protocol, and the blueprint of Resource oriented architecture (Weiss & Guinard, 2010) is followed for exposing the synchronous functionality of smart objects through a REST interface, known as Restful API. In the case of smart grid, WoT allows the use of universally accepted protocols to connect a number of physical objects of a cyber-physical system, such as the smart grid in a loosely coupled and scalable manner.

A WoT framework for smart grid applications needs to augment accepted protocols to deal with some of the specific requirements of cyber-physical systems. Smart grid developers would benefit from a WoT framework that can hide low-level implementation details and provide an application development environment for faster system development (Kamilaris, Trifa & Ptisellides, 2011).

The WoT framework proposed by Dillon et al. 2011 consists of a number of layers from the physical device layer to program interface layer. The layers are: WoT device, WoT kernel, WoT overlay network, WoT context and WoT API. The WoT framework is above the physical interface such as sensors, actuators, which interact with the physical environment. A WoT framework allows the web world to control the physical world using the data to perform smart tasks such as the smart energy management considered here. WoT device provides a resource based abstraction for the devices. Each physical device is modelled as a WoT resource that has a universal identifier, name and a state. The pervasive REST architectural style promotes the use of Resource as a first-class object and entities are modelled as resources, which can act both as clients and servers (Fielding, 2000). WoT kernel provides a low-level runtime for communication and management of WoT resources. WoT kernel is responsible for detecting newly connected or disconnected physical devices and their resources. WoT overlay network provides a network aware logical abstraction on top of the current internet architecture such as TCP/IP. WoT context discovers and constructs contextual information from the event stream in the overlay. WoT API provides abstractions that allow developers to interact with the WoT framework. WoT resource is the abstraction unit. Application developers can interact with each WoT device.

We have shown in this paper how WoT can be successfully implemented for the integration of a household to a smart grid.

A Smart Home in a Smart Grid

Figure 2(a) shows a smart home in Melbourne, Victoria, Australia, that has solar panels installed on the roof for local electricity generation and batteries for energy storage. The house in Figure 2 (a) has many electrical loads (1 - 6) made up of light loads (lights, computers, radios etc.) and heavy loads (plasma television, fridge, microwave cooker, washing machine, clothes dryer etc.). We have assumed in this study that gas is used for other loads, such as heating and producing hot water.

The house also has a set of batteries with a storage capacity of 300 Ampere-hours that can be charged from the mains or from solar panels. A smart inverter system is used to convert the DC power generated by the solar panels and the DC power delivered by the storage batteries to AC for connection to the 240V AC grid and the loads in the house. The smart inverter also has an inbuilt charger to charge the 24V battery system.

The house meets its electricity requirements from both the electricity grid as well as the grid-connected solar system. Electrical power can also be drawn from the storage batteries to meet some of the loads of the house as and when needed by the household. A smart meter, shown in Figure 2(a), connects the electricity system in the house to the smart grid.

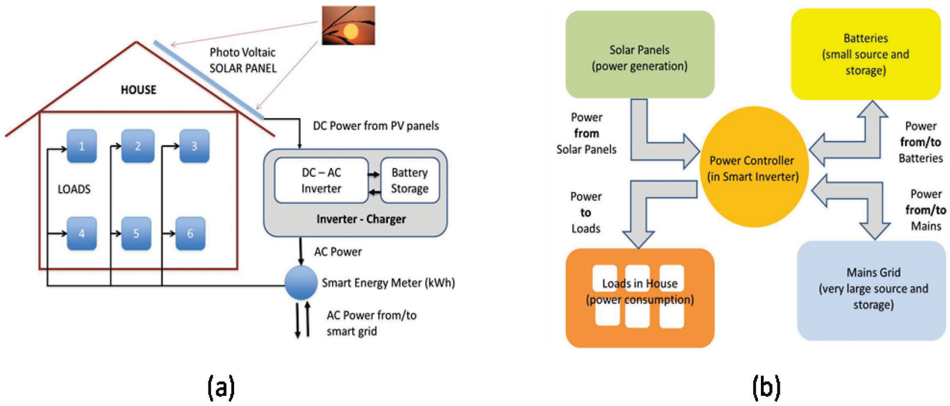


Figure 2(a) Smart home connected to a smart grid and (b) Power flow schematic

The flow of power between the grid and the house, and the power flow within the house are illustrated in Figure 2(b). It can be seen that the power controller in the smart inverter, which is connected to the grid via the smart meter, plays a pivotal role in controlling various power flows. When sufficient power is generated by the solar panels, the controller is programmed to make the power from solar panels flow to the loads, and any solar power in excess of the connected loads is exported to the grid. When solar power flows into the grid, the smart grid looks like a storage system of very large capacity. Or, solar power may be used to charge the batteries, thus enabling storage of energy locally. The inverter may also be controlled to charge the batteries from the mains. Furthermore, the inverter may be controlled to supply the stored energy from local batteries to some selected loads in the house. The control of the inverter is determined by the energy management strategy adopted by the householder using WoT for the smart grid.

System Architecture

The architecture for the cyber-physical system considered in the context of a smart grid is shown in Figure 3. The system architecture consists of three layers as shown below.

Physical appliances and their sensing and control using LowPan smart plugs are included in Layer 1. The smart plugs communicate with a dual router (2) which acts as the Gateway Layer. Application Layer (3) enables householders to acquire relevant information from the web and visualize their power consumption in various formats on desktop or mobile devices. The smart home network is linked to a smart meter and smart grid.

In Victoria, Australia, all households are being connected to the power utility's smart grid via a smart meter. Smart meter uses the utility cloud to record energy usage by the household for billing purposes. As part of the smart grid strategy, the utility is able to provide information on total daily energy consumption to the customer and the cost of electricity for the grid at any given time of day. But it may not be able to measure or control of power consumption by individual appliances in a household owing to privacy laws. However, the WoT approach enables the householder to obtain detailed energy usage profiles for individual appliances in a home, and thus empowers the householder to use such information together with the information from smart meter to manage energy usage at the household level.

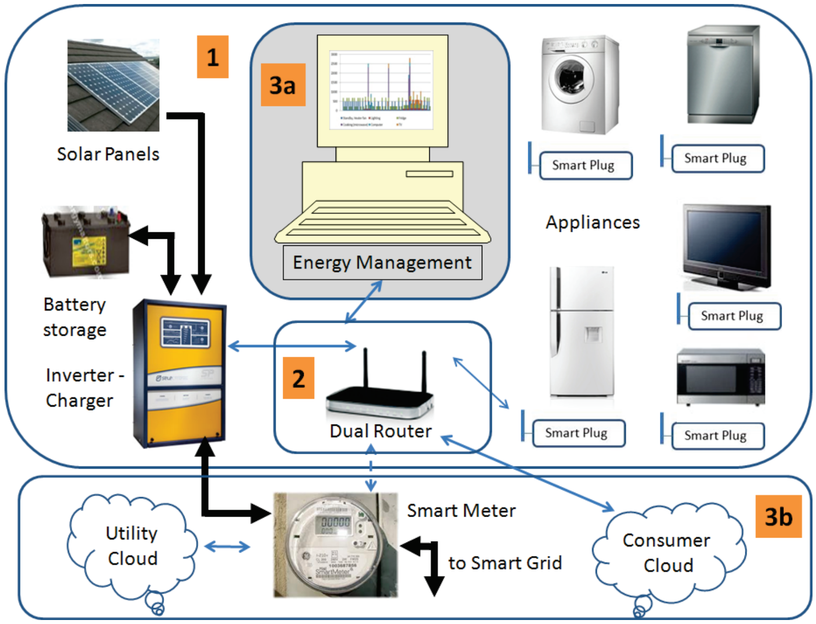


Figure 3 System Architecture
Layers: 1. Application sensing and control; 2. Gateway; 3. Applications

Appliances Sensing and Control Layer

Appliances Sensing and Control Layer provides interconnection between individual appliances or loads and power generating, energy storage and control devices (solar panels, batteries and inverters) in the home to the gateway by providing information back and forth on the measured power and energy as a function of time. The layer also provides appropriate control information to manage the operation of individual devices. Regulations do not allow customers to install a sensor on the metering system of the utility-grid because the metering system is an accurately calibrated system that is owned by the utility.

Monitoring the power consumption of individual appliances is possible with smart sensors or smart plugs. They may be plugged into electrical outlet to measure the power consumption of a connected appliance in real-time and/or monitor it over a longer time frame. It can also provide signals to control the power consumption of individual appliances remotely over a network. Its internal clock allows the computing and monitoring of real-time energy rates as well. A smart plug or sensor is based on Zigbee wireless standard (IEE802.15.4), which is gaining acceptance for home energy management because of its low power consumption. The sensor stores the measured electrical consumption data and wirelessly transmits the information to a gateway.

Gateway and Applications Layer

Smart plug nodes are discovered and manipulated by the gateway with the software installed on the device with Zigbee communication capabilities as shown in Figure 3. The Gateway software makes the information available as web resources. The gateway includes a micro web server, which enables access to individual appliances over the web, and allows the management of the appliances as structured URLS in a RESTful style (Kamilaris, Trifa & Pitsilledes, 2011).

The Gateway software delivers the information on power and energy consumption of appliances to the Application software, either as JSON (JavaScript Object Notation) documents or as HTML representation. A RESTful web API, developed as part of the Gateway layer web API is a web service, hypertext driven and supports operations using HTTP methods (GET, PUT, POST, DELETE) and supports media types such as JSON (JavaScript Object Notation), XML etc. The Application aspect shown in the architecture (Figure 3) enables the user to visualize energy usage information in various formats on a desktop or on a mobile device from the web. Modelling for context and for activity is combined as user preference in the user interface. The contexts under consideration in the energy management system are: weather, month, time of day, location (at home, away from home) etc. At the request of the user, the application may display the power consumed by individual loads or solar power generated over a day or energy storage values (Ramakrishnan & Ramakrishnan, 2012).

Smart Home Energy

Loads, Solar Generation and Energy Storage

Various graphs such as profiles of electric power in a smart home with user interfaces displaying distributed intelligent decision support system on the web are built on top of RESTful API offered by smart gateway as a WoT for energy management in a smart home. Figure 4 shows an example of the profile of power consumption of the household loads as a function time of day over a 24-hour period. We have shown in Figure 4 only those loads which are used every day on a continuing basis. Typical profiles of the electrical power generated over a 24 hour day by the grid-connected solar panel are shown in the same figure for summer and winter seasons. The solar panels are rated to deliver a maximum power of 1.2 kW.

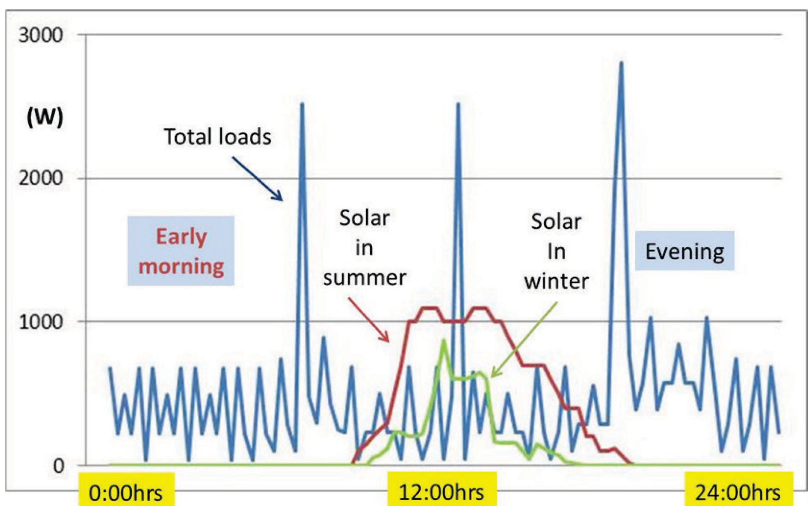


Figure 4 Profile of electrical power associated with the smart home over a 24-hour day

Electrical power is measured in watts (W), and represents the rate of flow of energy. The practical unit for electrical energy is kilo-watt-hour (kWh), which is 3,600,000 Joules (Watt seconds). Hence, the energy consumed over a day by the loads or generated by the solar panels is given by the area under the power curves of Figure 4. The calculated energies over a day using the measured values of power corresponding to Figure 4 are: Energy consumed by loads: 11.29 kWh; Solar energy (summer): 6.1 kWh; Solar energy (winter): 2.04 kWh. These energies may vary depending upon the usage of appliances, season and weather.

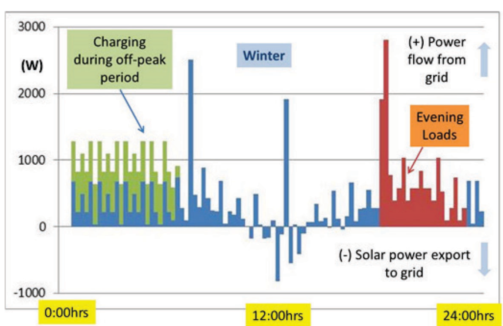
Energy Cost and Greenhouse Emissions

The cost of electricity to a household is based on the energy consumed by the household from the utility grid over a billing period, and so is the greenhouse emission for the household. An energy meter integrates over time the power drawn from the grid to give the amount of energy consumed over a billing period. Currently, some utilities charge a household for the energy consumed from the utility grid at 26.29 cents (Australian) per kWh when the power is consumed during peak hours of 7:00 am to 11:00 pm and at 11.87 cents per kWh for off-peak consumption. The household is compensated by a feed-in tariff for the solar energy exported from the house to the utility. This rate is used to reduce the amount in customer's bill for electricity usage. This can be seen as an incentive to promote a responsible lifestyle. However, the feed in tariffs in the different states of Australia vary from a very low disincentive value of 7.7 cents/kWh to an incentive value 70.4 cents/kWh.

The energy consumed by a household from the utility grid is produced using brown coal in Victoria, and thus has associated greenhouse emissions. In Australia, typical values of greenhouse emission for electricity generation from coal vary between 0.8 - 1.33 tonnes CO2 equivalent per MWh of electrical energy generated (Talberg, 2011). We have used a value of 1.33 kg CO2 per kWh energy drawn from the grid.

Energy Management Strategy

Energy management in a smart home is about controlling the flow of power over a day between household loads, the grid, solar panels and the battery storage (Figure 2(b)) in order to have a desired lifestyle at reduced electricity cost and emissions (Nouri & Keane, 2010). Referring to Figure 4, the profile of power consumption by loads has a peak during the evening period, from 6:00 p.m. to 11:00 p.m., when the microwave stove (~1500W) is used for cooking and a large TV (~250W) are used in addition to the fridge and lights. In our case, the energy consumed during this portion of peak period is 3.625kWh.



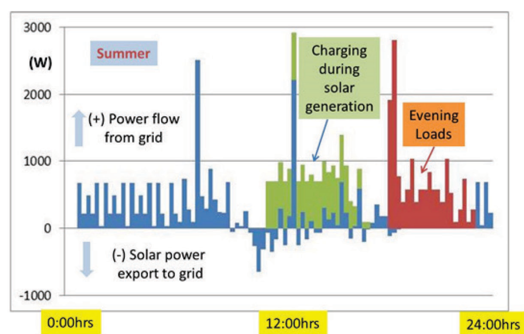


Figure 5 (left) Power flow option 1 of charging batteries during off peak period (12:00 midnight – 7:00 a.m.); (right) Power flow for option 2 of charging batteries during solar generation to supply evening loads

Figure 6 gives results of cost and greenhouse emission for a variety of scenarios based on 2 options shown in Figure 5. One option (option 1) is to draw this amount of energy from the storage batteries, which are charged during the off-peak period between 12:00 midnight and 7:00 a.m. The second option (option 2) would be to use the solar energy to charge the batteries if there is sufficient solar generation. The second option may be applicable only during summer. The results of power flow for these two options are shown in Figures 6.

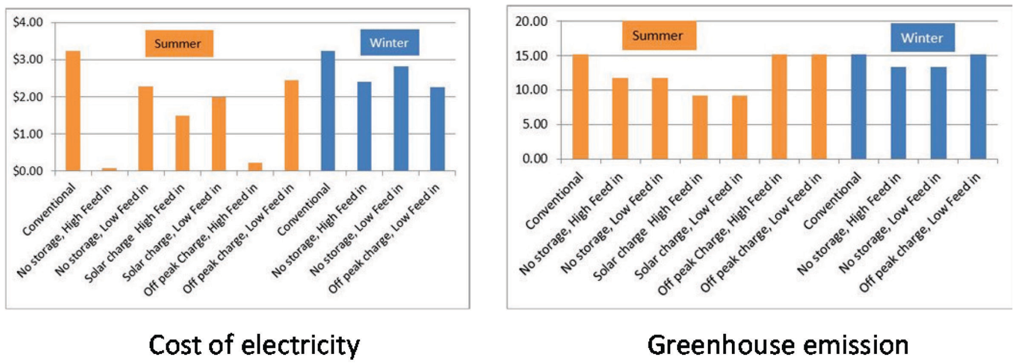


Figure 6. Cost and greenhouse emissions for various scenarios
(Conventional in the figure represents a home with no solar and no storage)

Conclusions

We have presented a system based on Web of Things (WoT) for energy management in a home in Australia that has smart grid-connected solar panels for distributed electricity generation and batteries for local energy storage. In order to reduce costs and/or greenhouse emissions consistent with smart-grid ideas, a dynamic adaptation has been considered of the energies derived from the power grid, local solar panels and local storage batteries for powering the house. With a focus on a cyber-physical software system that incorporates web-enabled physical devices and RESTful APIs, we have shown that the WoT approach is well suited for monitoring, integrating and controlling electrical appliances in a household to facilitate management of electrical energy consumption. It has been shown that WoT has a critical role to play in transforming the fine-grained power consumption data from smart grid-connected smart homes into an intelligent decision support system for reducing energy costs and managing energy generation and utilization.

Our paper shows a case study of web strategy for energy management at the household level to act locally while thinking globally to make sustainable living a reality. We believe that the WoT technology, such as the one described here, is a first step in the incremental transformation of the existing grid into the future integrated vision of smart grids. More sophisticated decision support systems must be developed in the future to provide transparency of the decisions taken by the smart grid by offering explanations in a user friendly manner.

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