Toward Developing a Distributed Autonomous Energy Management System (DAEMS)*

Adnan M. Abu-Mahfouz[1]
[1]Advanced Sensor Networks Research Group
CSIR Meraka Institute
Pretoria, South Africa
A.AbuMahfouz@ieee.org

T.O. Olwal[2], A.M. Kurien[2] and J.L. Munda[2]
[2]Department of Electrical Engineering
Tshwane University of Technology and French South African Institute of Technology
Pretoria, South Africa

Karim Djouani[2,3]
[3]Department of Electrical Engineering
Université Paris Est Créteil
Paris, France

***Abstract*— The design of innovative technological instruments and frameworks for smart energy management is a challenge for countries across the world, and the creation of a 'Smart Grid' still has unresolved research and development (R&D) problems. Distributed energy resources (DER) are a promising approach for renewable energy generation and encouraging wider participation in the green economy. To successfully implement DER, however, we still need to consider several issues that would benefit from applied research. In this paper, an evidence base for the expansion of the green economy will be introduced through R&D of a distributed autonomous energy management system (DAEMS). The DAEMS is envisaged to be self-organising, scalable and a reliable component for energy trading, client-side usage optimisation and DER management. Therefore the focus of this project will be on creating a technical platform for facilitating energy trading, thereby creating an energy market and empower consumers within the green economy, formulate algorithms for client-side energy efficiency, and find methods for real-time DER management in terms of energy consumption, generation and connectivity**

Keywords*— *Energy management system; renewable energy; energy efficiency; distributed autonomous systems; energy trading agent; DAEMS; distributed energy resources; smart grid

I. INTRODUCTION

The electricity supply industries of Southern Africa are dominated by the State owned utility of South Africa, ESKOM. ESKOM generates around 60% of the electricity produced in the whole of Africa. This is achieved by using 20 power stations to provide about 95% of South African electrical power. Out of the supplied power, 89.1% is from coal-fired generating plants. It is estimated that demand for power will increase at a rate of 1000 MW per year [1], which shows the need to increase ESKOM's generation capacity or looking for alternative energy sources. ESKOM has a massive R350-billion new-build program (Medupi, Kusile and Ingula) to fulfil the increase in power demand. However, this program is facing several challenges, which include the issue that it is two years behind the completion schedule and it incurs significant cost overruns; on-going labour unrest; violence and destruction of vehicles, plant and equipment [2]. On the other hand, the capacity shortages have been compounded by the decline of the produced power of the existing old stations.

These problems have serious implications for the electricity supply in South Africa. Moreover, relying mainly on coal-fired generating plants has a high negative impact on the environment due to carbon emissions. These problems create a need to build renewable distributed energy resources (DERs) instead of large, centralised generation plants. DERs require less time and money because of easy to install and low cost to procure equipment as compare with macrogrid based power systems. On the other hand, the building of the DERs require less money from the government assuming that the consumers will invest on such DERs and gain a return on the investment (ROI).

Deploying a huge number of these DERs requires a distributed autonomous energy management system (DAEMS) to manage and control them efficiently. The main functionality of such a system is to

- Generate renewable and clean energy at grid sites (potentially end users/prosumers);
- Reduce energy consumption on the grid sites (manage local supply/demand);
- Allow for real-time pricing, and energy trading between DER sites and between DERs;

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- Facilitate communication among system components with each other and with the back-end office.

All these functionalities, in one way or another, will support the transitioning of the South African economy to a low-carbon, resource-efficient and climate-resilient growth path. This is in line with, the President of South Africa's commitment for South Africa to achieve a 34% reduction in carbon emissions by 2020 and 42% by 2025. DAEMS will contribute to the achievement of this commitment by focusing on the research of renewable energy, energy efficiency and demand side management.

II. RELATED WORK

The focus of this section will be on reviewing the literature related to the energy trading agent and the real-time energy consumption management.

A. Energy trading agent

Energy trading algorithms are seen as a key software component in Smart Grid systems. These algorithms will ultimately be responsible for maintaining the fluctuating supply and demand sources, managing energy brokering in the process.

A key component of Smart Grid algorithms is the "agent". Smart Grid agents are described by [3] as intelligent entities with the ability to communicate with other agents in a cooperative manner. Agents automatically manage the energy of an underlying system that either learns or optimises energy transfer based on known or predicted information. These agents are used in energy management systems to model the interaction between real world entities with defined characteristics. An example of such a system is given in [4] where the market interaction is simulated by agents arranged in a logical tree structure.

The authors of [5], [6] identify three key Smart Grid agents. *Gencos* produce energy and is commonly used to refer to generating entities. *Gencos* only supply electricity in contrast to prosumers, which are able to supply as well as consume. This term is usually associated with residential and industrial entities with the ability to integrate renewable energy sources into the Smart Grid. Buyers do not have any generating ability and can only consume electricity, usually at a fixed cost.Several different approaches to implement agents exist and are based on well-known theories as well as abstract concepts developed from simulation models.

Game Theory can be used in Smart Grid systems to address demand side management as discussed in [7]. An example of such an implementation is given in [5] where agents interact based on game theory strategies to enable real-time energy trading.

A Fuzzy Logic based learning solution is given in [8] where a contract market is used to implement a bidding system between *gencos* and prosumers. Reinforced learning algorithms are used in [8], [9] allowing Smart Grid agents to learn based on environmental interactions.

A double auction model is introduced in [10] where *gencos* and prosumers submit bids to a central auctioneer. The auctioneer averages the bids to a common market price that is accepted by both parties as the common trading price. The paper also discusses a transactive market where end-user agents automatically adjust their consumption based on pricing signals. Similar algorithms are discussed in [11] where mixed-integer linear programming theory is used to optimise the demand response model associated with loads measured in a smart home.

Work done in [12] uses a stock exchange model over a discrete time period to implement similar functionality to the auction based models. The proposed system submits energy usage orders to the central stock exchange through the use of agents, which in turn is used to determine the electricity price for the given discrete time period.

Genetic algorithm methods are combined with weather forecasting models in [13] to optimally schedule the supply electricity to a micro grid load. The solution extends the existing smart agent concept by including the impact that weather has on a solar power system.

Various methods of implementing Smart Grid agents were introduced; all based on simulation or partial implementation outside of a multi-agent Smart Grid echo system. It is the aim of this research project to evaluate and implement suitable Game Theory, Fuzzy Logic, double auction and stock exchange models, for suitable implementation as *genco* and prosumer Smart Grid agents; identifying and addressing the intercommunication challenges amongst these agents when implemented within the DAEMS environment where decentralised authorities and renewable energy sources exist.

B. Real-time energy consumption management

The authors of [14] propose a pervasive network architecture consisting of appropriate home network interfaces and service logic to allow home users perform personalised, pervasive programming of the energy consumption of home devices by enabling real time monitoring of energy consumption in both active and stand-by modes. The optimised architecture implemented a residential gateway aimed at setting thresholds of energy consumption at home via an energy management device (EMD) and thus rationalise energy consumption to benefit the residential user. It also meant to monitor the energy consumption of large residential areas via an EMD and thus optimise energy generation to benefit the power distribution network operators.

Reference [15] examines energy-efficiency issues of heterogeneous radios with different capabilities and interfaces on a single sensor node platform. Through a detailed experimental study on hardware multi-radio platforms, using 802.15.4 and 802.11 radio technologies, it has been shown that a proper pairing of processor and radio is crucial for taking the full advantage of the energy efficiency of higher bandwidth radios. This can be achieved through a decoupling bridge that implements an asynchronous interface for communicating at maximum speed with any type of process, and on the other hand provides efficient high-speed implementations of different radio interfaces.

The authors of [16] present a novel foraging-inspired radio communication energy management strategy known as the FIREMAN method aimed at optimising the transmission energy allocation and saving in multi-radio networks. The energy manager mimics a solitary biological forager in an ecosystem, which is making optimal decisions that maximises its nutrients gain, survival probability and lifetime in a random environment. In order to model, estimate and control the power consumption among network devices, the authors of [17] have invented a computer-based processing system (e.g., host server), which receives historical device operation information (power consumption data) collected during the operation of the remote battery-operated device in accordance with a first set of operating parameters. The processing system calculates an observed battery life for the device based on the received historical power consumption data and a power capacity value representing the power capacity of the battery resident in the device.

Cherian, Keogh and Pacific [18] have disclosed a system for dynamically managing and controlling distributed energy resources in a transmission and distribution power grid. Multiple regions within a transmission/distribution power grid are autonomously managed using regional control modules. Each regional control module oversees the management and control of the transmission/distribution power grid and is further associated with a plurality of local control modules that interfaces with distributed energy resources within a region. Power production and power consumption are monitored and analysed by the enterprise control module, which, upon determining that power consumption within a region does not match power producing capability, dynamically reallocates distributed energy resources throughout the grid keeping the system balance.

In order to contribute to a pervasive network architecture powered by a local battery bank, charged by renewable energy sources and the power grid network, the eCOMBAT (an intelligent energy consumption combat module) module [19] will be customised to implement DER and main grid energy consumption system of real time users. The eCOMBAT was initially designed to measure energy consumption of communication devices in a pervasive environment and not in tailored to a micro-grid energy generation, storage and use system. This DER and main grid energy consumption management system will autonomously compute optimal energy consumption by aid of distributed devices in the network based on a pre-set threshold load condition and the battery bank's discharge characteristics. The amount of energy saved in the battery banks arising from the break-even between the amount discharged and consumed will be traded back into the power grid network operator. The aggregate power data will be communicated remotely via energy-efficient enabling technologies such as optical wireless communication, TV white spaces network and Wi-Fi back-haul infrastructure.

III. DAEMS SYSTEM

The proposed distributed autonomous energy management system (DAEMS) is shown in Fig. 1. DAEMS consists of the following components, which will be explained in this section;

- System infrastructure;
- Energy trading agent;
- Energy consumption management module;
- Energy efficiency improvement techniques

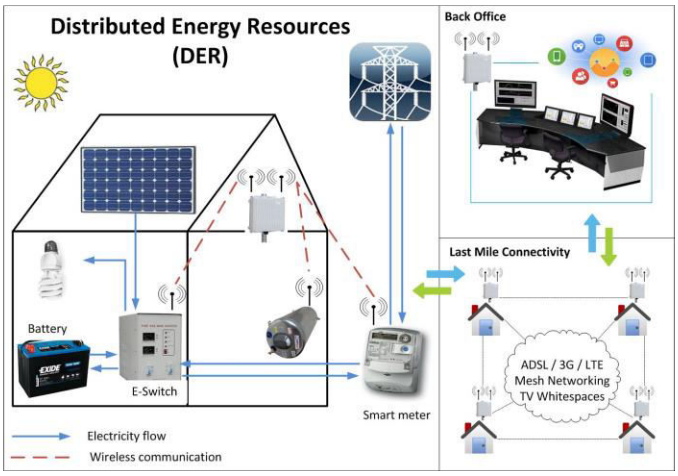

Fig. 1. distributed autonomous energy management system

A. *System infrastructure*

System infrastructure consists of the following

1) Gateway

The gateway device is the main control and communications module of the system and will implement the functions below:

- Communicate with the various components of the system (interface to home/site).
- Coordination of intelligent activities related to device control in the home/at a site
- Hosting an energy trading agent, an energy consumption management module and various energy efficiency techniques

Fig. 2 shows the developed gateway device, which enables Local Area Network (LAN) connectivity and two types of wireless connectivity; 802.11 (Wi-Fi) and 802.15.4 (6LoWPAN mesh). The Wi-Fi access point is used to connect Wi-Fi enabled devices to the internet and local network. The 6LoWPAN mesh is used to communicate with various low power sensing and actuation devices. The gateway is based on RaspberryPI that enables the hosting of various software and algorithms, such as network monitoring software and energy trading agent. The readers can be referred to [20] for further technical details of the developed gateway.

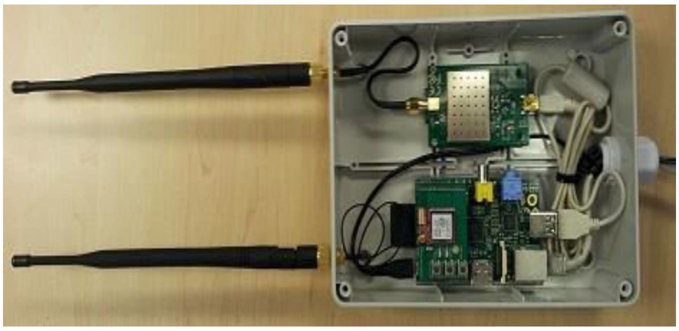

Fig. 2. Gateway device

2) Energy switch

The energy switch will implement all functionality relating to the physical transfer, metering and detection of energy. The main energy switch functions are listed below.

- Bidirectional energy metering
- Manage renewable energy harvesting
- Manage the interconnection and transfer of energy between the grid, appliances and renewable energy sources.

3) Solar power system

We considered the use of Microcare solar power system, which is manufactured by a local South African company called J&J Electronics [21]. Fig. 3 shows the solar power system that will be used in this project. This system consists of the following components:

- **Grid Tied Inverter (GTI):** The GTI feeds all of the power available from the solar panels to the AC Load. If the GTI is producing more power than what is required by the AC Load then the excess power will be used to charge the batteries. If the batteries are full, then all excess power will be exported to the grid. If the grid fails then the GTI will turn off until the grid comes back on line then the GTI will export the excess power back again.
- **Bi-directional Inverter (Bi-inv):** The Bi-inv controls the power flow in the system. Various options can be used to control the operation of the Bi-inv. If the grid fails the Bi-inv will draw power from the battery to supply the AC load. When the grid is on line, the Bi-inv will continue to supply all the power to the load from the batteries as long as the battery voltage is greater than "Battery run to" voltage selectable in the programming menu. If GTI produces power it will supplement AC load and reduce the power drawn from the battery. If GTI produces more power than what is required by the AC load, the extra power will be converted by the Bi-inv to charge the batteries or exported to the grid. If the battery voltage falls below the selected "Battery run to" voltage then the Bi-inv will synchronise with the Grid then transfer the load and GTI to the grid. The Bi-inv starts charging the batteries either using the power produced by the GTI or from the grid.
- **Smart electricity meter:** normal electricity meters are not aware of the direction of power flow. They will charge for power in both directions. Therefore, a smart electricity meter is needed to avoid this problem. On the other hand it will enable us to remotely monitor and control the meter.
- **PV array and Batteries**

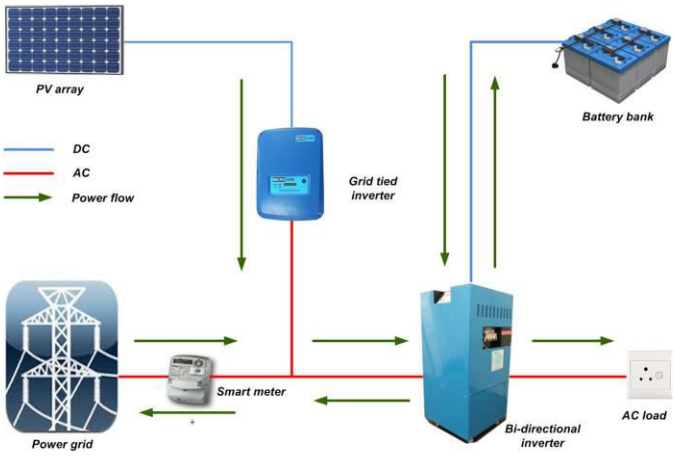

Fig. 3. Solar power system

In addition to the control options provided by Microcare power system, we will implement a new control mechanism that based on the energy trading agent. The new mechanism will increase the financial profit of such DER by identifying the best time to sell the electricity back to the grid.

4) Sensors

These include environmental sensors, smart plugs and other sensors that will be deployed in the home/at a site to help in energy efficiency improvement. One of the main sensors is the interface sensor node that will be attached to the solar power system, mainly to the Bi-directional inverter and smart electricity meter. These interface sensor nodes will enable the monitoring and control of the solar power system. The interface sensor nodes will communicate wirelessly with the gateway devices using 6LowPAN mesh. The status of the system and the power consumption could be send to the back-end system (or central authority). The back-end system could send control signals to the solar system, for example to switch the electricity off to disjoin this DER from the grid. On the other hand the gateway device will be able to send a command based on the energy trading agent to control the power flow in the system.

5) Communication infrastructure

Several wireless communication technologies will be used to allow the system components to communicate with each other efficiently, which are

- Between the gateway and the sensors: e.g. Bluetooth, WiFi, and/or IEEE 802.15.4
- Between the gateways in the same area: Free space optic (FSO) or IEEE 802.11
- Between the gateway and the back-end system: TV white space, WiFi or ADSL

B. *Energy trading agent*

One of the key assumptions underpinning the vision of such DERs is that it will have an energy trading agent to manage the trading of electricity between homes and DERs, while coping with the inherent real-time dynamism in electricity demand and supply. Participants will consume, and potentially generate, electricity and then any surplus can be traded to other participants. This trading agent should consider that the participants in the system have their own agendas based on their self-interest. This means, they may misrepresent their preferences to maximise their profit. For example, the amount of electricity required the capacity they can supply and prices they would accept. Currently, several strict regulation and audits are used to mitigate such kind of problem. However, this approach would be impractical if every household is a potential supplier and/or consumer. In the proposed DAEMS, we will implement an efficient energy trading agent that will handle these requirements. The DAEMS is therefore a platform for enabling a complex energy trading marketplace, with the end-user being able to adapt the system, i.e. install 'apps' on his system gateway, to join a specific broker or co-operative. The advantages of using agents in a DAEMS are:

- Smart Grid agents allow complex Smart Grid distribution and control problems to be solved in a decentralised manner;
- Agents eliminate possible single points of failure due to their autonomous nature with in the Smart Grid;
- The use of agents reduces human interaction, improving the system ability to adapt to dynamic energy transfer events;
- Energy trading agents are independent and autonomous authorities, enabling the estimation of energy trading costs without interference from 3rd parties.

Unlike the existing work, which is based on simulation or partial implementation, the implemented energy trading agent will be deployed in a real world solution, capable of implementing the body of knowledge contained within this agent.

C. *Energy consumption management module*

In order to save the power delivered by the battery bank to the residential appliances and thereby supporting efforts of the energy trading agents aimed at a reasonable economic value, a real-time energy consumption monitoring and management module (eCOMBAT module) [19] will be customised in the DAEMS to support the energy-efficiency programme linked to the renewable energy supply chain. The eCOMBAT mechanism will monitor in real-time the battery bank's energy charge and discharge behaviours, optimally minimise the energy consumption behaviours of multiple domestic appliances so as to create a substantial energy saving for the trading agent. Moreover, it will also manage the energy consumption in the communication infrastructures to the back-end office.

D. *Energy efficiency improvement techniques*

Several energy efficiency programs have been used to help customers save energy and to reduce the energy consumption during the peak-hours. For example the "Power Alerts" have been used to appeal to residential household consumers of electricity to change their consumption patterns based on Power Alert broadcasts on national television. The Power Alerts are structured in such a way to minimise the discomfort and inconvenience to the public whilst empowering the public to avoid power interruptions. The success of the Power Alerts does however depend on the participation of the public, who has to switch off some appliances based on the alert level.

The "Utility Load Manager (ULM)" system [22] is acting when Eskom experiences severe system overload. When the power utility has a supply or network constraint, a message is sent to the display unit instructing the household user to limit power usage. If the household continues to exceed the limit in terms of power usage, it is automatically disconnected from the electrical network. The household can then SMS to a specified number and be reconnected for a few minutes to conform to the imposed limit, or will be cut off again for non-conformance. National implementation of the ULM system to more than 8-million residential customers will displace in excess of 6750 MW of load during network constraint periods.

In the proposed DAEMS, we will develop dynamic demand side management techniques with the objective of achieving energy efficiency and acting in crisis situations to avoid electricity interruptions. Our techniques will complement the existing energy efficiency programmes. However, it will have the following unique characteristics:

- The existing programmes rely mainly on the participation of the people to be successful. Our programme will minimize the required human interaction and will act autonomously and dynamically, while being sensitive to end-user privacy and autonomy of their home.
- Several programmes try to reduce energy consumption only when there is a supply or network constraint (e.g. during the peak-time). Our technique will not only consider this but also it will save energy during the entire day.

Another method to encourage consumers to save energy and avoid electricity interruptions is by enabling dynamic pricing programmes. Generally, these tariffs take the following forms:

- **Time of use (TOU)**. Under TOU, prices are differentiated based solely on a peak versus off-peak period designation, with prices set higher during peak periods. TOU pricing is not dynamic because it does not vary based on real-time conditions.
- **Critical peak pricing (CPP)**. Under a CPP tariff, the higher critical peak price is restricted to a small number of hours (e.g., 100 of 8,760) each year, with the peak price being set at a much higher level relative to normal conditions.

- **Real-time pricing (RTP)**. Under RTP, hourly prices vary based on the day-of (real time) or day-ahead cost of power to the utility.

In our system we will develop a real-time pricing technique based on a day-ahead forecasted national demand that well be provided by ESKOM. As shown in the Fig. 4, the forecast demand is displayed in half hour intervals [23]. Based on this chart our RTP technique will provide different pricing for each half hour in the day. Again based on the RTP the system will dynamically switch on and off the appliances in such way to benefit the consumer (reducing the electricity bill) and as a result save energy.

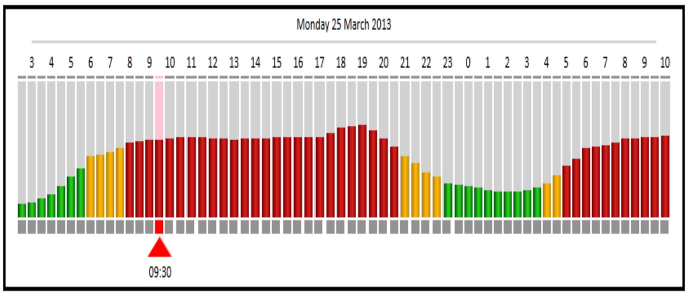

Fig. 4. Forecast national demand [23]

IV. Conclusions

One of the most important challenges that face several countries across the world is the creation of the "Smart Grid". This is because the creation of Smart Grid covers a broad array of energy system capabilities and services enabled through pervasive information and communication technology (ICT). These capabilities and services are aimed to fulfil several objectives that will require addressing several research challenges, such as the distributed energy resource (DER) protection, managing storage devices, interconnection standards, robust energy delivery, efficiently managing and controlling the DER, energy trading issues and system security. These significant challenges could be addressed through a distributed autonomous energy management system (DAEMS), which reliably interconnects DERs and is self-organising and scalable. This paper explained the major components of DAEMS system and highlighted the benefits of these components.

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