A Systems Approach to the Smart Grid

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***Abstract*—This paper presents the case for using a systems approach to analyse the requirements and behaviours of the Smart Grid as well as designing relevant solutions. By linking systems thinking to agent-based modelling, we discuss how a Smart Grid can be modelled as Multi-Agent Systems by reviewing some related state-of-the-art research. This paper goes on to outline two research areas that we are developing, namely, demand response using dynamic pricing and emergent behaviours of a Smart Grid.**

***Index Terms*—Systems Thinking; Agent-Based Modelling; Smart Grids;**

I. Introduction

As the world pushes towards a more sustainable and resilient electrical supply there is a shift towards smart technology to revolutionise the electricity market. In Europe, one target of the Strategic Energy Technology (SET) Plan [1] states that by 2020 the grid should be able to integrate up to 35% renewable electricity effectively matching the demand to the supply. The European Technology Platforms Strategic Deployment Document for Europe's Electricity Network of the Future [2] quotes the International Energy Agency in approximating that EUR 500 billion will be invested by 2030 in electric grids. Without the use of smart technology this expenditure will not be used to move away from conventional centralised generation and distribution that is characteristic of todays electricity market. The smart technology in this context includes but is not limited to smart-meters, electric-vehicles, distributed storage, micro-generation, and bidirectional communications networks. Also, a shift towards distributed generation and grid optimisation is necessary to combat an increase in energy consumption and alternative energy sources. Clearly this advancement of distribution and generation will make the Smart Grid system and energy industry more complex. Complexity of Smart Grid could be defined as consisting of components which are distributed and interconnected with bidirectional flow of both energy and information. For instance, as the grid gains autonomous behaviour of its components, it will lead to 2-way communication between appliances, households, neighbourhoods, utilities, substations etc. As a complex socio-technical system the Smart Grid is likely to exhibit emergent behaviours suggesting the need for sophisticated theoretical studies now and mitigating strategies during build out.

The concepts of Systems Engineering are well adapted to approaching complex problems and could be beneficial in Smart Grid environments. Further, an agent-based modelling approach, which is a tool in control systems and simulations, is one method of estimating or observing any emergent behaviour. In this paper, we discuss how system thinking and agent-based modelling approaches can be used when tackling the problems of analysing Smart Grid systems, understanding potential emergent behaviours and developing Smart Grid functionalities involving multiple agents.

The paper is organized as follows: Section 2 and Section 3 will discuss the systems thinking approach using relevant concepts of systems engineering, methods and limitations of agent-based modelling. Several examples of applications of agent-based modelling approaches to Smart Grid are discussed in Section 4. Section 5 identifies key research areas for applying the systems thinking and finally formulates the technological problem surrounding demand response and emergent properties.

II. Systems Thinking for a Smart Grid

Acknowledging the electricity sector as being complex leads us to treat it as a 'wicked' problem as defined by Rittel and Webber [3]. Conklin's adaptation [4] of wicked problem characteristics is a useful standpoint from which to view Smart Grid development. Conklin argues that solutions are unique and must be approached that way; Smart Grid solutions may vary by country or even by region.

In this context the design and deployment of the Smart Grid is arguably a wicked problem as a whole and even the Smart Grid sub-systems can be regarded as wicked due to their interactive nature. Conklin goes on to say that while understanding and learning about the problem environment is important and natural it alone does not lead to a satisfactory or timely solution. Alongside study and understanding, experimentation and pilot programmes such as those undertaken by the European Union are necessary. Another way of coping with the complex problem of a Smart Grid is to simplify or tame the situation [4]. This approach leads to a solution more quickly but the conclusion/implementation is short lived as the wicked problem re-emerges. Even if the technology exists for some or all of the Smart Grid (e.g., technical architecture as described in Deployment Priority 1 of the Strategic Deployment Document [2]) the challenge of integrating it as well as understanding the consumers' requirements still remains.

In an early paper, Doyle [5] expresses the lack of controlled research on the effectiveness of systems thinking. He also

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explains that such research would involve aspects of cognitive psychology which would be complicated and time consuming. However such a study would be necessary to determine or quantify the effect of such an approach. In a more recent paper, Maani and Maharaj [6] present an experiment they conducted to determine a relationship between systems thinking and complex decision making. Whilst the study was small in scale and could be viewed as subjective, the results showed that the relationship between systems thinking and complex decision making is not obvious. Its evidence supported the view that certain types of systems thinking may be more suited to improving performance. The authors noted that another evident reason for better performance was the approach taken to a problem; understanding the system structure and relationships (e.g., feedback) as well as observing outcomes of decisions led to better performance.

Taking a systems view encourages a complete solution which would include aspects such as user requirements and cross-system integration.

III. Modelling Smart Grid as a Multi-Agent System

There are various enablers to make the transition from systems thinking to systems modelling whereby quantitative and qualitative understanding can improve. Simple tools such as rich pictures (see Fig. 1) and system maps are used to understand the constituents of the system. A picture can be taken to another level of analysis using a system map which allows boundaries to be defined and system elements to be placed in the correct domains. More formal tools such as Unified Modeling Language (UML) can be useful in describing systems using standardised structure which can be easily understood.

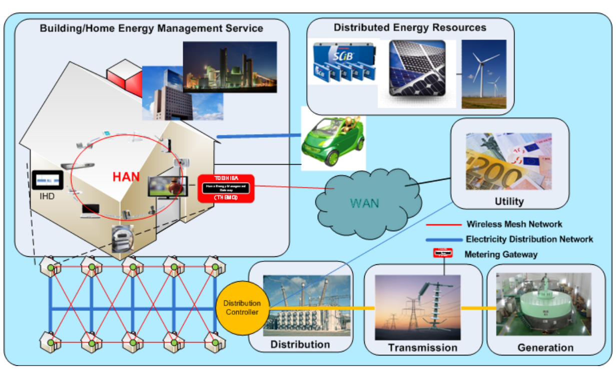

Fig. 1. Component view of a Smart Grid

Agent-based modelling (ABM) can also describe a system by allowing the user to define discrete 'agents' by their characteristics and behaviours. Nwana [7] describes agents as having a combination of the following three characteristics; ability to cooperate, act autonomously and the ability to learn. The specific combinations of these characteristics depends on the function of the agent. The contextual environment for the agents to act in can also be defined. Setting up a simulation in this style is a bottom-up approach as the constituent elements have defined behaviours whilst the system behaviour emerges from the interactions of the constituent agents. This allows emergent properties of a system to become apparent which may or may not have been intuitive.

Whilst ABM creates a useful framework for development of constitutive system elements it is through Multi-Agent Systems (MAS) that agent interactions can be focused on. It is due to these interactions that emergent behaviour arises. Gabbai et al. [8] give a good definition for MAS: *"a collection of autonomous, social actors where, through local interaction and social communication, emergent global behaviour occurs."*

Even agents with simple functions can elicit complex emergent behaviour through their interactions [9]. Albiero et al. [10] apply simple behavioural rules to multiple agents to create collective behaviour which would be difficult to produce using an algorithmic approach. Researchers in various fields have used ABM as a means to simulate intelligence with relative success. This paper suggests MAS as an appropriate agent approach for describing and investigating the Smart Grid domain.

There is a wide variety of software and tools to create ABMs and the remainder of this section contains a brief overview of some popular platforms (NetLogo, MATLAB, SWARM, MASON, JADE).

For small scale ABMs the most suitable platforms include MATLAB [11] and NetLogo [12]. Railsback et al. [13] recommend NetLogo as a user-friendly tool with a large amount of documentation and examples for beginners. Their study [13] shows that even though NetLogo is simple to program and run it can be applied to create sophisticated simulations for a range of domains (see the NetLogo website for examples [12]). However its lack of access to algorithms used by its commands makes reproducibility difficult which can deter some users.

For larger and possibly collaborative simulations it is advisable to use a lower-language simulation tool for example, SWARM, MASON and JADE. SWARM [14] has an active user group and comes in JAVA and Objective-C based platforms. Railsback et al. [13] appreciate its well organised structure but point out that it can be a challenging environment for beginners.

MASON [15] is comparable to SWARM in terms of scale and was written with specific requirements in mind. Luke et al. [15] explain that they required an environment which was able to; run on different operating systems, stop mid-run, have a separate visualization interface and be easily embedded into larger libraries.

The Java Agent Development Framework (JADE) [16] is a popular tool within research carried out in the Smart Grid domain as it is compliant with the standards set by the Foundation for Intelligent Physical Agents (FIPA). FIPA (http://www.fipa.org/) was created as the eleventh standards committee for the IEEE in 2005 and seeks to promote inter-operations of agents and their services.

The decision on which platform to use for ABM or MAS modelling is dependent on several factors including; programming experience of the user, complexity of the model required, portability and the need for collaborative working. For smaller models where a concept is being trialled or a quick prototype is required, NetLogo would be most suited for all types of users. If creating larger, more complex models then a low language platform like JADE might be more appropriate. As JADE has been used in various research papers and is FIPA compliant it is the most appropriate for MAS within the Smart Grid.

IV. Applications of Agents in the Smart Grid

A Smart Grid can be viewed as a system containing various agents. The actual agents used and their characteristics can vary depending on what area is being researched or analysed. The National Institute of Standards and Technology (NIST) has written a report entitled ‘NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0’ [17] which has a useful picture depicting the actors and domains in a smart grid as shown in Fig. 2. This is an overview of domains that could exist in a smart grid and is a good starting point to understand the various stakeholders that exist in this environment.

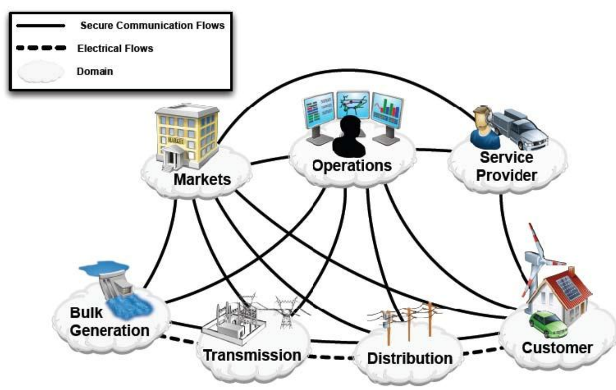

Fig. 2. NIST domains and actors for a Smart Grid [17]

Agent-based designs for Smart Grids have been implemented with Ghosn et al. [18] simulating a self-healing network using JADE. In this example, six agent types were used:

1) Device Agents
2) Distributed Energy Resource (DER) Agents
3) Consumer Agents
4) Intelligent Prevention Control Agents
5) Intelligent Response Control Agents
6) GUI Agents

These agents were chosen as the authors were primarily concerned with self-healing problems associated with an intelligent grid.

Pipattanasomporn et al. [19] discuss a simulation using four agents (listed below) as they focus on controlling a distributed grid as opposed to solely analysing fault finding/fixing:

1) Control Agent
2) DER Agent
3) User Agent
4) Database Agent

The paper focuses on the responsibilities of the control, user and database agents. As well as discussing the theory behind agent functions, they go on to develop a simulation environment to test the agent-based system. The MATLAB/Simulink environment was used to create a simulated circuit which interfaces via Transmission Control Protocol (TCP) connections to the multi-agent system. This demonstrates the capability that exists whereby novel agent-control models can be simulated in a circuit under various conditions (e.g., islanding).

Karnouskos and Holanda [20] give their appliance agents consumption profiles that are based on a survey done by the US Department of Energy. This allows simulation to be based on known consumption patterns to test validity of agent-based control systems. This type of analysis is non-trivial and pivotal to increase confidence in new control philosophies that are required for the future. As the authors state, their agent data is not sensitive enough to differentiate between demand changes through the year, which could be dependent on weather, holidays etc. Enhancements of these simulations can be used to predict possible emergent behaviours that could arise as the grid modernises.

A futuristic paper by Galus and Andersson [21] develops the idea of energy hubs [22] by specifically looking at the recharging of Plug-In Hybrid Electric Vehicles (PHEV). The problem space consists of consumers driving to a workplace and plugging their cars in for charging. Obviously without any control this would lead to a surge in power demand. The authors suggest using a customer preference value (which is unique for each consumer) to indicate how much consumers are willing to pay for electricity. The customer preference value allows the agent to establish the individuals’ perceived benefit of energy and so will start to buy energy only when this is reflected in the price.

The European Union and various partners are involved in a number of field trials in different countries. Each trial has a set objective and timeline associated with it. The aim of running field trials is to develop and test capability that can be used in the Smart Grid. Results are then analysed and published by the partners. Two such trials are discussed; the SmartHouse/SmartGrid (SHSG) project and the Active Distribution networks with full integration of Demand and distributed energy Resources (ADDRESS) project.

The European Union SHSG Field Trials were held in three different countries (http://www.smarthouse-smartgrid.eu/index.php?id=43) and focused on different challenges:

1) *The Netherlands (Hoogkerk)*-This trial has twenty-five interconnected houses which together create a virtual power plant through various devices including smart meters, heat pumps, hybrid vehicles and photo-voltaics. The trial uses agent-based control software to negotiate cheaper power and maximise benefits for the consumers. A major objective of this trial is matching demand and supply from various resources on a mass-scale.

2) *Germany (Mannheim)*-This trial is focused on flexible electricity prices where customers can specify their requirements for device operation through a customer portal.
3) *Greece (Meltemi)*-This trial involves ten cottages in the Meltemi Camp which are predominantly used in the summer. Critical grid operations like islanding and load shedding are being trialled at this small scale.

Agent-based controllers were utilised in Hoogkerk and Meltemi to provide the microgrid with intelligence.

ADDRESS is a project that is founded by the European Commission under the 7th Framework Programme. ADDRESS (http://www.addressfp7.org) focuses on developing and validating solutions to enable active demand. The project started in June 2008 and is planned to continue for four years until 2012. It aims to develop technical solutions at the consumer and power system level to enable active demand. The first project results from 2009 focus on country-specific surveys, scenario (or use case) approaches and conceptual architecture for a smart grid [23]. The survey found the following:

1) The rise in Renewable Energy Sources (RES) is expected to increase the need for Active Demand (AD) services.
2) Energy retailers will be the key agents to deploy AD. The retail market is still linked to the distribution business but there are no significant barriers to decoupling these two functions.
3) Smart meters will be a key enabler for AD development. Individual country approaches to smart meters broadly fall into three categories; one where the regulator has defined standards, one where the private sector has been left to incentivize smart meters, and one where no decision has been made.
4) The low level voltage networks in most European countries have the ability to accommodate the ADDRESS concepts.

The first conceptual architecture to emerge from ADDRESS [23] consists of four main sections as shown in Fig. 3:

1) Aggregators
2) Energy Box - interface between aggregator and the consumer
3) Distribution System Operators
4) Markets and Contracts

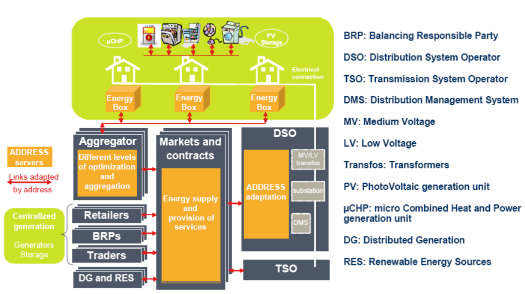

Fig. 3. ADDRESS conceptual architecture [23]

Within this architecture, the aggregators perform an important function as the negotiator between the other sections. The aggregator will collect signals from the market and power suppliers and compare it to data from consumers. Real time price signals and optimisation techniques will be used to meet consumer demand. Clearly an agent-based approach following principles as described by a number of research papers for example Dimeas and Hatziargyriou [24] and Rahman et al. [25] would be suited to this function.

These examples show a variety of agents that can be used to simulate or portray the research challenge from various perspectives. As current trials are utilising aspects of agent-based methods this should aid in increasing confidence of such systems within industry.

V. RESEARCH AREAS

Agent-based methods can be used to create specific technical solutions as well as understand the interactions of various elements. The authors are currently working on two areas:

Specific Agent Based Solutions: Various Smart Grid researchers and organisations are using agents to create solutions for specific Smart Grid applications. The authors are currently developing agent methods to address demand response using dynamic pricing. Game theory will be used as the basis to achieve desired response patterns, for example; a group of households collaborating to reduce their collective peak to average ratio and hence gain a favourable tariff.

Emergent Properties of the Smart Grid: A Smart Grid can be viewed as a system of systems where each system is comprised of a diverse set of passive and active system components; belonging to various stakeholders, that interact with each other to provide a type of service or function. On the distribution side, the low voltage electricity system (from super grid side), energy management systems (e.g. home, building, factory etc), billing systems, micro generation systems and electric vehicle charging systems could be some examples of such systems. Fig. 4 shows the Smart Grid comprising of four systems; Generation, Distribution, Transmission and Consumer. The consumer system is then broken down into a further 5 constituent systems.

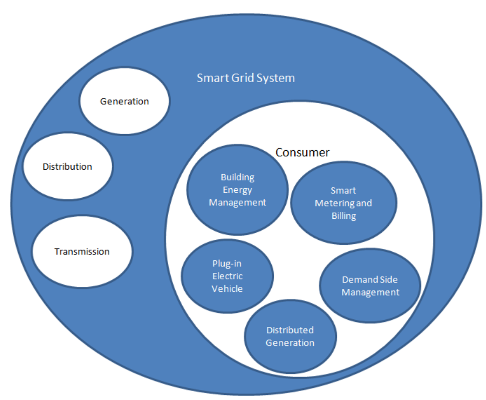

Fig. 4. A system view of the Smart Grid with the Consumer sub-system.

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The design of such systems is an unprecedented task which presents many challenging research and engineering questions. Continuing with the idea of systems within systems, emergent properties resulting from the interaction of such components have not been investigated. The authors propose to undertake research whereby the Smart Grid is analysed from a top-down as well as socio-technical perspective with the aim of discovering emergent behaviour.

VI. Conclusion

Systems thinking helps to increase the understanding of interfaces and challenges in developing a resilient Smart Grid. Complex problems have been addressed using this framework in a variety of fields however there has been no explicit application to Smart Grids. As discussed, the use of agent-based models is suited to both analyses of the system as well as a tool to create practical solutions. Understanding the constituents of this complex system and simulating their collective presence will allow for the design of a Smart Grid with desirable emergent properties. From a commercial perspective this will also provide a rational focus on creating new products and services. Other future research work to be carried out by the authors will be to focus on using dynamic pricing as a tool for demand management. The aim is to model households and the utilities as agents with underlying game-theoretic behaviour. The results will determine the market conditions required and behaviour expectancy of households to produce effective demand management.

VII. Acknowledgments

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