A Systems Engineering Approach to Resolving Structural Barriers to the Implementation of Demand Response

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Abstract— **A principal mechanism for achieving the policy goal of the reduction of greenhouse gas emissions is the widespread electrification of transport and heating coupled with the parallel de-carbonization of electricity generation. This requires a major expansion of renewable generation (principally wind) together with new nuclear and clean fossil. This paper reviews both the policy position within the UK and the implications for system balancing that large-scale intermittent generation, such as wind, presents to the System Operator (SO). One proposal for helping to maintain system balance is the use of Demand Response (DR) by the SO. It is by no means clear whether the existing industrial structure can provide the right incentives for the realization of significant DR capacity. This paper presents a method of classifying barriers and describes experience in developing a Systems Engineering methodology, using the Systems Modeling Language (SysML), as an approach to modeling the structural and operational aspects of the British system with the objective of understanding barriers to the implementation of DR.**

I. Introduction

There is now general acceptance amongst policy makers that there is a need to act on the emissions of greenhouse gases in order to counter dangerous climate change from anthropogenic global warming. In the UK concern over the implications of climate change led to the Stern Review which established the economic case for addressing the issue [1]. This led in 2008 to the UK Climate Change Act that has committed the UK to achieving emissions reductions of 34% by 2020 and 80% by 2050, both relative to 1990 levels [2]. Whilst the 2008 Act does not place targets on individual industrial sectors, the Department for Energy and Climate Change (DECC) has published its view of how individual industrial sectors, including the electrical power sector, might contribute to these objectives [3]. In its 2050 Pathways Analysis it presents the case for achieving these goals through a policy of gradually transferring transport and heating energy demand to electricity whilst simultaneously de-carbonising electricity generation. This is reflected in DECC's Pathway Alpha – which it regards as the most likely scenario – that shows a relatively flat overall energy demand between today and 2050 but a doubling of electricity generation from just less than 400 TWh per year today to more than 800 TWh per year in 2050 [3].

Simultaneously, the pending need to replace aging generation plant has provided the opportunity for a fundamental shift in the nature of the UK's generation mix in favour of low-carbon renewable generation. By 2050 DECC expects the GB system to consist mainly of a mix of renewables, nuclear and CCS plant in roughly equal quantities.

This policy, however, represents a shift in the generation mix away from relatively controllable thermal generation, with its associated buffer store of fuel, to non-thermal intermittent generators such as wind. The existing "predict and provide" demand-led operational model depends on generation being available when it is needed and there is therefore potentially a significant system balancing problem. For example, National Grid, the GB SO tasked with balancing the system, expects that the requirement for balancing services will increase from 3.5 GW today to 8 GW by 2020 [4].

One mechanism that has been proposed for addressing the problem of balancing a system with a large proportion of intermittent generation is to change the operational model from demand-led to generation-led. In such a model it is necessary to exercise a level of influence over demand that has not been implemented before, for example through the use of Demand Response (DR) services. DR services use the inherent flexibility that certain types of demand have to allow the time shifting of energy consumption. DR does not necessarily reduce overall fuel consumption, as might be expected from energy efficiency or energy conservation, however DR does offer the prospect of increased electrical efficiency especially where there is a high proportion of intermittent or inflexible generation. Together DR, energy efficiency and energy conservation comprise a group of low-carbon demand side services [5].

Over the next few decades there is therefore likely to be a significant opportunity for DR. This is recognised by both DECC in its Pathways Analysis and the GB System Operator (SO) [4]. In its recent study into the options for delivering secure and sustainable energy supplies the UK Regulator, Ofgem, has also recognised the need for greater participation from the demand side [6].

It is by no means clear how such an operational change might be accommodated by an industry that has evolved around the existing "predict and provide" demand-led model. It is probable that the existing industrial structure is no longer optimal under such a scenario and may significantly hinder the implementation of demand side measures through the existence of barriers to implementation. The resolution of such barriers requires not only that barriers are identified but also that a mechanism by which structural change might be effected be available.

This paper presents one approach – using Model Based Systems Engineering (MBSE) and the System Modeling Language (SysML) – to the identification of potential barriers.

II. Methodology

The approach presented here has three stages: -

- **Establish a precedent for major structural change:** it is important to establish that radical change is possible before identifying barriers.
- **Determine a classification for barriers to implementation:** correctly classifying identified barriers helps to bound the potential solution space.
- **Define a modeling approach:** to be able to identify and characterize barriers the chosen modeling approach must be capable of capturing the relevant aspects of the system under analysis.

The remainder of this paper discusses each of these stages in turn, beginning with a review of the two major policy-driven structural changes within the GB electricity industry since the Second World War. A framework for classification of barriers to DR follows this before the paper concludes with a description of experience in developing a modeling approach based on MBSE and SysML.

III. Structural Change Within the GB System

The eradication of barriers may involve substantial structural change within the industry. If this is the case, then it is important to understand if such change can be enacted via policy. An examination of the evolution of the UK industry reveals that such radical change is not without precedent.

The UK electrical generation, transmission and distribution industry has, like many around the world, evolved over a great many years. Prior to 1947 it comprised more than 550 separate electricity generation and supply undertakings. After the Second World War the UK Government decided to rationalise this situation through nationalisation. The Electricity Act 1947 [7] created a single Central Authority, twelve Area Boards covering England and Wales, and two Area Boards in Scotland. In England and Wales, the Central Authority was responsible for generation and transmission whilst the Area Boards were responsible for distribution. In Scotland, the vertically integrated Area Boards were responsible for generation, transmission and distribution. In 1957 a further Act was passed [8] that separated the Central Authority into the Central Electricity Generating Board (CEGB) and the Electricity Council. The role of the CEGB was to provide generation and transmission whilst that of the Electricity Council was to oversee the industry.

This structure remained largely unchanged until 1989 when the UK Parliament enacted the Electricity Act 1989 [9]. This repealed the previous Acts and laid the legislative framework for the transition from public to private ownership. The 1989 Act retained the twelve Area Boards but allowed for the transfer of all their assets to new companies. The purpose of the 1989 Act was to introduce competition into generation in England and Wales and to prepare the industry for eventual privatisation.

The 1989 Act and subsequent Acts have fundamentally changed the structure of the industry. The industry today is characterised by a system of licensing and a market-based approach to electricity supply based around the British Electricity Trading and Transmission Arrangements (BETTA), introduced in 2005. Competition, overseen by the industry regulator Ofgem, is today the major driving force in the industry.

This analysis indicates that the industrial structure in existence today is largely a result of technical constraints and economic policy enacted via primary legislation. BETTA, and the New Electricity Trading Arrangements (NETA) before it, is widely accepted to have been successful in driving down the cost of energy to the consumer [10]. The structure of the industry has evolved to provide electrical energy to consumers reliably and affordably whilst engaging private industry to promote innovation. However, it has done this without the constraint of limited greenhouse gas emissions.

This history tells us that there have been two significant and radical structural reorganizations of the British electricity industry, both driven by policy. There is therefore a clear precedent for radical and far-reaching structural change in response to Government policy. Considering this evidence it is not unreasonable to assume that if structural barriers to the implementation of DR are identified through the methodology presented here, and the political will to resolve them is present, then appropriate legislation might be enacted to do so.

IV. Classification of Barriers

Barriers can be defined as those elements of the system that could prevent or restrict the implementation of DR. Such elements might be processes, people, policies, organizations or any of a number of other aspects of the electricity industry. Their origin might be socio-economic, techno-economic or political. Although this represents a complex picture, it is possible to identify three principal mechanisms by which a barrier might manifest itself: -

- **Technical:** Absence of an agreed format, standard or means for the exchange of an essential commodity (e.g. data).
- **Legal/regulatory:** A rule or regulation preventing two parties from exchanging an essential commodity because to do so would breach some legal provision.

- **Commercial:** A conflict arising from the existence of an existing contract or arrangement that acts to disincentivise the use of DR.

The common element to all of these mechanisms is that the barrier arises where two stakeholders are required to establish a relationship. It is at the interface created by this relationship that the barrier occurs. In the first two cases the purpose of the relationship is for the exchange of a commodity that is essential to the operation of DR. In the latter case it is because the new relationship would in some way be commercially disadvantageous for one or both parties.

Under the categories of technical and commercial barriers it is unlikely that outright barriers to implementation exist. Rather barriers are likely to impose constraints that necessitate costly workarounds thereby negatively impacting the business case for DR services when the technology is in its most vulnerable, embryonic phase. Resolution to technical barriers might, for example, involve the augmentation of smart metering and smart grid technology with DR capabilities. Commercial barriers might be resolved by a renegotiation of a commercial relationship between two contracting parties in order to facilitate implementation. In such cases resolution is likely to be entirely within the ambit of the DR industry.

Under the category of legal/regulatory, however, it is entirely possible that outright barriers do exist. Proceeding with implementation may simply not be possible under the legal framework as it is today. In such cases policy or legislative change is necessary to resolve the barrier. Resolution of such barriers is only possible through the action of Government in response to appropriate lobbying on the part of the DR industry. The inability of the DR industry alone to resolve these barriers means that they may effectively prevent DR until they are resolved.

Belhomme [11] and Strbac [12] have separately considered the issue of barriers to DR and cited examples of barriers that might be expected to occur (see TABLE 1). However, in neither case is the existence of these barriers confirmed or more specific detail as to the nature of these barriers reported. Indeed there appears to be an absence of detailed research in this area within the available literature.

TABLE 1
EXAMPLE BARRIERS TO THE IMPLEMENTATION OF DR

Technical	Lack of ICT infrastructure
	Billing and information management
	Increased complexity of system operation
Legal / regulatory	Incentives
Commercial	Consumer acceptance
	Contractual issues
	Conflicts of interest
	Pricing
	Lack of understanding of the benefits

The objective of this research is to identify barriers and to fully characterise them such that appropriate action might be initiated to resolve them. The remainder of this paper describes experience in developing one particular methodology for this task.

V. AN MBSE METHODOLOGY FOR ANALYSING BARRIERS

The implementation of DR implies potentially substantial change to the existing structure of relationships within the industry. To understand where barriers might exist, and how they might be overcome, it is necessary to employ a modeling approach that has the ability to capture these complex relationships. A complex organisation such as the electricity industry contains both technical and human assets. Relationships are governed by legal rules, commercial arrangements and social constraints, as well as technical constraints. This leads to an intricate web of relationships that have both objective and subjective characteristics. Some are completely defined and others have significant ambiguity. This presents a significant problem to many traditional modeling approaches.

To develop a model both static and dynamic relationships must be captured, i.e. not just the parties themselves but also the transactional behaviour between the parties. This requires an Enterprise Modeling methodology. The knowledge about the relationships and the stakeholders comes from the industry itself, through literature and interviews. This knowledge is then captured in the form of a model of the industry.

To identify barriers to implementation the focus of analysis must be the relationships between the entities within the system. These relationships are instantiated via interfaces between the entities. The purpose of these interfaces is to facilitate some kind of transaction, i.e. the passing of some item from one entity to another. Items could be physical objects, information or other commodities such as energy. It is the point at which items are transferred across these interfaces that incompatibilities might occur and barriers be encountered.

The mix of technical and human assets means that the problem is well suited to analysis using Systems Engineering tools and MBSE in particular. MBSE provides the ability to model both the structure and the behaviour of a system. MBSE also allows expansion of a model to explore new functionality and its effect on the overall system in a holistic way. This is essential if barriers are to be identified.

MBSE is a methodology, however to be able to develop a model a modeling language is required. SysML is an extension to the Unified Modeling Language (UML) that provides a number of additional features designed to expand the language's utility beyond predominantly software systems [13]. SysML provides the strict semantics of UML but with extensions to provide the flexibility to capture human relationships as well as technological ones [14]. However, experience of using SysML, as opposed to UML, for organisational modeling appears absent from the literature. This is possibly because of the relative youth of the SysML specification or possibly because of its relative unfamiliarity outside of the Systems Engineering community.

VI. EXAMPLE: MODELING FREQUENCY CONTROLLED DEMAND MANAGEMENT

To gain experience in applying MBSE and SysML to the electricity industry domain, they were applied to an example service: Frequency Controlled Demand Management (FCDM).

A. Overview of Frequency Controlled Demand Management

To manage the system and maintain balance the British SO – National Grid – purchases a number of ancillary services aimed at increasing or decreasing generation or load in real-time and near real-time. One of these services, FCDM, is a fairly rudimentary DR service in which a load is abruptly disconnected, usually via frequency sensitive relays, if the system frequency falls below a defined low frequency threshold. Response is rapid (within two seconds). A provider of FCDM is required to make the service available 24 hours a day and to deliver the service for up to 30 minutes. There is a minimum capacity requirement of 3 MW [15].

B. Modeling Structure

In SysML, structure is captured using *block definition diagrams* and *internal block diagrams*. The block definition diagram uses blocks to model entities and different kinds of association to model the connections between them. A block definition diagram for the British industry pertaining to the FCDM service is shown in Fig. 1. This diagram shows the composition hierarchy and the important dependencies for the entities that compose the FCDM domain of interest.

With reference to Fig. 1, the central actor within the FCDM domain is the SO. The SO has multiple dependencies. It despatches generation and manages the despatch control part of the FCDM service. The despatch control part of the FCDM service in turn configures the controllable demands. The FCDM relays measure the power system frequency via the distribution network, which is connected to the transmission network. The FCDM relays also control the loads.

shows the internal block diagram for the FCDM service. There are three types of item that flow between the different parts of the system: configuration information, frequency and power. The latter two are input directly into the controlled demand. Frequency is used by the relay to control its operation and power passes through the relay to the load. The configuration information is received by dispatch control and passed to the relay.

C. Modeling Behaviour

Functional behaviour is captured in *use case diagrams* and shows which actors within the domain of interest use which functions of the system.

A use case diagram for the FCDM service is shown in Fig. 3. This diagram contains the SO from Fig. 1 together with a new actor: the consumer. The SO uses the function provided by the FCDM system that provides the functionality to configure the relay. The consumer uses the function provided by the FCDM system that provides the functionality to close the relay, following a disconnection. The function that opens the relay is automatic in response to the measured frequency and is not initiated directly by an actor external to the FCDM service.

D. Analysis

The use of SysML allows the key interfaces, and the detail of those interfaces, to be identified. For example, from Fig. 1 it can be seen that a relationship must exist between the SO and the despatch control such that the SO can manage the FCDM service and the FCDM relays can be configured. Note that at this stage no assumption has been made as to how those interfaces might be implemented, only that they must exist and what must be passed across them (from Fig. 2).

Similarly the functionality required for the system has been identified in the use cases in Fig. 3 and the actors that utilise that functionality identified. There must therefore be appropriate interfaces to allow those actors to exercise that functionality.

In this way and by further increasing the complexity of the model the details of the interfaces that are required can be discovered. New services can be added to the model and new interfaces between new entities and existing entities identified. The methodology presented here is therefore capable of revealing the detail of relationships and can be used to identify barriers.

However, whilst the methodology is capable of capturing aspects of relationships beyond the purely technical, the process of transcribing incomplete and ambiguous data into a SysML model is not a simple one. In this it reflects to some extent the experience of others in using UML to model organisations (see [16-19]). With non-technical systems there is perhaps the need for an intermediate step between knowledge gathering and detailed modeling in which the modeller can explore the domain of interest without being tied to a rigid semantic framework. Such a modeling step must be flexible enough to maintain its consistency and cohesion even with the level of ambiguity that is encountered in the operational relationships within a large organizational structure such as the British electricity industry.

VII. CONCLUSION

Successful achievement of the UK carbon reduction targets is dependent on the electrification of transport and heating, and the simultaneous de-carbonisation of the electricity system. This represents a major challenge to an industry that has evolved around a “predict and provide” model primarily based on fossil fuelled generation. The new operating paradigm will necessitate a much greater involvement of the demand side in system balancing through the extensive deployment of DR services.

However, the industry as it is today may not be amenable to the large-scale introduction of DR. There may be present significant barriers to implementation that might require radical change to the structure of the industry if they are to be removed. Such change must be policy-driven and an examination of the evolution of the industry leads to the conclusion that there are precedents for such change.

Barriers can be classified as technical, legal / regulatory or commercial. Technical and commercial barriers might be overcome with additional expense but legal / regulatory barriers might require policy changes. Knowing that change is possible an approach to identifying barriers can be developed.

This work has presented a methodology based on MBSE and SysML that is being actively used to gain an insight into the organization and operation of the industry today. An example of applying this methodology to an existing DR service, FCDM, has been described. Experience in applying this methodology has shown that whilst SysML provides the capability needed to produce detailed models of DR services, the need to transcribe incomplete and sometimes ambiguous organizational data into a rigid semantic framework can be difficult. In this respect the experience here mirrors that of other researchers that have used the parent language of SysML, UML, for organizational modeling tasks.

The research presented here indicates that whilst the MBSE methodology shows some promise for this type of problem, there is a clear need for further work refining this approach. In particular the interface between the rigid semantic framework of modeling languages such as SysML and the somewhat ambiguous world of human relationships warrants further exploration.

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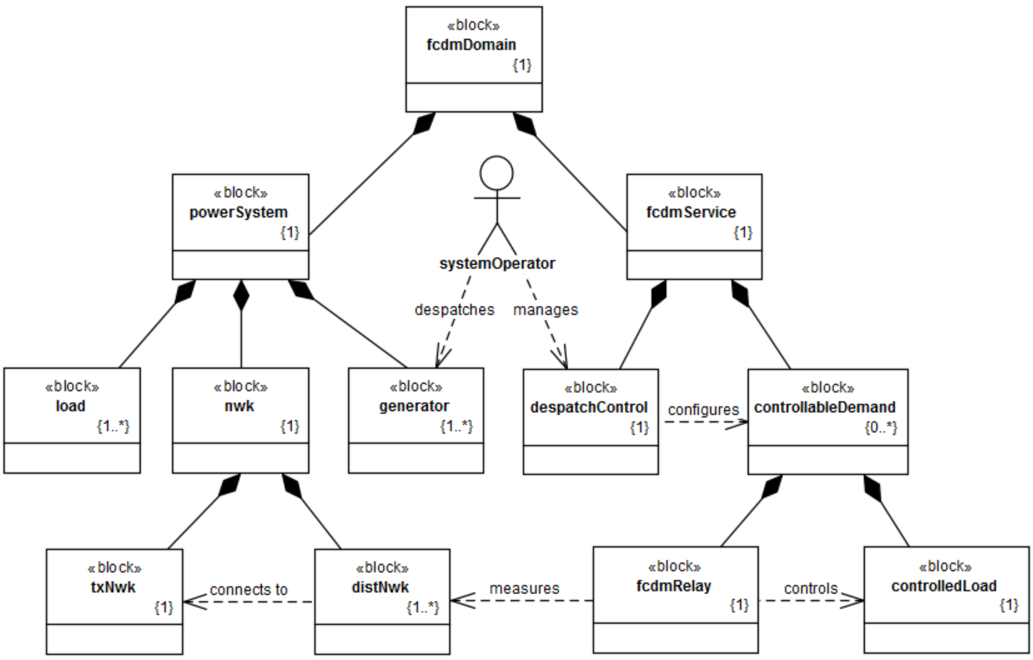

Fig. 1. Block definition diagram for the British electricity industry within the context of the FCDM ancillary service.

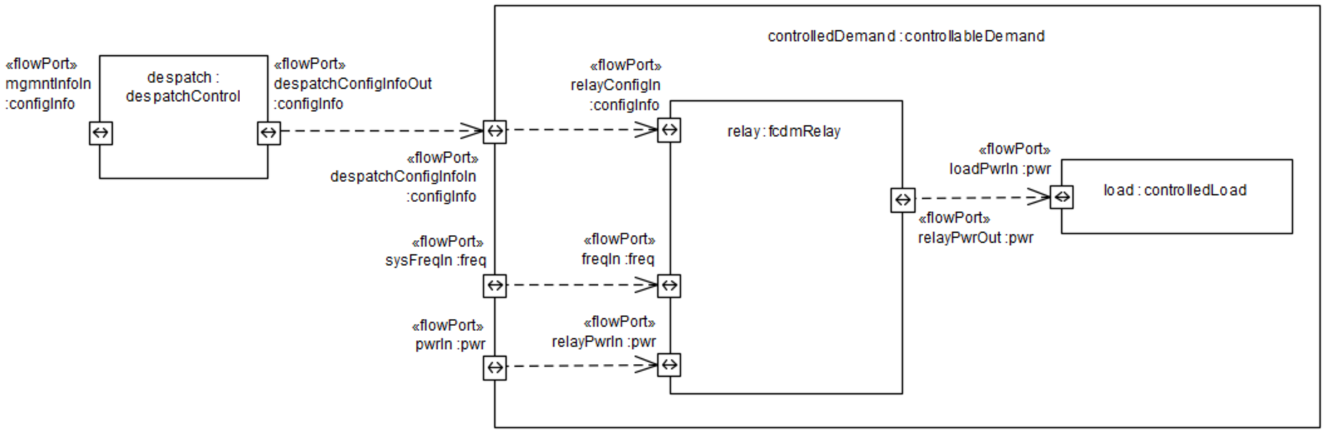

Fig. 2. Internal block diagram showing the item flows for the FCDM service.

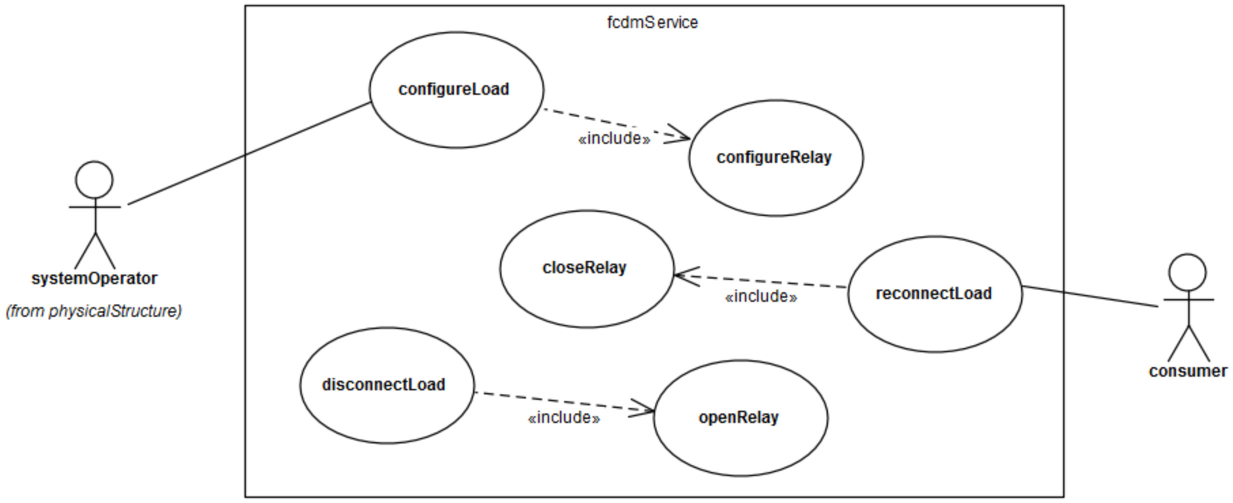

Fig. 3. Use case diagram for the use of the FCDM service by the SO.