Supergen III: Highly Distributed Power Systems

System Level Concept Definition

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Executive Summary

Highly Distributed Power Systems

The electricity supply industry in the United Kingdom (UK) is experiencing drivers to move away from relying almost exclusively on large transmission connected thermal power stations, and to accommodate smaller, more environmentally sustainable forms of generation connected across the network.

The Highly Distributed Power Systems (HDPS) concept is based around the future vision that large numbers of such generators, many independently owned and operated, are connected across all voltage levels within the distribution network. Similarly, the adoption of demand side management measures and, to a lesser extent, energy storage technologies is significantly increased as a means of accommodating this new generation which is not always controllable in the way that central generation is. At the same time, the level of large-scale thermal capacity is expected to be reduced as planned plant decommissioning is not fully offset by large scale new build projects (e.g. nuclear, CCGT, clean coal or large-scale renewables such as offshore wind). Although the transmission infrastructure of the UK is being modified to support the bulk transfer of power from remote large-scale renewable sources, its role in supplying the total demand is diminished as the function of distributed and microgeneration is enhanced. As HDPS develop, generation connected to the distribution network becomes increasingly a key component of how the electricity supply system as a whole is planned, designed and operated. Fundamental to these system tasks is obtaining a sound understanding of the distributed resources' reliability and availability of HDPS generation within the contexts of their fuel source, technology and control flexibility. The HDPS concept can be summarised by the statement "many loads – many sources", in contrast to the traditional "many loads – few sources".

This discussion paper has been prepared by members of the UK Engineering and Physical Sciences Research Council (EPSRC) Supergen 3 HDPS consortium[1]. It builds upon the initial concepts presented in a previous document by drawing upon experience gained by the consortium over the subsequent period in which the project has been active.

Harnessing the Benefits of Local Generation & Controllable Load: The Cell Concept

The cell concept is seen as a potentially important means to facilitate the utilisation of local generation and controllable demand as a system level resource where applicable, and more generally as a means of mitigating network connection constraints on local generation. These cell entities are defined based on the emergence of intuitive groupings of distributed resources deriving from the underlying structure or topology of the network. By establishing cells, the scope of the control problem surrounding the integration of these distributed resources is greatly reduced as these entities can be requested to provide services or perform network management tasks, the implementation of which is an internal function of the cell using the distributed resources at its disposal. Moreover, cells can be grouped hierarchically and used with a strong degree of functional abstraction, thus allowing for a more directed utilisation of resources, whilst at the same time minimising the complexity of the required information and communication technology (ICT) infrastructure. The zone of control as demarcated by cells will be used to structure the use of generation,

[1] HDPS consortium website: http://www.supergen-hdps.org

flexible demand and network reconfiguration resources in providing system services and at the same time for the managing of local network constraints.

The cell concept is presented and discussed within section 2 of this report where it defines the terminology used to describe cells and then proceeds to outline their key technical attributes such as structure, demarcation criteria and objectives. This provides the basis for the ongoing research of methods and techniques that contribute to the concept realisation.

Market & Regulatory Framework

While re-nationalisation of the UK energy sector is a possibility, a competitive marketplace for the trade of electric energy and a system of regulation for the industry's inherent monopolies are likely to continue and the HDPS concepts, including cells, have been developed in this context. The specification of such economic mechanisms must be goal driven. The differences between a conventional power system and an HDPS that impact on the design of the marketplace have been identified by the research undertaken to date. These are explained and the associated research opportunities outlined. Those topics selected for investigation by the consortium are expanded upon and the key research questions listed.

Market and regulatory options for HDPS are presented and discussed in section 3 of this report where some of the most pertinent research questions are expressed.

The Evolution towards HDPS

The HDPS concept represents an innovative long term vision for a major part of the electricity supply system in the UK. As such, it is necessary to evaluate the capabilities and limitations of the HDPS approach.. Is the move towards a more highly distributed future part of the solution to the challenges that the electric industry is facing today? Furthermore, this transition towards a “many loads – many sources” future will prove to be a test for the different stakeholders within today's electric industry who will be required to adapt their prevailing practices to a new and changing environment.

In section 5 the use of Distributed Energy Resources planning techniques for evaluating HDPS capabilities is discussed. The role of planning Distributed Energy Resources in informing the transition towards HDPS is analyzed and some of the challenges that traditional network planning practices will face are discussed. Finally, relevant research questions that remain to be answered are presented.

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1 Introduction

The electricity supply industry in the United Kingdom (UK) is experiencing drivers to move away from relying almost exclusively on large transmission connected thermal power stations, and to accommodate advanced and more environmentally sustainable forms of generation connected throughout the system. The primary drivers for this change arise from growing concerns surrounding the negative environmental impact of greenhouse gases emitted during the combustion of fossil fuels [1], improve system efficiencies, and to a lesser extent a general desire to reduce the level of losses incurred during power transfer from sources to consumers. Strong regulatory incentive mechanisms have been put in place to ensure that the electricity supply industry recognises such externalities and, moreover, meets the challenging targets set by the UK government [2].

However, as this change in the generation portfolio is put into effect, fundamental questions emerge as to how such a distributed system can be managed given the significant number of entities participating, their geographical distribution, the impact of fuel source intermittency, and other network technical constraints. The role of large-scale renewables – such as on- and offshore wind farms – have been widely debated and many research programmes initiated to quantify their impact. In addition to these technologies, many forecasts for the UK generation portfolio over the coming decades have also highlighted the likelihood of a significant level of smaller-scale distributed and microgeneration connected at the lower voltage levels of the distribution network [3] (with ratings of the order of several kW to tens of MW). Even if the total capacity of these small-scale resources is of an order of magnitude such that it is comparable to and indeed theoretically displace large-scale thermal plant on the basis of ratings, major technical questions still remain regarding network support functions such as participation in system frequency control and local voltage support or regulation. Furthermore, the response of local generation to network transients and faults and their role within system planning and restoration scenarios must also be explored.

Additionally, while the connection of small-scale generation can be regarded as an important future development in addressing some of the negative externalities for the electricity supply industry (although its effectiveness has yet to be fully quantified), due attention must also be given towards the benefits obtainable from the adoption of energy efficiency and demand side management measures. The intelligent coordination of consumer demand – for example through the rescheduling of certain loads to more opportune times – and the use of local generation will have a profound impact on the characterisation of the customer from the perspective of the network operators. Moreover, the emergence in the longer term of economically viable energy storage technologies (electrical, chemical or thermal) has the potential for changing the demand behaviour of consumers and thus adding a further dimension to the challenges to be addressed. It is vital that the implications of any changes are fully explored and, indeed, opportunities created to improve the overall management and performance of the electricity supply system.

The discussion above is characterised by a high level technical consideration of the role of sustainable small-scale generation and demand side measures. Clearly, in parallel to this, care must also be taken to ensure that an appropriate market and regulatory framework exists with which to initially promote and reward such innovation and, eventually, ensure its widespread adoption as technologies mature. A key role for this framework will be to support those technologies that specifically offer the features or behaviour that will be desirable within an electricity supply system. These are very different from conventional power system considerations and require new analysis tools and techniques.

1.1. Highly Distributed Power Systems (HDPS)

The HDPS concept is based around the future vision that large numbers of generators, many (perhaps mostly) independently owned and operated, are connected across all voltage levels within the distribution network. Similarly, the adoption of demand side management measures and, to a lesser extent, energy storage technologies is significantly increased to help absorb these new sources of generation which are not all schedulable in the manner of conventional generation. At the same time, the level of large-scale thermal capacity is likely to be reduced as planned plant decommissioning is not fully offset by new build projects (e.g. nuclear, CCGT, clean coal or large-scale renewables such as offshore wind). Although the transmission infrastructure of the UK is being modified to support the bulk transfer of power from remote large-scale renewable sources, its role in supplying the total distribution demand will be diminished as the function of distributed and microgeneration is enhanced in conjunction with appropriate demand side measures. Within HDPS, generation connected to the distribution network becomes a key component of how the electricity supply system as a whole is planned, designed and operated. Fundamental to these system tasks is obtaining a sound understanding of these resources' reliability and availability within the contexts of their fuel source, technology and control flexibility. The HDPS concept can be summarised by the statement "many loads – many sources", in contrast to the traditional "many loads – few sources".

This discussion paper has been prepared by members of the UK Engineering and Physical Sciences Research Council (EPSRC) Supergen 3 HDPS consortium (see Appendix A for further information). It builds upon the initial concepts presented in a previous document [4] by drawing upon experience gained by the consortium over the duration of the project. The following sections add further depth to the context for HDPS outlined above, by firstly highlighting a scenario exercise with a time horizon of 2050 for distributed and microgeneration capacities and, secondly, by describing the key approach with the potential to assist in harnessing the benefits of local generation and demand side measures – the decentralised vision and the cell concept.

1.1.1. Visions of the Future – HDPS Scenarios for 2050

The rate of transition for electric power systems from few to many sources is expected to increase markedly as time passes towards 2050. A number of scenarios have been developed by researchers within the HDPS consortium that specifically explore the potential levels of small-scale generation (particularly low and zero carbon technologies) and demand-side measures that could be connected or applied to distribution networks within the UK [5].

Although a comprehensive review of the scenarios is outside the scope of this document, it is worthwhile to consider the level of the predictions for the uptake of several microgeneration technologies for the year 2050. Within the 'Low Carbon' scenario it is projected that there will be approximately 32 million households in the UK and that micro-wind turbines and photovoltaic modules will be installed in 7% and 10% of households respectively. Assuming a modest electrical rating of 1.5kW, this would amount to an installed capacity of

8.16GW and represents a sizable portion of UK generation capacity when added to other distributed sustainable technologies of differing sizes such as combined heat and power (CHP).

1.1.1 Why a Decentralised Vision?

Existing electrical energy systems were designed and built to accommodate large-scale generating plant, and given that demand has been traditionally viewed as uncontrollable and inflexible, operation and management of the system has been centrally controlled (Figure 1). At a regional level, electricity is delivered from transmission to the distribution networks and then to end consumers in a unidirectional fashion via a number of voltage transformations. Tight real-time control at the transmission level maintains the balance between demand and supply at all times, facilitated through balancing services from central generation. Power is bought and sold in the wholesale markets, through the interaction of large scale generators and energy Suppliers. Network controls are hierarchical in nature, becoming increasingly sparse towards the end-users, and cross vector interaction is limited to large-scale generators.

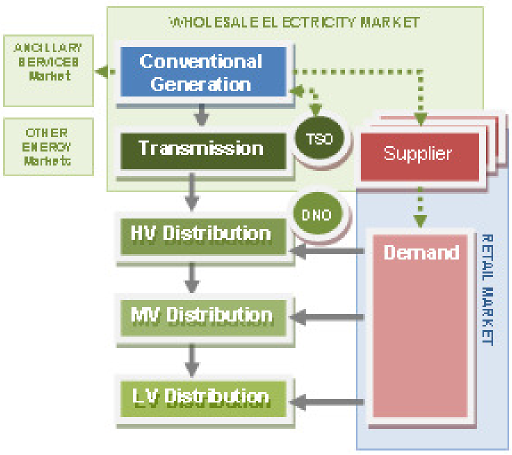

Figure 1: View of conventional of power system

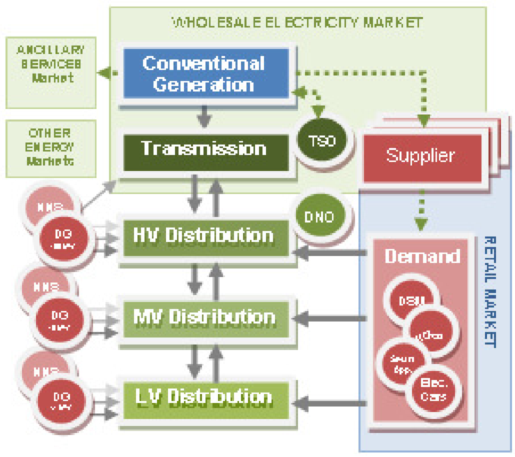

Figure 2: View of emerging power system within existing market framework

The aforementioned "game-changing" developments, together with associated and, in the main, stand-alone new network systems (NNS), are illustrated in Figure 2 within the existing market framework. However the work of HDPS 1 has demonstrated that these changes cannot be effectively implemented within the existing technical schemes and market frameworks and may as a result compromise the system's security, economic, and environmental performance. This represents a barrier to the full attainment of the *sustainability potential* of the system changes.

A radical decentralised systems solution to such a highly distributed energy future (see Figure 3) is clearly required that puts end users at the heart of system operation, provides effective technical and market integration of all end-use technologies within the network, and provides the accessibility and flexibility to incorporate future technological innovations. The cell concept developed in HDPS 1 provides an architecture through which this extensive integration of DERs and facilitation of decentralised control and market engagement can be delivered. The HiDEF programme will prove the fundamental features by which such a vision might be realised.

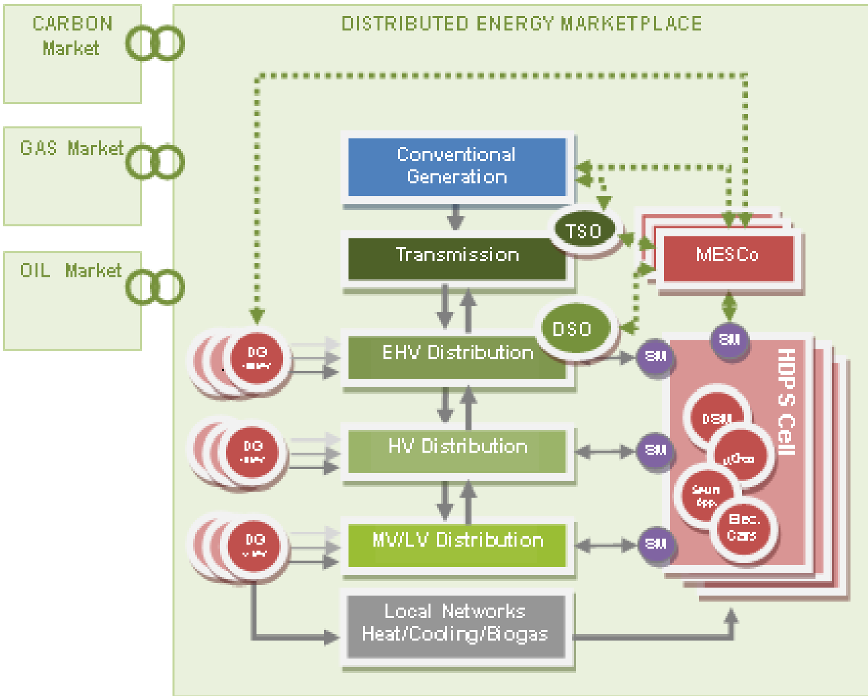

Figure 3: View of the Distributed Energy Future

To be sustainable and resilient a future energy system must incorporate distributed energy resources where they are (and known to be) competitive, socially acceptable and environmentally beneficial, but integration is much more than merely fit and forget connection of the DERs themselves. It is essential to incorporate

- coordinated operation of resources through decentralised controls that provide system management (SM) functions from each cell to transmission and distribution system operators (TSO & DSO) and supports operational resilience and fast recovery from loss of function
- decentralised participation through well structured distributed energy marketplaces that remove the obstacles caused by the present separation of wholesale and retail energy markets and at the same time protect the energy poor. This could involve the formation of what may be regarded as multi-energy services provider (MESCo's), and multi-energy infrastructure for optimal integration of local, district, and bulk transportation of energy including gas and heat networks.

1.1.2 Harnessing the Benefits of Local Generation & Controllable Demand

Given the magnitude of the forecasted capacity, a number of fundamental research questions arise as to the role of local generation (both HV and LV connected) within the context of the overall electricity supply system:

(i) Firstly, should local generation be regarded merely as a negative load, thus acting to uncontrollably modify 'demand' profiles as observed from the perspective of the transmission system?

The answer to the above question is clearly dependent upon the penetration level the nature of the control response that can be expected from local generation either autonomously or given the range of likely external requests. Moreover, it is assumed that the transmission connected generation portfolio contains a suitable mix of large-scale renewable and low or zero carbon emitting thermal plant. The controllability of the latter being vital for system balancing as these forms of generation will remain the most flexible resources from a real-time operational perspective.

For the case of distributed generation connected onto the high voltage (HV) network, the advantages of trimming the output of units due to local network constraints has been demonstrated in [6] within the context of the active management of networks. However, the ability of intermittent distributed generation to respond to requests for increasing output is limited given the uncontrollable nature of the primary energy source. Furthermore, the generally poor load factors would restrict any desire for switching off such sources.

If LV microgeneration is considered, the typical examples of highly intermittent renewable sources such as microwind and PV do not offer much scope for control, and heat led microCHP depends on both the heat demand of the dwelling and the capacity of any associated thermal storage reservoirs within the design. Appendix B provides example microgeneration output profiles for microwind, PV and heat led microCHP technologies. The deployment of a significant level of energy storage at this level is not certain and thus limits one potential avenue of control actions available to smooth the variability of generation output. Furthermore, if the assumption is made that the ratings of these small generators are based on either the availability of a resource (such as heat) or the demand of the customer, then large scale intentional export for long periods of time for financial gain is unlikely (given energy and power limitations). Thus the general impact of local generation could be to modify the value of after diversity maximum demand (ADMD) used by distribution network operators as part of their planning for future developments and require that certain operational practices be reconsidered to avoid connection constraints.

The challenge for the HDPS consortium for this treatment of local generation is to understand the nature of the modified demand profiles with diversity applied given the range of local generation technologies and then subsequently aim to ensure that no unnecessary barriers to connection exist due to network constraints such as local voltage regulation. Furthermore, a clear understanding of the dynamic behaviour of small-scale generation is essential in augmenting the representation of demand groups within system stability studies. Indeed, the tripping of small-scale generation of a significant capacity in response to system wide disturbances (e.g. due a comparatively large system frequency excursion occurring because of the loss of a large thermal station with the assumption of a UK system with lower overall system inertia constant) could aggravate emerging disturbances by subjecting the system to potentially large levels of previously hidden load. It is reasonable to assume for the latter task that some form of additional network control or monitoring infrastructure is required if network constraints are to be mitigated without costly primary system reinforcement. Controllable demand and energy storage will be a valuable resource for smoothing the highly intermittent unit output or compensating for the loss of a large thermal unit given the proportionally lower levels of this type of generating plant.

(ii) Alternatively, should local generation (and indeed demand) be utilised as a system level resource?

Certain distributed generation technologies with their larger ratings and potential for using less intermittent primary energy sources (e.g. municipal waste to energy) offer greater levels of controllability and are thus applicable for use as a system level resource once significant levels of penetration are reached. The coordination of the response of these assets to make their targeted use operationally straightforward requires careful consideration. It is likely that distributed generation, but perhaps not microgeneration, will be used as a coherent system level resource. Microgeneration may be best suited to a passive role of reducing overall losses and emissions by generating closer to consumption and utilising cleaner technologies (when possible) respectively. Alternatively, the inherent heat storage capability may provide for some measure of control provided sufficient buffering and storage capacity is available. Regardless of their active or passive role, the behaviour of both distributed generation and microgeneration must be understood and the supportive measures for control well defined. The manipulation of microgeneration due to local network constraints could be advantageous and would be managed locally. The selection of which distributed resources to use has both technical and economic implications, particularly for the case of constraining off generators to alleviate a localised voltage rise on a radial LV circuit.

(iii) What control structure is required for the realisation of the role of local generation and controllable demand?

In either treatment of local generation, it is proposed that areas of the distribution network be demarcated as cells. These entities are defined based on the emergence of intuitive groupings of distributed resources (generation, storage and controllable demand) due to the underlying structure or topology of the network. By establishing cells, the scope of the control problem surrounding the integration of these distributed resources is greatly reduced as these entities can be requested to provide services or perform network management tasks, the implementation of which is an internal function of the cell using the distributed resources at its disposal and may in fact be collective control within the cell. Moreover, cells can be grouped hierarchically and used with a strong degree of functional abstraction, thus allowing for a more directed utilisation of resources, whilst at the same time minimising the complexity of the information and communication technology (ICT) infrastructure required. The zone of control as demarcated by cells will be used to structure the use of generation, flexible demand and network reconfiguration resources in providing system services and at the same time for the managing of local network constraints. Although it should be noted that not all cells will offer the full range of functions due to the limitations placed on their distributed resources. This cellular concept is explored further in section 2.

However, for the purposes of this investigation of HDPS, it is assumed that the network is predominately static, and thus reconfiguration is restricted to incremental improvements or extensions of existing automation schemes (driven by regulatory pressure over performance indices such as customer minutes lost). In so doing, the scope of the problem to be addressed is reduced and allows for the easier identification of the role and capabilities of local generation, energy storage technologies and demand management. The emergence of network constraints that may require reconfiguration is expected to be apparent from the results of system studies, and is an area that will be taken further within the Supergen 1 Flexnet consortium [7].

(iv) What reward structure is required to ensure the participation of local generation and the allocation of controllable load?

To ensure participation, the market and regulatory structure has to be in place to provide a financial incentive to encourage the offer of network services or to compensate for loss of revenue or increased demand cost should local generation be curtailed. Local generation will participate if it is competitive and there is profit to be created. If for environmental reasons local generation is to be encouraged this may achieved by either providing policy driven incentives, such as renewable obligation certificates (ROC), or by penalising their competitors, as with the EU Emissions Trading Scheme. Long term drivers may be deployed to encourage the development of desirable dynamic characteristics and control features. It is important to note that encouraging the use of more expensive generation has an undesirable effect on energy prices and this must be justified by the environmental benefits.

(v) What is the role of planning tools in guiding and justifying the transition towards a HDPS future?

If the move towards HDPS is to be evaluated and indeed justified, appropriate tools are required to asses the effectiveness of HDPS to achieve its objectives under the perspective of the different entities participating. Planning tools, based on the principles of optimisation and multi criteria analysis, can provide useful information of what is the potential of HDPS and what targets can be reached with an optimal integration of local generation. A multi criteria approach to the problem can help to illustrate the different perspectives of an increased number of market players. Moreover, exposing the tradeoffs between the different development objectives can provide useful information and guide the decision making process

The use of local generation planning tools can be argued as a redundant task in a liberalised market where investments are usually dictated by the forces of the market; however, it is not the plan itself (as an investment tool) which is of importance, but rather the information that can be obtained from the optimisation process. The knowledge of what constitutes an optimal integration of local generation (in terms of mixes, sizes, locations and possibly operation modes) can provide valuable information about HDPS potential and also guide benchmarks for grid operation and development, and inform further proposals of policies and incentives.

Current network planning techniques will need to be adapted to take into account the increased uncertainty associated with distributed generation and modified load profiles that result from the domestic use of micro generation and more widely adopted load controls. The possibility of using distributed generators (or other distributed energy resources) as investment options for distribution network planning will need to be considered by regulators. Furthermore, in a future where local generation of electricity and heat is envisaged, it is likely that integrated energy systems planning (i.e. gas, electricity, and heat) will ensure a better use of local resources.

1.2. Overview

The discussion of HDPS within this discussion paper is structured as follows:

Section 2: Details of cell definitions, network demarcation and functions are provided that outline the technical basis for HDPS. Key research questions for the consortium are also discussed.

Section 3: Details of the market structure that will enable or support the technical proposals given in Section 2. Further research questions related to this field of study are also given.

Section 4: A number of case studies will be presented for the application of HDPS using network models taken from the UK Generic Distribution System UKGDS library. The behaviour of cells forming part on a HDPS will be described from the perspective of the transmission network as well as more local functions.

Section 5: The transition towards an HDPS future is analyzed from two different perspectives. First, the suitability of planning tools to inform the further development of HDPS effects is discussed. Then, some of the changes that current planning techniques will need to overcome are presented.

Section 6: This section summarises the HDPS concept and reviews the areas of further investigation for the consortium within the time available in the current project, but also looks ahead to a follow on project/extension.

2 The Cell Concept

The cell concept is a potentially important means to help facilitate to the utilisation of local generation and controllable demand as a system level resource where applicable, and more generally as a means of mitigating network connection constraints on local generation. This is vital for ensuring support for the widespread use of distributed resources and demonstrates their potential value for not only providing a mechanism for loss reduction by reducing bulk power transmission levels, but also for collective active participation within the interconnected system where the level of dispatched central thermal plant is anticipated to decrease. This section firstly defines the terminology used to describe cells and then proceeds in section 2.2 and 2.3 to outline their key technical attributes such as structure, demarcation criteria and objectives. The integration of cells within the overall systems is considered in section 2.4. Section 2.5 highlights the key research questions that remain to be addressed by the consortium. The inherently technical discussion in this section will be supplemented by a discussion of potential market structures in section 3.

2.1 Terminology

The term *cell* is used to define an area of network in which a collection of distributed resources can be controlled in response to a number of allocated objectives. These can be defined with a scope that is either external or internal, and are specified at both the time of the cell definition and by an external parent entity when operational. Specific elements of this definition are elaborated upon as follows:

> *Distributed Resources* – include local generation, energy storage, controllable demand or network secondary assets (e.g. transformer tap-changer relays).
>
> *Objectives* – refer (i) externally to the control of real and reactive power imports or exports through the cell's primary system interfaces and, (ii) internally to the control of internal network conditions within the cell.
>
> *External Parent Entity* – is the term associated with any higher management system (e.g. energy or distribution management systems) or a larger hierarchical cell that may seek to meet its objectives by making use of an enclosed cell's functionality.

A cell is graphically represented as shown in Figure 4 where the key functional elements and external interactions are illustrated. The cell is shown as an abstraction where its electrical capabilities are defined from a black-box perspective and lends itself to a hierarchical structure in which cells can be further subdivided. Cells can be classified broadly according to being either LV or HV with a corresponding difference in the scope of their objectives given the type or functionality of distributed assets available.

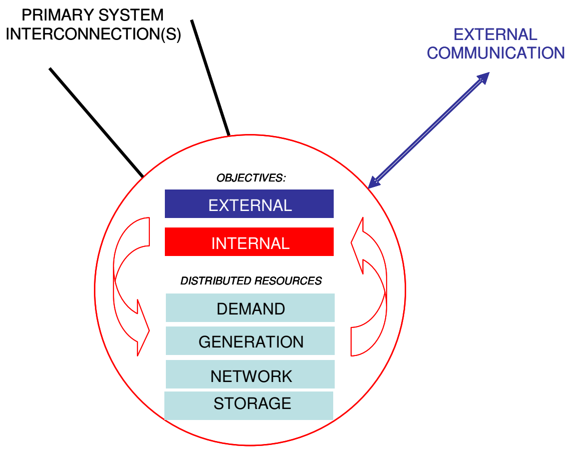

Figure 4: Cell functional elements and external interactions

2.2 Demarcation of Cells

Cells within HDPS are demarcated based on the underlying structure or topology of the network and are thus expected to include a variety of distributed resource technologies. This approach simplifies the points of connection through which the controlled action influences the system. As a consequence of this definition, cells are likely to be formed at the various levels of network substation and extend down through distribution circuits to either passive consumers or distributed resources (which could in turn be other smaller cells). Furthermore, the demarcation of cells should also be influenced by incorporating existing control zones or network ownership/responsibility boundaries (e.g. independent distribution network operators). The physical size of cells is dependent upon the scale of external service objectives that are to be allocated or the existence of internal constraints, as well as the degree of acceptable complexity incurred within a hierarchical structure. It is evident that load (or indeed generation) density within sections of distribution network will be a major factor in the demarcation of cells. In the case of small scale generation and load resources, their nature requires that encapsulated populations must be large enough to afford sufficient diversity to provide for a controlled action.

An example of the demarcation of HV cells onto a section of distribution network is shown in Figure 5 below where 11kV circuits from primary substations and 33kV circuits from bulk supply points (BSP) are shown. The BSP and its associated 33kV distribution have been defined as a cell and include various distributed resources. Three further cells have been allocated based on primary substations with the justification that within these areas there are significant levels of distributed resource that justify sub-grouping within the BSP cell. These three sub-cells are distributed resources falling within the control of the cell defined at the BSP level.

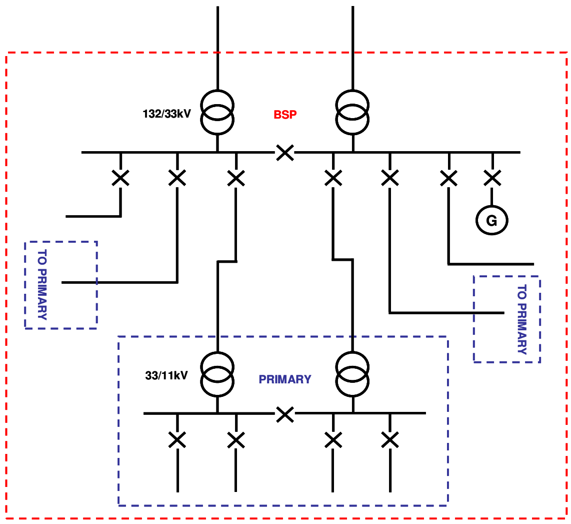

Figure 5: Example HV cell demarcations

By demarcating based on network topology, cells may have dominant characteristics depending upon the number and type of load and generators connected to that section of network. Classifications such as residential, commercial/business or industrial can be applied to define their behavioural characteristics and a further geographical description such as rural, urban and suburban to give an indication of their scale. The specific scale and mix of technologies will vary significantly between classifications giving rise to a range for the objectives that a cell can be allocated.

A further example is given in Figure 6 where both HV and LV cells have been demarcated. The LV cell has been created due to the high level of microgeneration connected within new-build property developments. Within this cell the objective is primarily internal and relates to the voltage regulation of the LV cable network. The many microgeneration devices within a cell may be controlled as are larger units, or alternatively may be subject to broadcasted cell-wide control signals.

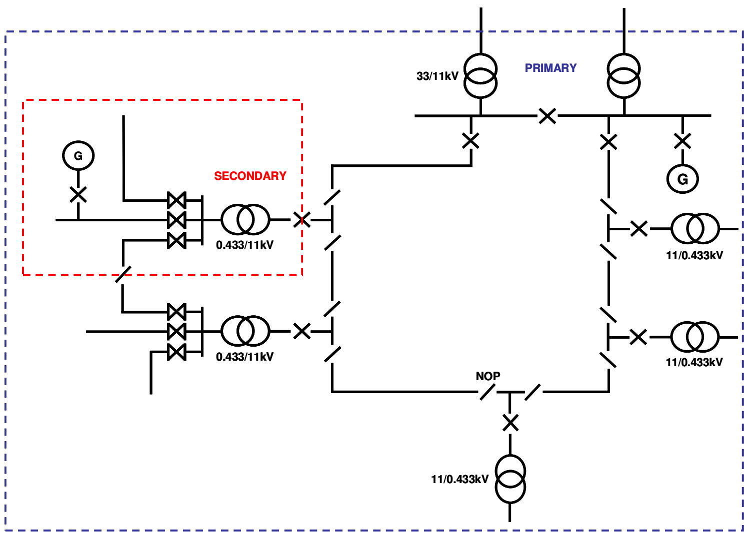

Figure 6: Example HV and LV cell demarcation

2.3 Cell Objectives

The objectives that a cell can be allocated are defined as having either external or internal scope. Examples of both are provided in the text below.

2.3.1 External Services

- Support for system frequency through the ability to curtail or increase net generation export and reduce net demand. This assumes that either cells are large enough to participate or that coordinated use is made of a large number of smaller cells with prior knowledge of their characteristics – this being achieved through the action of a parent cell.

2.3.2 Internal Constraint Mitigation

- Avoidance or mitigation of local thermal constraints. This will be of particular note within HV distribution circuits where the combination of larger generators and constraints arising from network expansion will be most significant.

- Ensuring good voltage regulation within the cell by acting to resolve issues by using the distributed assets available. Issues could arise due to the coincidence or otherwise of demand and intermittent generation profiles or from the actions taken to realise an externally allocated objective.

- Island the cell in response to a loss of the grid supply to ensure that local consumers are not interrupted. This would be supplemented by the requirement for reconnection when the grid is sensed to be operating within statutory tolerances. Intentional islanding is not considered further within this paper.

2.4 Technology Requirements

In order to meet the control objectives allocated to cells, it is apparent that a wide variety of technologies will be required ranging from ICT systems to network support devices including power electronics interfaces for generation and distribution style FACTS devices [8]. An important aspect of the development of the cell concept for HDPS will be to clearly identify the performance requirements for these technologies and, importantly, how they can be integrated at a system level [9].

2.5 System Wide Integration

From the system perspective cells represent an effective method for utilising any flexibility in the operation of a large number of small-scale distributed resources. If the installed capacity of local generation is, as forecasted, going to make up a significant part of the UK generation mix, its participation in system operation must be considered. The participation of local generation in the UK electricity market prior to gate closure is examined in section 3. From a system balancing or ancillary service perspective, cells represent resources that can be allocated objectives within limitations of their declared capabilities; both in terms of absolute capacity to perform a task and the time in which it can be accomplished. Given the hierarchical nature of the control structure proposed and the response time of equipment, cells may not generally represent a fast acting resource and could in many instances be regarded as a secondary asset.

2.6 Key Research Questions

A number of research questions can be formed with regard to the HDPS cell concept from a technical perspective and are listed below. It must be noted that the specific answers to these will depend upon those given to the main questions discussed in section 1.1.2.

- What are the appropriate minimum and maximum sizes for cells?

    - What is the most appropriate methodology for demarcating calls and what are the main criteria to be used?

    - Minimum size – as demarcated by the distribution from secondary or primary substations? At what scale does the cell become insignificant as a resource?

    - Maximum size – using the boundary demarcated by Grid Supply Points (GSP) onto the transmission network? Would this simplify the interaction of distributed resources with the transmission system, i.e. reduce the number of entities? (This refers to participation in the balancing mechanism as a coherent system resource and not to the selling of "spill" to a supplier.)

- How are cells to be characterised? This particularly refers to specification of services that can be performed.

    - Much work has been done in the past to classify load types and this allows for complex aggregation of demand groups for simplifying studies. Does a similar process need to be applied to generation technologies? This would allow for cells to be represented as "black boxes" and when cells are grouped hierarchically gives a good degree of functional abstraction. (This would of course assume that internal constraints are managed appropriately and that any control functions are well defined.)

    - How can the diversity between groups of similar small generators be established? This will be essential for the aggregation noted above.

    - What are the behavioural characteristics of various cells? The parameters required for an assessment of:

        - System service provision – ramp rates, capacity provision, uncertainty, etc
        - Transient response – stability of generation

- What control functionality is required within a cell? Specifically:

    - What data is required on a cell's distributed assets and what update frequency is appropriate?

- What ICT platform should be used for the implementation of the required control functionality?

- Does the cell control always require accurate knowledge of the state of its distributed energy resources or is there sufficient diversity and sufficient confidence in the characterisation of many small sources to adopt a broadcast-type control?

- What are the network technology requirements for the devices that will enable cells to meet their objectives?

3 Market & Regulatory Structure

The current trend across Europe, in energy trade, is towards larger, more liquid and less centralised energy markets. Competitive energy trade is one of the key pillars of UK and European energy policy. It is almost certain to remain so throughout the period of time with which the work of this consortium is concerned. How then might the mechanisms of trade be structured so as to continue to promote efficient use of resources and support system level requirements under the technical scenarios proposed in this project? There are rich challenges associated with answering this question. A competitive electric energy marketplace is a unique environment. The traded commodity can not be readily stored in bulk and must be delivered in real-time. There exist inherent monopolies in the wires and the physics of energy flow in a power system necessitate advanced techniques of analysis. An HDPS differs from a conventional power system in several key ways that impact on the structuring of an energy marketplace. These include the:

- Increased number of electric energy sources and lower average rated capacity
- Increased penetration of un/semi-controllable sources and controllable loads
- Connection of controllable energy resources to lower voltage and less reticulated areas of the network
- Increased weighting on the objective to reduce greenhouse gas emissions

The following subsections explain these particular issues further and the opportunities for research that they offer. This is followed by a list of key research questions that the consortium would like to address.

3.1 Increased source granularity

In terms of demand the UK power system is already highly distributed. As outlined in Section 1.1.1 above, the number of generators, controllable loads and storage systems is expected to be much greater in a HDPS. However, there are at present already a reasonably large number of generators supplying energy to consumers and the mechanisms currently in place to facilitate the trade of their power may be adaptable.

Consumers and owners of small-scale generation will continue to desire protection from the risks associated with the wholesale marketplace. Today's typical domestic and commercial supply contracts between consumers and energy retailers offer such protection. As the penetration of DER grows the role of energy retailers offering aggregation services will likely grow as more plant owners come to desire representation in the marketplace. While there are a great many ways in which this aggregation may be arranged it is essentially just a contractual arrangement. A much larger challenge lies in the operation and control of a system in which the state of plant is principally determined by a decentralised free market. The network may be divided into "cells" (See Section 2) for the provision of a single point of control, but each cell may contain individual items of plant being aggregated by different companies. Controlling the DER, so as to adhere to system constraints, must be done in the most economically efficient, in the least environmentally damaging manner and according to contracted access arrangements. Furthermore, the details of any control measures undertaken must be fed back to the marketplace such that they may be taken into consideration during the settlement process. This interface between the technical domain and the commercial mechanisms requires formal modelling in order to be described effectively such that the consequences of certain structural choices may be researched.

3.2 Shifting of control

Citizens have grown accustomed to drawing power as they wish from the grid. System loads are by and large passive and, with the exception of dual rate white metered loads, only the largest make adjustments to their consumption according to price signals or system conditions. It is likely that the fluctuating nature of the power output from generators exploiting renewable energy sources will necessitate an increase in the adoption of active loads. As control shifts from being almost purely supply-side, an opportunity opens for the energy marketplace to offer appropriate consumer choice, not only in terms of cost, but Quality of Service (QoS) also. At the same time advances in smart metering holds the promise of conveniently supporting such a migration.

3.3 Reduced reticulation

The connection of controllable energy resources to lower voltage and less reticulated areas of the network may also offer new possibilities for structuring the relationship between the market and the system for management of network constraints. There are generally three options for power system constraint management.

1. Only permit the formation of energy trades if delivery is physically feasible.
2. Impose delivery charges which increase as network constraints are approached.
3. Request extended bids and offers which include costs associated with the adjustment of participant's desired position.

The third option most closely describes the method currently used in the United Kingdom. In a highly reticulated network it is difficult to determine the direction of each participant's energy flows. In turn, this poses difficulties in determining if a particular delivery is feasible and which participants are responsible for congesting the network. Distribution networks are typically less reticulated than the transmission network to which the majority of generation is connected at present. Therefore, there may be opportunities to utilise options one or two in an energy marketplace for an HDPS.

Furthermore, the lower voltage of distribution networks may open up opportunities for more widespread use of power electronics technologies such as FACTS and phase shifting devices. These would provide a limited ability to direct the flow of electrical energy. How this might be managed on a wide scale and how efficient interaction with the marketplace might be achieved is open to investigation.

3.4 Dual objective optimisation

Along with concern over the UK's dependence on natural gas imports, concern over the environmental impact of electricity generation is a primary motivator for a move to HDPS. Increasingly, the energy marketplace simultaneously minimise costs to the consumer and encourage reduced emission of greenhouse gasses. The European Union Greenhouse Gas Emission Trading Scheme (EU ETS) is an example of how a second marketplace running parallel to electricity trade, in this case trading allowances, may give weight to this new objective. There are other ways in which the greenhouse gas output of certain technologies may be taken into consideration and this is a subject of research for the consortium.

3.5 Aims

Several opportunities for research have been outlined at a high level above, and these together require a significant body of ,work. However, choice in QoS and alternate mechanisms for GHG emission trade, while interesting, are somewhat independent from more fundamental concerns and as such may be considered secondary. It is appropriate as an Engineering consortium to be positioned towards the technical aspects of the marketplace and as such the specific aims of the current effort are to:

- Model the technical and commercial elements of an energy marketplace and formally define their interfaces
- Investigate constraint management techniques to determine if those not suitable under the current system may be applicable under HDPS.

3.6 Key Research Questions

As effort continues in the modelling and simulation of elements of an HDPS, the following key research questions remain in focus:

- Will the organisation and transaction costs associated with the operation a competitive energy marketplace for a HDPS exceed the benefits of competition?
- What degree of DER aggregation is necessary for efficient functioning of the marketplace?
- What relationship is necessary between the system of network control and the marketplace to allow supply stability to be maintained while permitting open competition to drive down costs to the consumer?
- What opportunities are there for offering consumers choice, not only in terms of cost, but QoS also?
- What is the point at which savings to the consumer outweigh the inconvenience of lower QoS?
- What techniques for the management of network constraints are most appropriate for a HDPS in which substantial quantities of generation are connected at the distribution level?
- What system of subsidy or emissions trading may be implemented such that an appropriate mix of plant types is promoted in a cost effective manner?
- What signals do those in the commercial sector require in order for investment in the correct technology to be encouraged and that ultimately reduce costs to the consumer?
- How may competitive energy marketplaces permit participation by plant types with highly intermittent output?
- If renewable energy resources are to be utilised for environmental reasons, what impact is this likely to have on energy prices and is this justified by the benefits?
- What impacts have network flow limits and other technical constraints on market operation and how might the introduction of locational or zonal pricing measures affect the market?

4 HDPS Network Application Case Studies

The HDPS concept has been applied on a radial suburban network as a case study to demonstrate its large scale deployment on realistic networks. For the purposes of study the network model has been taken from the UK Generic Distribution System (UKGDS) library [10] which has been built with extensive industrial consultation.

In each case, cells will be demarcated based on the characteristics of the network and its assumed consumers and local generators. The hierarchical structure that is applied to each type of network will illustrate the different objectives from a system perspective that could potentially be allocated. Clearly at this stage many of the previously highlighted research questions have not been concluded. The following case studies have been developed by making some early decision of what may be appropriate, and are provided here specifically to provoke a debate on the relevance or appropriateness of these choices and to gauge the benefits foreseeable.

4.1 Case Study I – Radial Suburban Network

4.1.1 Suburban Network Overview

A single line diagram of the UKGDS EHV3 network is shown in Figure 7 and is representative of that to be found within a suburban area within the UK. The network is supplied from a grid supply point (GSP) containing two 400/132kV transformers and uses 132, 33 and 11kV distribution voltages. Overhead line circuits are exclusively used at 132kV and a mixture of overhead line and cable circuits are in use at the lower voltages. Two transformers with on-load tap-changing are installed within all BSP (132/33kV) and primary substations (33/11kV). The minimum level of supply security is set by providing dual radial supply circuits for each HV substation, and interconnecting circuits exist for deriving a supply from an adjacent network supplied by an alternative GSP. LV 400V distribution is not explicitly modelled as part of UKGDS and it has therefore been assumed that the supply arrangement is based on that shown from a primary substation in Figure 6. The demand on this network is a mixture of residential and industrial, with both single and mixed demand groups (principally as observed from primary substations).

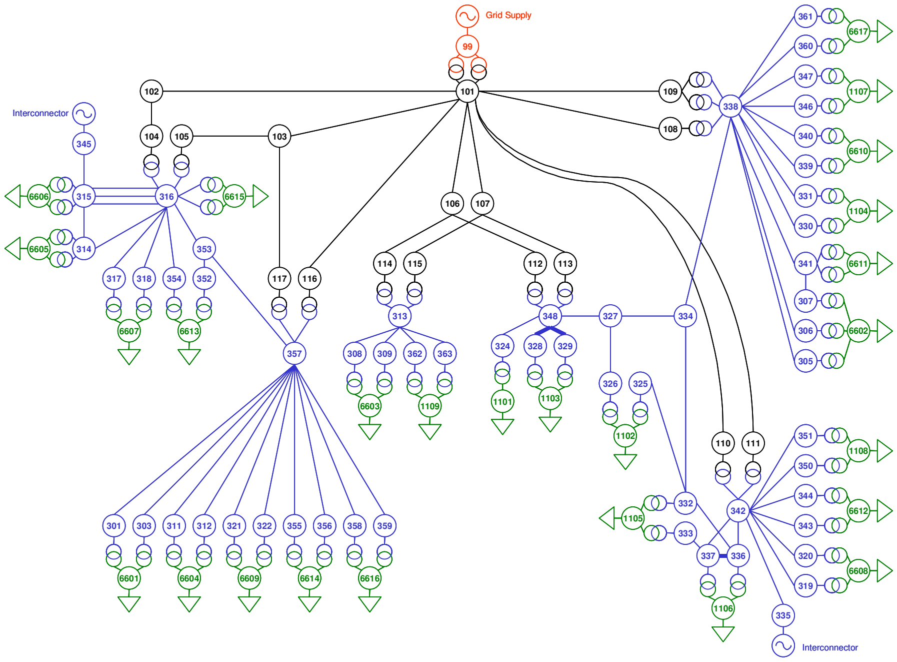

Figure 7: UKGDS EHV3 - Radial Suburban Network

4.1.2 Allocation of Network Cells

The network cells have been allocated to an area as shown in Figure 8, with the smallest cells assumed to have been allocated to encapsulate the distribution from primary substations. Larger cells have been allocated at BSP (A – C) and GSP with the consequential creation of a hierarchical structure.

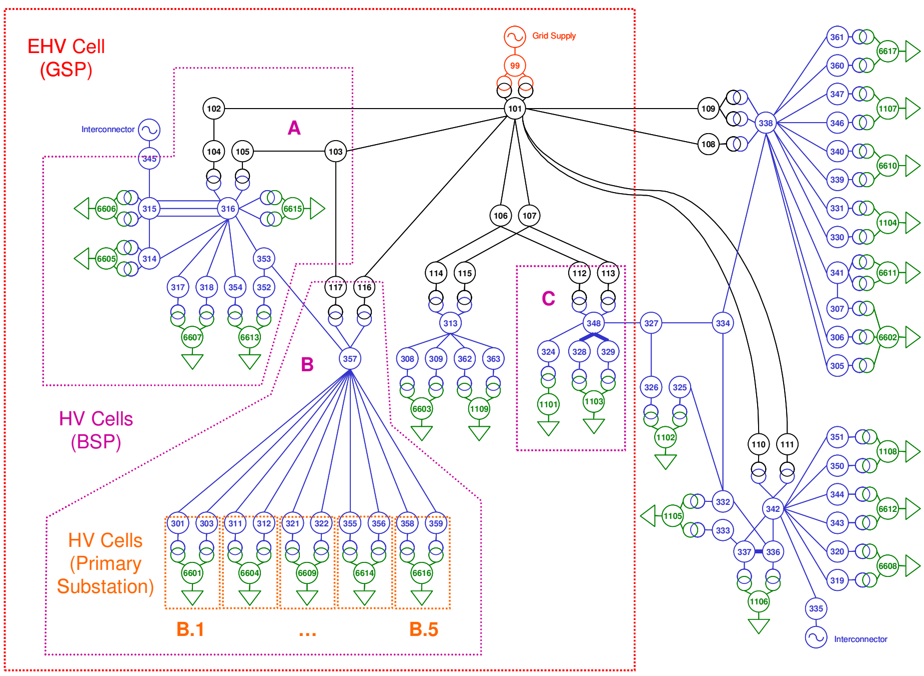

Figure 8: Allocation of Suburban Network Cells

The allocation of HV cells B1 to B5 at primary substations has been assumed to have been made based on there being high levels of generation connected, either directly at 11kV or in the form of microgeneration at LV. Other cells could have been allocated within A and C but have been omitted for clarity – alternatively the larger cell may represent an area of lower DER density. A summary of the distributed resources available to each cell and their objectives is provided in Table 1. Each cell has a management controller located at the main substation within the cell and can communicate with the cell above and its distributed resources. The flow of data is shown in Figure 9 and in effect utilises the data concentration principle widely used as part of existing SCADA systems. However the additional link between cells A and B has been added due to their direct electrical interconnection.

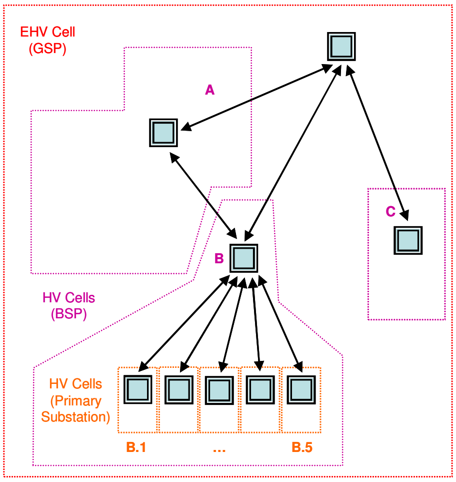

Figure 9: Suburban Cells Data Flow

Cell	Resources	Objectives
EHV	• Cells A, B and C	• Control of import/export through grid connection [External]
A	• Generation connected at 33kV onto BSP • BSP Transformer OLTC • Network reconfiguration assets	• Regulation of 33kV network voltages [Internal] • Control of import/export through BSP [External] • 33kV network fault level [Internal]
B	• Generation connected at 33kV onto BSP • BSP Transformer OLTC • Cells B.1 – B.5 • Network reconfiguration assets	• Regulation of 33kV network voltages [Internal] • Control of import/export through BSP [External]
B.1 – B.5	• Primary Transformer OLTC • Generation connected at 11kV • Specified groups of LV microgeneration • Flexible demand	• Regulation of 11kV network voltages [Internal] • Control of import/export through Primary Substation [External]
C	• Generation connected at 33kV onto BSP • BSP Transformer OLTC • Network reconfiguration assets	• Regulation of 33kV network voltages [Internal] • Control of import/export through BSP [External]

Table 1: Summary of Suburban Cell Distributed Resources

The functionality of the management controller for each cell is based around a standard off-the-shelf embedded controller. A simple database is maintained of a cell's distributed resources and their status. Appropriate software is provided to utilise the available distributed resources in order to satisfy the given internal and external objectives. The capabilities of each cell are visible to external entities and are updated on a regular basis.

4.1.3 Example Operational Task – GSP Export Increase

As an example, consider that the EHV cell is given the objective of increasing real power export to the grid within a specified time frame that is appropriate given the declared capabilities of the cell. The main stages of achieving this objective for the EHV cell are shown in Figure 10.

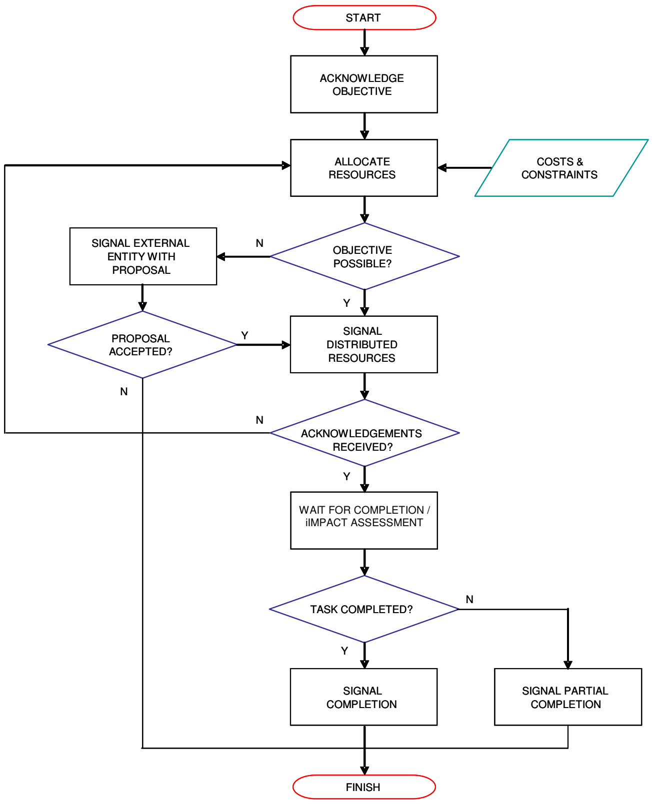

Figure 10: Case Study - GSP Export Increase Flowchart – EHV Cell

The EHV cell management controller will first acknowledge receipt of the objective and will then optimally allocate resources according to a predefined cost function and set of constraints. This optimisation problem will take into consideration both the financial and carbon costs associated with using a particular resource as well as their technical attributes. If an acceptable solution has been reached, appropriate objectives are set for the cell's resources and then signalled along with a request for an acknowledgment. However, if an acceptable solution cannot be obtained, the EHV cell will signal the external entity and provide notification of how much of the objective can be met given the current availability of resources. The external entity may then accept this offer and signal appropriately. Upon receipt of this the EHV cell management controller will signal its resources according to the accepted solution. The failure to receive an acknowledgement from distributed resource will necessitate the reallocation of resources to meet the objective.

For this example the cost function will be based on the relevant attributes of cells A, B and C with respect to the fuel and carbon costs of their generation technologies (including the costs associated with shedding load if generation cannot be increased) and any EHV network constraints.

The EHV cell's distributed resources will signal upon meeting their objective and this will be confirmed by the management controller using primary system measurements. A confirmation signal will then be sent to the originating external entity to complete the process.

The process within the lower level cells is very similar to that given for the EHV cell in terms of the allocation of resources – opportunities may exist for certain cell operations even in circumstances where limited DER status and network information is available. Taking cell A as an example, its objective is met using the 33kV generation connected to the BSP. However, a constraint in the form of network fault level could arise and thus additional network splitting could be required if additional units are operating. Mitigation of this constraint would make use of the network reconfiguration assets according to the solution of the resource allocation problem.

5 The Evolution towards HDPS

The HDPS concept represents a long term vision for the electricity supply system in the UK and is a clear departure from the dominant prevailing approach of meeting demand from new central generation, say for example the Government's proposed new nuclear build programme, or the plans for large new carbon capture ready ultra super-critical coal plant. If the system is to move towards this alternative vision, it is critical to evaluate the capabilities of HDPS in terms of attaining the key metrics for reduction of losses, reduction of carbon emissions, reliability of supply, reduction of cost, all subject to systems constraints. The industry has to know whether the move towards a highly distributed future part of the solution to the challenges that the electric industry is facing today. Also, a transition towards a "many loads – many sources" future will prove a test to the different stakeholders within today's electric industry as they will be required to adapt their practices to a new and changing environment. In this context it is important that the potential and limitations of the HDPS approach is quantified.

In this section, the use of Distributed Energy Resources planning techniques for evaluating HDPS capabilities is discussed. Besides this, the role of planning Distributed Energy Resources in informing the transition towards HDPS is analyzed and some of the challenges that traditional network planning practices will face are discussed. Finally, relevant research questions that remain to be answered are presented.

5.1 Towards HDPS under a Multi Objective Perspective

Distributed Energy Resources planning, namely the procedure of optimising the use of distributed resources in a particular distribution system given a set of objectives and constraints, can provide valuable information about the potential of HDPS and define the targets that can be reached with an optimal use of available resources. Even if the planning exercise is performed at a cell study level, it can reflect the challenges of the system as a whole. The particular objectives of HDPS as previously mentioned are: reduction of losses, reduction of carbon emissions, reliability of supply, reduction of cost, subject to systems constraints. It is unlikely that a single planning solution will satisfy all of these. Trade offs between the objectives are necessary. Therefore, multi objective planning tools can help to illustrate these trade-offs, and reflect in an appropriate way the perspectives of different market players.

As a first step it is necessary to define the particular requirements for an adequate DER planning technique for HDPS evaluation. These requirements are amply discussed in [11]. It is defined that an appropriate planning technique to be used in the HDPS context should consider:

- Multiple Objectives: As aforementioned, the single objective planning paradigm is no longer useful in an environment where several instances interact, and where the importance of one objective in relation to other is difficult to define. Additionally, a multi objective approach permits the inclusion of non-monetary terms in the planning process.
- Flexibility: An appropriate planning technique requires a high degree of flexibility in terms of the objectives and constraints considered. These should be dictated by the planner (or researcher) and not constrained by the technique itself.

- Uncertainty: HDPS will create an environment of increased uncertainty, both in terms of local generation production and in terms of the temporal and spatial distribution of loads and generators. As a result, the planning technique must be able to cope with the most relevant uncertainties of the study.
- Dynamic Energy Profiles: Similarly, the intermittent behaviour of some energy sources and the increased variability of loads at a distributed level create the need of considering the whole energy profiles in the study. The "peak load" or "worst case" scenario planning approach is no longer useful, as the temporal relation between generation and load gains importance.
- Dynamic Planning: Finally, the dynamic nature of the planning process must be considered. This refers to the changes of the power system over time (loads and generators) and the possibility of investments happening at different points in time. While this requirement is common in power systems planning, there are few techniques that include it, as it proves to be quite demanding in computational terms.

5.2 Planning in an HDPS Context

Section 5.1 focuses on the use of planning techniques to evaluate the potential of future HDPS. However, it is also necessary to consider the role of Distributed Energy Resources planning in guiding the development towards this HDPS future. While the focus of power systems planning in a deregulated environment is to find the best schedule of investments to serve a future demand, it is unlikely that a liberalized market where investor's (and consumer's) liberties and choice are highly valued will change towards a centralized system where local generation location, type and sizes are dictated by central government. However, the knowledge of what constitutes an optimal distribution of local generation (and resources) can guide benchmarks for grid operation and development, and inform further proposals of policies and incentives. Adequate policy tools and market signals can guide the development of the power system in an optimal manner to achieve HDPS objectives. Therefore, appropriate DER planning techniques, that consider the requirements numbered in the previous section, can serve as valuable source of information for policy makers and electric industry stakeholders.

A similar discussion to the one proposed in section 1.1.2.(i) needs to be addressed while considering local generation planning. Should LV connected micro generation with a low degree of controllability be assumed just to modify the aggregated demand profile and ADMD? Under this premise micro generators with a low degree of controllability will be considered as negative loads, and not as planning resources whose location, type, and size can be decided. Clearly, in the case of distributed generation, with larger capacities or increased controllability, it is rational to consider them as a system planning resources whose location, type and size should be evaluated (if not decided). Additionally, if they are available, distributed resources as storage and Demand Side Management need to be included in a planning analysis.

When considering current network planning practices, it is clear that an HDPS future will have a considerable impact and that current planning techniques will need to be adapted accordingly. Aggregated load profiles will change due to micro-generation. Distributed generation and the uncertainty related to diverse energy sources will require to be considered in the network planning process. Also, future options of grid reconfiguration or automation must be considered. Appropriate network planning techniques that might include scenario analysis, risk analysis, decision theory, fuzzy models and similar techniques will have to be adopted or developed if appropriate. Certainly, this is one avenue of further research that should be pursued by this or other Supergen consortium.

Other aspect that needs to be analyzed is the possibility of Distribution System Operators (DSO) to include distributed generation (and/or other energy resources as storage) as investment options in future network developments plans. Current regulation does not allow DSO to invest in, own or operate Distributed Generators for network support. As a result, regulation should be adapted, either to permit DSO to invest in DER when appropriate, or to put in place adequate incentives that allow the investments to happen in the right places.

Moreover, in a HDPS future, network developments (that might include DER investments) will need to respond not only to a minimum equivalent cost objective (which might include equivalent cost terms for losses, carbon emissions and other attributes), but also consider other objectives harder to be quantified as cost such as reliability, energy quality or environmental impact. As a result, network planning techniques could benefit from a multi criteria approach, already discussed in previous paragraphs. Visualization of all the possible trade-off between competing objectives can be an invaluable source of information for adequate decision making.

A HDPS future proposes local generation of electrical and thermal energy. A considerable number of micro generation technologies for heat and power use natural gas as primary fuel. Therefore, if an optimal use of resources if going to be looked for, it is natural to think that network planning should not be restricted to the transport of electricity (electrical network planning), but needs to include gas networks and heat transportation, if this can take place. While optimizing each of these networks separately could guarantee an optimal use of resources, it is more likely that integrated energy systems planning will lead to a more efficient solution. At present, some energy companies are not only providing electrical energy but also natural gas to customers. This trend is likely to continue in a future where energy transformation can be localized and in small scale. Therefore, it can be expected that integrated planning techniques would be required in a HDPS future.

In the HDPS future a significant proportion of electricity will be produced locally. It is expected that the role and importance of the transmission network will change. While the bulk of energy will no longer be transmitted from centralized power plants to distributed loads in the same quantities, the transmission network will still play a key role in permitting the flow of energy between different HDPS cells, and ensuring the energy diversity and reliability of the system. In this context, it is necessary to analyze how will current transmission network planning techniques will need to be adapted. Which would be the drivers for the expansion, or replacement of equipment, of the future transmission system? How will HDPS cells be considered from a transmission planning perspective? These questions have no easy answer, and become much more intriguing if the role of different energy carriers (i.e. natural gas networks) is considered. If a strict optimal use of resources is a priority, different energy carrier’s networks will need to be planned in conjunction, as its interdependence is increased in the HDPS future.

Moreover, while distributed energy resources will provide a great share of the energy consumed, the remaining and newly built centralized generation (renewable, nuclear or cleaner fossil fuel based) will be required to ensure system balance. Can this key balance be ensured by a competitive market? Or which market signals can be put in place to ensure that an adequate balance and generation margin exists in the system as a whole? In an extreme scenario would centralized generation for system balance need to be planned centrally?

5.3 Key Research Questions

How to guide the transition towards an HDPS future is one of the main research challenges of this consortium; however, specific research questions can be posed in terms of what was outlined in this section. Research continues towards the implementation of a DER planning technique. In order to develop an appropriate framework that could be use to analyze HDPS potential some of the main questions that remain to be answered are:

- How should the controllability of DG be included in the planning process, as controllability will depend on the market framework proposed?
- Which is the best way to aggregate micro generation energy profiles to be included in the planning process?
- How can other Distributed Energy Resources (storage, Demand Side Management) be modelled to be included in a planning framework?
- What is the sensibility of the solutions in relation to the quality of the input information?

Other challenges are related to questions that were already presented in previous sections. Particularly, regarding the market framework that could be put in place in HDPS and how HDPS cells will be allocated, in terms of size, resources and functionality.

HDPS cells are an innovative concept and in relation to planning techniques some questions that need to be answered are:

- Can HDPS cells be considered as a system resource from a network planning perspective?
- Which is the best configuration for an HDPS cell regarding different objectives, and assuming that location, size and type of distributed resources can be decided?
- Can DER planning guide the allocation of cells in terms of size, resources?
- How will transmission planning techniques need to be adapted for the HDPS future?
- How will HDPS cells be considered from a transmission planning perspective?
- How can system balance be ensured?

Finally, some other questions that were introduced in this section and that need to be considered as further research avenues are:

- Should Distribution System Operators be able to invest in and operate DER for network support?
- What are the requirements and specification for an “integrated energy systems” planning technique?

6 Conclusions

This discussion paper has elaborated on the HDPS approach to power generation and use and has highlighted promising technical/economic approaches, in particular the cell concept and associated market structure and planning issues as key areas for research:

6.1 The Cell Concept

The cell concept has been presented as a potentially attractive but flexible mechanism for the utilisation of local generation and controllable demand as a system level resource where applicable, and more generally means of mitigating network connection constraints on local generation. This is regarded as being vital for ensuring support for the widespread use of distributed resources and demonstrates their potential value for not only providing a mechanism for loss reduction by reducing bulk power transmission levels, but also for collective active participation within the interconnected system. The functionality that cells possess will depend on the role that different types of local generation are allocated. It is therefore vital that the behaviour and control functions of these units are well understood. Moreover, the performance requirements for specific interfacing and network supporting technologies must be clearly explored.

6.2 Market & Regulatory Structure

A competitive marketplace for trade of electric energy and a system of regulation for the industries inherent monopolies are seen as essential components of an HDPS. The specification of such economic mechanisms must be goal driven and the consortium intends to investigate the available options for their design. The objectives of a HDPS marketplace are to reduce costs to the consumer and to reduce negative environmental impact caused by electric energy generation. The primary goal in this area of research is to establish which financial mechanisms allow these objectives to be most effectively achieved.

From a high-level perspective structures for market architecture may be divided into the centralised and into different degrees of decentralisation. There are benefits associated with all and will have to be the subject of investigation. The close relationship between the marketplace and the system of network control is recognised and the same concepts of decentralisation will be applied in the technical domain also. Modelling of technical and commercial aspects of an HDPS is underway, but focus remains on the ability to answer key research questions using the associated software.

6.3 The Evolution towards HDPS

If the move towards HDPS is to be evaluated and indeed justified, appropriate tools are required to asses the effectiveness of HDPS to achieve its objectives under the perspective of the different entities participating. Planning tools, based on the principles of optimisation and multi criteria analysis, can provide useful information of what is the potential of HDPS and what targets can be reached with an optimal integration of local generation.

What's more, the transition towards a highly distributed structure of power systems will require current network planning techniques to be adapted. These will need to take into account the increased levels of micro and distributed generation and the related uncertainty. Moreover, increased local generation of heat and electricity and a growing concern about the optimal use of resources will require the development of appropriate integrated energy planning techniques.

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8 List of Abbreviations

ADMD	After Diversity Maximum Demand
BSP	Bulk Supply Point
CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat and Power
DER	Distributed Energy Resources
DG	Distributed Generation
EHV	Extra High Voltage
EPSRC	Engineering and Physical Sciences Research Council
GSP	Grid Supply Point
HDPS	Highly Distributed Power Systems
HV	High Voltage
ICT	Information and Communications Technology
LV	Low Voltage
NETA	New Electricity Trading Arrangements
OLTC	On Load Tap Changer
ROC	Renewable Obligation Certificates
UK	United Kingdom

APPENDICES A & B

Appendix A: Supergen III – Highly Distributed Power Systems

Academic Partners Imperial College London, Loughborough University, University of Bath, University of Manchester, University of Oxford & University of Strathclyde

Industrial Partners Rolls-Royce plc & ScottishPower EnergyNetworks plc

A.1 Key Objectives

The main objectives of the Consortium's programme of work are as follows:

- Identify the most effective conceptual design for the realisation of a highly distributed power system (HDPS).
- Creation of an integrated appraisal framework for the economic, environmental and technical assessment of HDPS.
- Assessment of market transformation and network access approaches in support of HDPS development.
- Realise a simulation facility capable of characterising, modelling and appropriately analysing the behaviour of a HDPS.
- Engineering of management and control system for effective coordination of DERs in HDPS.
- Realisation of DER inverter interface and control modes compatible with HDPS control, protection and power quality requirements.
- Demonstration of modular DER integration and interfacing.

A.2 Research Themes

Electrical power system design, modelling, analysis
Through the realisation of models and analytical tools, the Consortium is testing the feasibility of a power system utilising many small DERs. In so doing the work will provide better understanding of the behaviour of DERs and network customers with such devices. Furthermore the cumulative and interactive behaviour of many small devices will be demonstrated, and the impact on network operation assessed.

Power system economics and market mechanisms
Appropriate charging mechanisms are required to incentivise any move to suitable DERs. Both long term and short term market signals need to be assessed. The Consortium will examine alternative measures for the realisation and operation of a HDPS.

Integrated appraisal of energy systems
A framework will be developed by the Consortium to assess the technical and economic feasibility of HDPS and also to examine the fiscal and regulatory context required to facilitate these developments where they have been identified as beneficial. This is a multifaceted problem whose many varied features will require careful and equitable combination. This will contribute to the better assessment of energy system design options.

Protection, control and communications interfacing
Effective integration of small scale DERs within an operational environment is required if they are to be coordinated to provide desirable influence on the power system. The attainment of mechanisms for plug and play integration features will be essential.

Power electronic interfacing
The realisation of "network-friendly" power interfaces for the modular connection of DERs of various types will support the possible realisation and manageable connection of many devices.

The systems approach adopted by the Consortium will support the cross-disciplinary collaboration and the realisation of modular network integration solutions.

Appendix B: Microgeneration Typical Electrical Outputs

B.1 Microwind

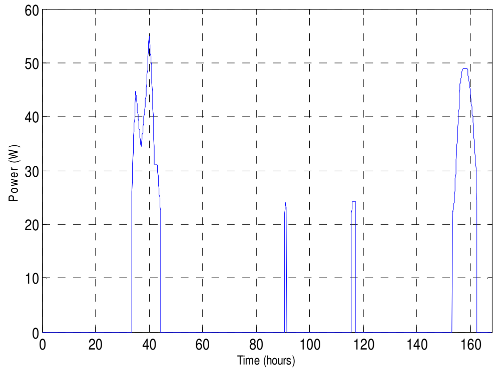

Figure B.1: Simulated generation profile for a 1kW microwind turbine located on the roof of a dwelling in an urban area for a typical transition winter week

B.2 PV

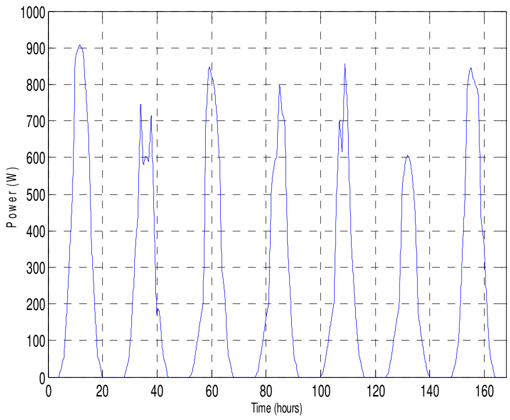

Figure B.2: Simulated generation profile for a 1kW solar array of a detached dwelling for a south facing module in winter

B.3 Heat Led MicroCHP

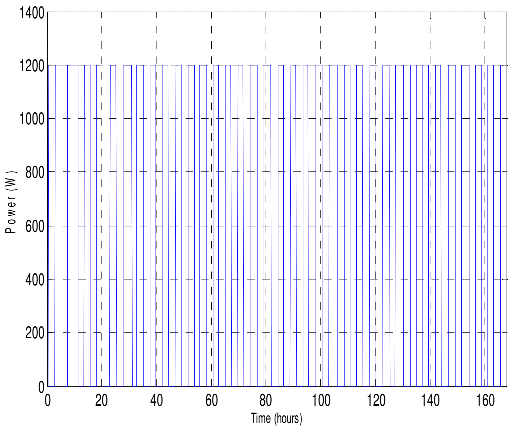

Figure B.3: Simulated generation profile for an internal combustion engine MicroCHP unit supplying water and space heating to a semi detached dwelling with continuous occupancy during winter