Programme Area: Smart Systems and Heat

Project: EnergyPath Operations

Title: Developing Whole–Systems Analysis to Explore Future Great Britain Energy System Challenges

Abstract:

A working prototype of EnergyPath Operations has been used to test the dynamic operation of elements of an architecture, as a set of detailed business processes across three domains: markets, physical assets, flows of information & control. This report sets out the learning from this exercise.

Context:

DNV GL and a partnership between Hitachi & EDF worked independently on a functional specification to develop the first phase of EnergyPath Operations - a software tool that allows designers to better understand the information and communications technology (ICT) solutions they will need to implement to deliver new home heating solutions.
A first version of this tool is now being developed by DNV GL and the Energy Systems Catapult. EnergyPath Operations will provide knowledge to users on how to design ICT systems, the cost implications of such designs and the viability of various systems.
This project compliments the EnergyPath Networks software modelling tool which will be used in the planning of cost effective local energy systems.

Developing Whole–Systems Analysis to Explore Future Great Britain Energy System Challenges

Case Study: Facilitating Markets for Mass Deployment of Hybrid Heat Pumps in Localised Areas

Smart Systems and Heat Phase 1 – Work Package 3

Final Technical Summary Report

Document Control

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	Name	**Position**
Author	Daniel Mee	Senior Manager – Energy Systems Architecture, Innovation
Reviewer(s)	John Batterbee Richard Halsey	Head of Architecture and Transformation, Innovation Programme Manager
Approver	John Batterbee	Head of Architecture and Transformation, Innovation

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Smart Systems and Heat Programme

Heating accounts for almost one third of total UK carbon emissions; to achieve the 2050 target of an 80% reduction in carbon emissions, the UK must decarbonise the domestic heating market at the rate of 20,000 homes a week by 2025 – the current rate is less than 20,000 homes a year.

Given the importance and challenge of decarbonising heat, the ETI established a Smart Systems & Heat programme (SSH). The programme aims to create future–proof and economic local heating solutions for the UK. This is by connecting together the understanding of consumer needs and behaviour with the development and integration of technologies and new business models to deliver enhanced knowledge to facilitate a UK heat transition from 2020.

The Energy Technologies Institute (ETI) launched SSH and funded Phase 1 of the programme, which was delivered by the Energy Systems Catapult and its partners. This document is one of a series of final reports and outputs from Phase 1.

Executive summary

Tools and approaches for a successful transition – from analogue and high carbon to digital and low carbon, delivering economic success while reducing systemic risk

Phase 1 of the SSH Programme has addressed three topics within a transition to a world–class decarbonised UK economy:

- Changes within individual homes in terms of fabric, heating systems and control
- Strategies and spatial planning for local areas in terms of economic, social and emissions goals and the energy distribution networks and supply chain activities required to support the transition across tens of thousands of homes and businesses
- The operation of the whole UK energy system, both as a series of markets and businesses and also in terms of the control and integration of the millions of individual sub–systems that deliver cleanliness and comfort (and other energy services within and around buildings)

Each of these themes was addressed by a series of development activities in SSH Phase 1, called "work packages". This report provides an overview of the third work package, concerned with business operations. The main outputs of this work package are:

- A Business Model Game, which is designed to facilitate workshop sessions to enable people to construct new models for domestic energy service delivery, by combining a set of building blocks in different ways[1],[2].
- A discussion of the fundamentally different ways that an energy system might be constructed and governed, with 12 different architectures used to illustrate the thought process.[3]
- A set of detailed business process models within the software tool Sparx Enterprise Architect for the test case of the operation of hybrids of gas–boilers within one of the architectural examples in the previous output.
- A working prototype of EnergyPath Operations – a simulation tool to test the dynamic operation of elements of an architecture, as a set of detailed business processes across three domains: markets, physical assets, flows of information & control.

This report also has a considerable amount of technical detail on Sparx EA and the processes captured within it, and on the EnergyPath® Operations prototype. The most detailed information is attached as Appendices. As well as the key documents referenced in this report, there are very many deliverables from the work package, which can be found in the ETI Knowledge Zone.

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[1] Five promising consumer business models to transform low carbon
heating and well-being in the home - engagement pack, ETI Knowledge Zone

[2] (the game itself)

[3] Energy Systems Architecture Methodology: Enabling Multi-Vector Market Design, ETI Knowledge Zone

Each of the outputs has been tested and validated in different ways, as can be seen from the supporting reports and documentation. Together they provide a toolkit to explore the possible ways that a future UK energy system might provide a better environment for innovation and competition, in order to better meet the needs of consumers while delivering affordability, reliability, sustainability and social equity.

The test case of hybrid heat–pump operation was used because it often emerges from wider systems analysis by ETI and others[4] as a potentially attractive solution for domestic heating in the UK, at least out to 2050[5]. It also provides a number of challenges that the current Energy Systems architecture cannot solve, not least the close coupling of gas and electricity as sub–systems, economically and operationally. The specific system architecture was chosen both because it is different enough that it forced the team to work through the detail from a clean sheet of paper, and also because it has some attractive features.

The result of the work is not a conclusion that hybrid heat–pumps or the specific architecture are the best solution but an illustration and validation of the tools that have been developed. However, one conclusion from the three work packages is that it could be possible, in the future, to deliver domestic energy services affordably, reliably, sustainably and equitably using hybrid heat–pumps and within a detailed system design that:

- Creates an environment where businesses have an incentive to deliver decarbonisation in the most cost–effective way, while keeping their customers satisfied and engaged.
- Consumers get better energy service propositions where suppliers can differentiate themselves and target specific customer segments, while retaining a fair share of the added value that attracts customers from these segments.
- Where people are able and willing to pay for services, the system architecture enables this.
- Where safeguards are in place to protect vulnerable consumers and deliver better energy outcomes for them.
- Many more people are more comfortable in their daily lives than the reality today, while primary energy use reduces[6].
- Market and governance structures incentivise the design, implementation and operation of the architecture end–to–end in order to avoid costly and unnecessary peak demands that are also high carbon events.

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[4] Reference required to non ETI example

[5] Options, Actions, Choices

[6] We were surprised how many households currently tolerate significant discomfort caused by poor design and control, despite being able to afford their energy bills. Work package 1 demonstrated this and the root causes quite conclusively. This situation makes people resistant to changes – in case they produce even worse experiences.

- Individual players within the system are able to participate without having to understand and sign up to many thousands of pages of standards, codes and other technical and legal documents. Where the design of a system is modularised, and based on explicit principles, individual players only need to understand their own business and its interfaces to the rest of the system.
- When new technologies and solutions are developed, they have an explicit entry route into the system without protracted discussions, such as for example battery storage technologies have stimulated in the UK.

We believe that these benefits are achievable through the use of architectural approaches and that SSH Phase 1 WP3 has delivered the beginnings of an architectural tool kit that is an important enabler of the debates, discussions and decisions of industry stakeholders, for them to deliver decarbonisation with economic and social benefits.

Enabling participants to invest in decentralised energy sub–systems, and for them to get a fair share of the benefits to the whole system, is not an explicit benefit of this approach. Any analysis of future low carbon energy systems will show that the proportion of investment in decentralised assets is much higher than today – battery electric vehicles, heating systems, micro–generation, building fabric, electricity and heat storage, local energy centres, etc. Any system that does not facilitate millions of individual investment decisions and the co–ordinated operation of these assets will struggle to be affordable, secure and low-carbon. The future of energy is intelligent agency, not command and control. Enabling decentralisation is therefore a mandatory requirement, whatever approach is taken. Many innovators see the current architecture as a barrier to entry and strongly inhibiting of innovation and competition[7].

The tools developed to support systems engineering, in systems as diverse as the Internet and new aircraft design, could have significant benefit within the future of energy. This learning has emerged from the work package 3 team within SSH Phase 1. In order to understand this, it might be helpful to use a metaphor from the ETI Perspective on Systems Architecture[8].

If we imagine a family home that has been in occupation over generations, it will have been extended, refurbished and redecorated many times. Over time it may have come to seem a little idiosyncratic and less than ideal – a hodgepodge of extensions and alterations. Now we face a situation where it needs radical change and major investment over a short period of time to meet a new set of requirements. We could continue with a series of one–off decisions and contracts, where we have different contractors working on different parts of the home, practically all of the time. This would have obvious risks and be likely to lead to a lower function building at higher cost, with major problems along the way.

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[7] https://www.theiet.org/sectors/energy/resources/modelling-reports/fpsa-challenge-6.cfm

[8] Tools for Future Energy Systems

An alternative would be to employ an architect to develop a set of options and then designs and contract structures to deliver some preferred combination of them. We see that major rebuilds of homes look better and work better when an architect is involved.

The proposition in this report is that a Systems of Systems Architecture approach should be adopted, not that a single "Architect" is appointed, nor that all decisions must be made up front. Testing the tools that have been developed in other industries shows that an architectural approach has significant potential benefits for the UK energy transition.

There remains the challenge of culture change and adoption. The transfer of these tools from people who understand them, to energy system experts who are unfamiliar with the tools and language and uncertain about the benefits is not straightforward. Within an environment like the Energy Systems Catapult, this is possible, but implementation will require much broader understanding and adoption. Stakeholders will need to find the solutions that work for them and to work across the industry to develop and adopt a shared architecture. The benefits of an architectural approach have been widely recognised[9]. This report describes the application of systematic architectural tools to the challenges.

This is quite a technical report. The main report gives an overview of what has been done, which should be accessible to the general reader who has at least an intuitive understanding of systems thinking. The more detailed appendices require a willingness to understand the concepts and tools that have been applied. The inducement for any organisation to absorb and reflect on this material is the proposition that the benefits set out above are available to a well-executed systems approach and that the risks of the hodgepodge approach are severe in terms of cost, timescale, mishaps and functionality.

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[9] https://www.theiet.org/sectors/energy/resources/fpsa/fpsa-background.cfm

I. Introduction

Most of the component technologies to decarbonise heating in homes are already available. Heat–pumps, insulation, district heating, hot water storage, batteries, control systems etc already exist. There are gaps – for example in our understanding of the safety issues involved in replacing natural gas with hydrogen for heating in homes, or (to pick one tiny component) in the availability within the UK of sufficiently long ventilation piping to span through a wall with thick external insulation. There are also significant opportunities for innovation and cost reduction, for example in novel compact domestic heat stores or better algorithms for heating control.

However, it would be fair to say that these technologies mostly need better engineering and supply chain development and integration into packaged solutions rather than fundamental innovation. Innovations are more likely to be in manufacturing and work processes and the integration and delivery of components, than in the individual technologies. Energiesprong[10] is a good example of the kinds of systems innovation thinking that is required. The level of investment required in this engineering and supply chain development is significant, as shown for example in the Hy4Heat[11] and HyDeploy[12] programmes.

As well as better engineered and integrated sub–systems, future energy systems will need to operate with different market arrangements, business models, service propositions, financing structures, policies and governance mechanisms. There is widespread agreement on the need for this, and also on the opportunity for innovation to add significant additional value. The digitisation of energy, as part of a broader trend, typically called "the Internet of Things", will open up possibilities that were not available before.

Although there is agreement that the future energy system architecture needs to be different and will be different, there are many competing and credible ideas about how it should be constructed and operated. The work package 3 team set out to explore all of the systems and operational issues that would need to be addressed if hybrid gas–boiler heat–pumps were to be implemented at scale, within the wider context of a future, decarbonised energy system. That context was set through whole systems high level analysis from ESME scenarios about the future evolution of the whole system at a high level[13]; from learning about local area planning for delivering emissions reductions across the three local areas, namely; Bridgend, Bury and Newcastle; and from real–world trials in buildings.

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[10] https://www.energiesprong.uk/

[11] https://www.kiwa.com/gb/en/products/hy4heat-project/

[12] https://hydeploy.co.uk/

[13] https://www.eti.co.uk/insights/options-choices-actions-uk-scenarios-for-a-low-carbon-energy-system

Just as current industry visionaries launched the Future Power Systems Architecture (FPSA) project, the SSH systems engineers were developing a systems analysis based on future states where hybrid heat–pumps were a functioning part of an effective decarbonised energy system. The FPSA project set out at a high level which issues need to be addressed and the SSH team outlined how they might be addressed.

The central message from all of this is that a decarbonised future UK energy system in a more digital world will not function the same way as the current system – it cannot. The expectations of better service that consumers are developing from other digitised industries will interact with the characteristics of new technologies to create a new situation, where experiences from the past may be actively misleading.

Innovation in individual technologies is not the most important element in this transition. Systems, governance, policy and business innovation and entrepreneurship are key, and technology is an enabler.

This report is divided into sections which explain the value of the work completed:

Section 1 describes the proposed methodology for initial systems engineering of the future GB Energy System. It starts with the idea that there should be a balance between top–down and bottom–up development. Top–down approaches are often tainted with the idea of a single decision maker delivering 'an answer' in a dictatorial fashion, however the rules of the internet and digital mobile telephony rules were created top–down and were still highly collaborative with industry members coming together to work on common goals.

We assert that workshops have a place for capturing ideas but that once the debate moves on to a level of detail with a large number of stakeholders then something formal is required. We have developed a process and set of tools which capture the ideas of many parties and allow them to be refined and integrated, where they're compatible or for compromises to be found, where they conflict. We have built in change management approaches so that it's easy to see which things and which organisations will be affected when another change occurs. We've built a full set of configuration management approaches too which allow for designs and ideas to be constructed and managed in multiple combinations. This allows for lots of ideas to be developed and tried out, in combination, much faster and much more cheaply than when that's done in isolation.

Section 2 concerns itself with a candidate conceptual architecture we took through the process described in section 1, developed against a single use–case description. This effort was undertaken to ensure that the process could be tried, reworked and improved. Most of this work was developed out into detailed design elements inside the SparxSystems® Enterprise Architect® Tool. Rather than recreate that work here, the whole repository of data has been made available for review.

Section 3 describes the development of the prototype EnergyPath® Operations (EPO) tool. The development of the tool has been the most significant undertaking for this project and has yielded results in a number of key areas; namely around dynamic network modelling and around predictive allocation of future technologies and behaviours to houses (e.g. heat pumps and estimated behaviour of consumers with time of use tariffs). The tool has been created to look at the performance of technology, market structures and business models in the context of all the parts of the system.

Section 4 then contains the analysis from the run–through of the process to illustrate the sort of outputs that EPO can create to gain insights against. It should be noted that the EPO tool is a prototype and that, as a result, the analysis performed is for illustrative purposes to show what can be achieved.

The Energy Systems Architecture Methodology[14] report explains the process used to down–select a single exemplar architecture, not as a chosen "solution" but rather something to use to develop the methodology described. That chosen architecture was analysed for problems and several risks were identified, alongside suggested approaches to de–risk the issues.

Dynamic systems simulation is an important generic de-risking tool. There is no currently available tool for multi–vector systems simulation and a significant part of the work package was to develop a prototype platform, EnergyPath® Operations (EPO). This enables selected parts of the whole system to be simulated across the physical assets, business processes, communications and controls that comprise those parts.

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[14] Energy Systems Architecture Methodology: Enabling Multi-Vector Market Design, ETI Knowledge Zone

1. Architecting Methodology

1.1. The Purpose of Architecting

The purpose of architecting is to develop the architecture; an architecture is a set of rules and structures within which it is possible to design solutions to individual problems.

A single organisation cannot solve architectural challenges on its own. The complex interplay across many actors and silos, overlapping problem spaces and multiple interfaces needs an approach which can organise the challenges, break–down the problem into manageable pieces and then assemble a solution.

In other industries (notably the aerospace, defence and telecoms, including digital mobile telephony and the Internet") a Systems of Systems Approach (SoSA) to developing architectures has been shown to be a very successful method in developing solutions to just such complex problems. Designing an architecture is a form of high–level design which concerns itself with concepts and structures rather than the specific implementations, leaving a framework in which innovation is enabled and supported (Figure 1).

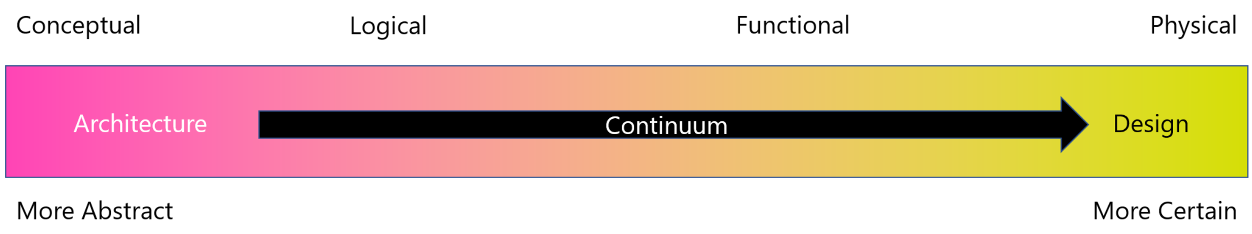

Figure 1 – The Architecture Continuum

For organisations wanting to operate within the energy sector it is often quite daunting to understand all the applicable rules. An energy supplier needs to be familiar with a significant number of codes and standards which detail information far beyond the responsibility of the supplier. Business–as–usual, therefore, operates around industry wide codes whereas an architectural approach can lead to role–based–rules, where each organisation only needs to understand and operate in its specialist area. The intention with this is to reduce the barrier to entry through simplification.

There are other benefits of an architectural approach such as:

- Expressing problems at various levels of detail to allow for the analysis of problems and effective decision making at the most appropriate level.
- Delineation of responsibilities across multiple actors means that activities are not duplicated.
- Increased implementation speed as co–development happens in parallel rather than responding to a change somewhere else in the system.
- Reduced rework cycles as more understanding is obtained prior to execution

The first part of the SSH1 WP3 work has been to develop a methodology for designing an architecture with the intention of helping the wider energy sector to explore and develop future possible architecture.

1.2. Top–down versus bottom–up

Innovation development comes in different flavours and approaches but are often divided into top–down and bottom–up approaches. The former characterised as starting with a definition of the highest–level problems, proposing solutions, designing answers and then testing that the solutions add up to a solution. The latter being the arrangement of innovation into solutions that satisfy needs. Top–down is generally more controlled but often slower. Bottom–up unlocks the value of a huge number of innovators but can have emergent consequences which cannot be predicted prior to implementation.

Both approaches come with their challenges and advantages and the approach developed here seek to combine both. A common top–down approach to development is systems engineering.

Model Based Systems Engineering (MBSE) is an approach to systems engineering which builds models throughout the development phase rather than capturing information in text only formats. Requirements captured in this way benefit from focus on the interfaces and in the co–development of items to ensure compatibility between them such that the whole is optimised rather than a focus on the individual parts.

This project has utilised an MBSE modelling tool, SparxSystems® Enterprise Architect® as the basis for the architecting process. The outputs created in it are available on the ETI knowledge portal and serve as an example of the work that can be developed.

The advantages of this tool are that it supports both top–down and bottom–up development. It is possible to create the structure of an architecture collaboratively and then pull together the models of bottom–up designs to join the two together.

1.3. Development flow

The standard V–diagram has been modified, below (Figure 2), to illustrate how top–down and bottom–up come together. The top 'V' is developed collaboratively and jointly and helps to inform the innovation of products and services, whereas the lower 'V' represents the design and innovation efforts of the whole sector and how they influence the requirements of the shared environment.

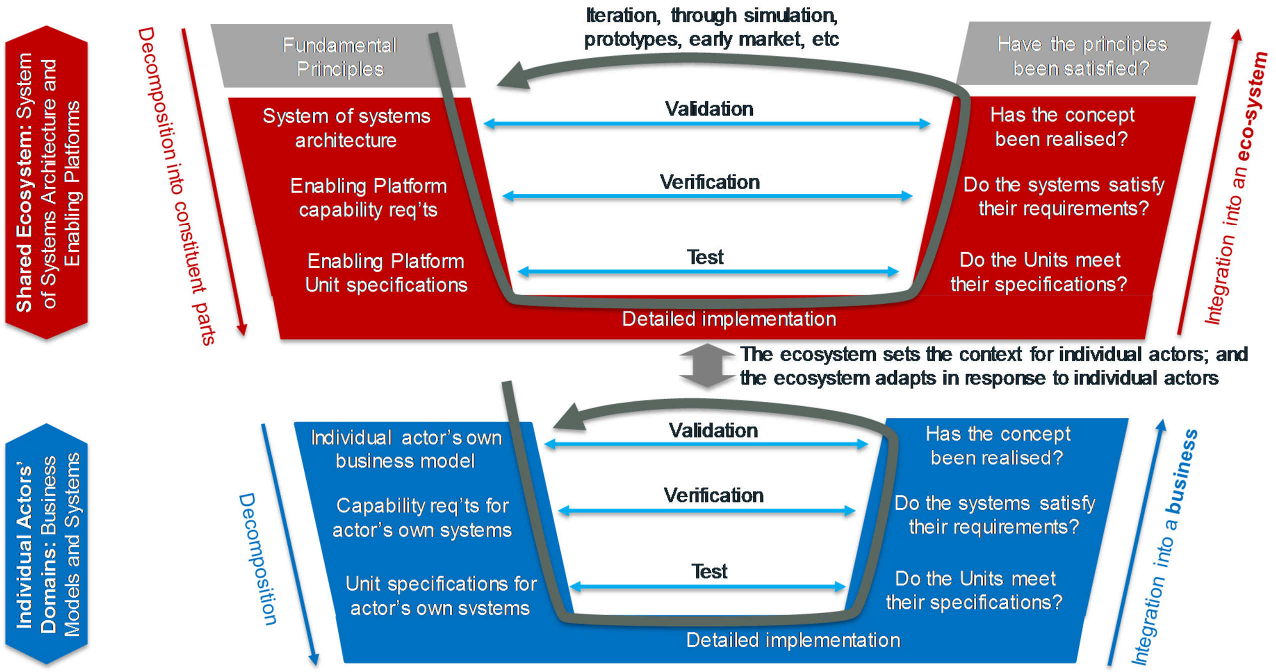

Figure 2 – Double V Diagram

1.4. Configuration and Change Management

The energy system is a complicated environment with many variables. Change management means having a structured approach to managing changes as they are needed such that a change in one area is communicated to other affected parties such that the necessary adjustments can also be made.

This is different to the notion of compatibility which covers the idea that a given solution to a problem in one area is compatible with a subset of solutions to problems in other areas. There are overlaps where solutions are compatible, or in many cases, necessary to support one another. Configuration schemes track the sets of solutions which are compatible with one another.

The detailed approach to configuration and change management is described in detail in section 7.

2. Candidate Energy System Architecture

In order to work through the architecting process a case–study was chosen such that a walkthrough of the process could be developed. This section describes the generated architecture.

The case–study question asked about the implications of adding large numbers of hybrid heat pumps into a localised area.

As the team studied the current state of the art and previous experience, the reality of switching homes threw up issues such as:

- Impacts, on other energy system actors, from the installation and operation of the devices (for example distribution network operators) without apportionment of supply–chain costs
- Considerations on how to deliver on consumer wants and needs across a broad range of socio–economic groups, with socialisation of costs where appropriate and necessary
- Issues around financing significant capital outlay for individual consumers without unfair lock–in
- Policy and regulation affecting the ability to supply, appropriate tariffs and consumer protection

Consumer protection emerges as a central issue. Currently consumers are expected to do their own systems integration across different policies and technologies, understand the future evolution of the national and local energy system, place sub–contracts for fabric modification, heating systems design and installation and control and make applications for the various permissions and elements of financial support. Even where some of the contractors are able to take elements of these for them and they can employ professional advisors, the risks, costs and project management requirements are daunting.

On the other hand, suppliers are operating in an environment where consumer protection strongly mitigates against innovation. It is only allowed where it can be shown to work in advance.

The Energy Systems Architecture Methodology[15] report explains the process used to down–select a single exemplar architecture, not as a chosen "solution" but rather something to use to develop the methodology described. That chosen architecture was analysed for problems and several risks were identified, alongside suggested approaches to de–risk the issues.

Dynamic systems simulation is an important generic de-risking tool. There is no currently available tool for multi–vector systems simulation and a significant part of the work package was to develop a prototype platform, EnergyPath® Operations (EPO). This enables selected parts of the whole system to be simulated across the physical assets, business processes, communications and controls that comprise those parts.

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[15] Energy Systems Architecture Methodology: Enabling Multi-Vector Market Design, ETI Knowledge Zone

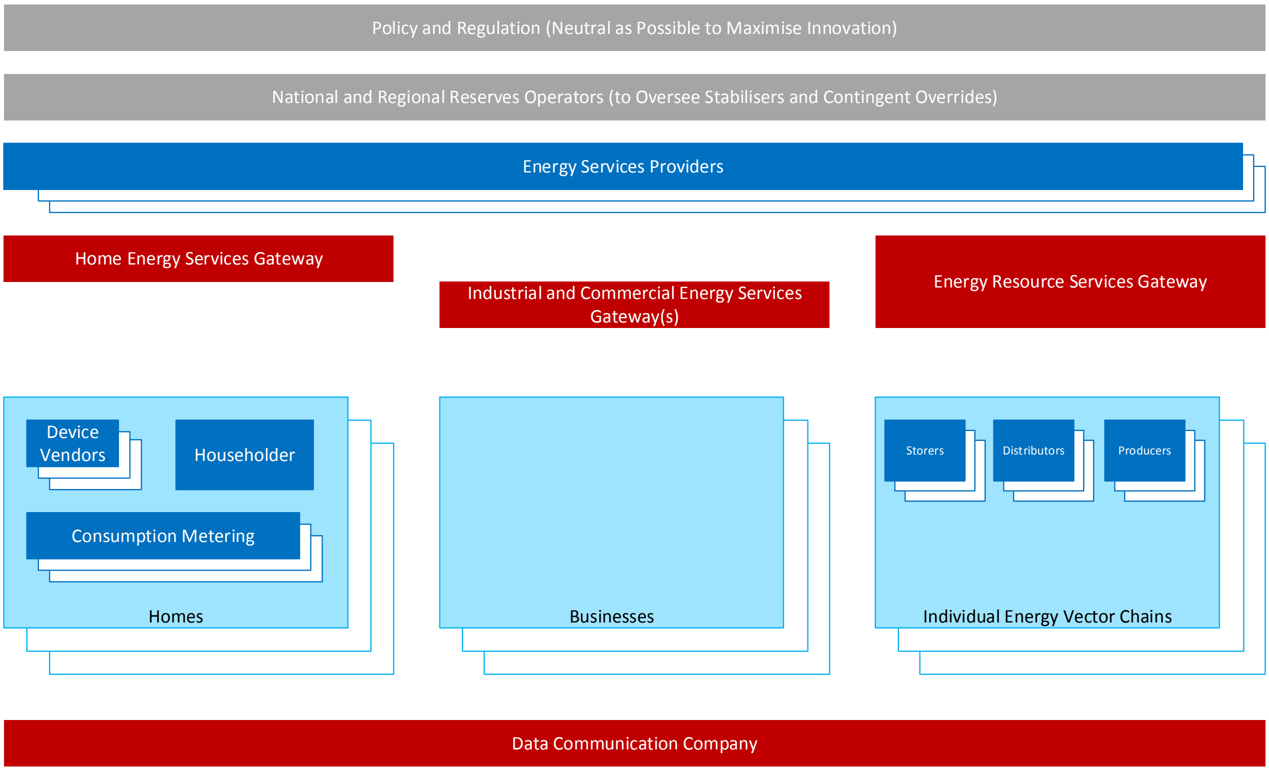
Although it would be ideal if every detail of the whole UK energy system could be modelled at once, this is completely impractical:

- There is insufficient information available on every building, occupant, energy asset etc across the system to provide the data inputs; and
- The computational power required to model sufficiently long-time sequences with sufficiently small time steps, is infeasible.

Fortunately, a great deal can be learned by modelling different parts of the system in greater detail, while using only an outline representation of the rest of the system. How to aggregate parts of the system and how to estimate parameters from available data are key challenges that require a considerable degree of sophistication to produce a useful tool to support the sector.

The test case chosen for developing the business processes and simulating their operation was hybrid heat–pumps reaching significant penetration levels in a given local area, which might be thought of as a number of council wards within one of the three Local Authorities involved in work package 2.

The business processes are specific to a particular architecture and one of the promising example architectures was chosen from this piece of work.



Red indicates shared platforms whilst blue indicates proprietary

Figure 3 – Conceptual Future GB Energy System Architecture Diagram

The conceptual architecture, shown in Figure 3, was chosen as the exemplar for this project and used as the basis of the development work, as it was assessed to have features which were aligned to solving the identified high–level problems. It has sufficient complexity that looking at future alternatives should be no more complex. Note that this is not the "right" or "best" architecture, just one selected to be able to develop out processes and tools around.

Shared functions are shown in red; competed functions in blue; and governance and system operations in grey.

The key feature of the architecture is that Energy Service Providers supply their customers with integrated energy solutions. The business proposition is the sale of valued services rather than kWhs as commodities. In addition, two gateways provide the capability of joining many customers to many providers at all stages of the value–chain.

The Data Communications Company performs a similar function in this architecture to today. Indeed, the most promising future architectures tend to have a Smart Meter infrastructure with a secure front–end via the DCC and an open back–end via connection of the Smart Meter by the customer into the Home Network. Table 1 explains the key attributes of the exemplar architecture to demonstrate the difference with business as usual against some key issues.

	Attributes		
Feature	Business as Usual	Exemplar Architecture	Implications
Customer Proposition	Sale of kWh of energy (gas, electricity, LPG etc).	Sale of services, with outcomes guaranteed by service providers.	Service Provider becomes responsible for equipment and service within the dwelling (beyond the meter). Service Provider now has attributes such as performance, reliability, carbon intensity etc. within their scope and is responsible and rewarded for their skills in technology selection and integration. This is a fundamental transfer from the customer to the supplier, although the customer remains in control of the outcome.
How capacity is rewarded	Investments are determined through regulated costs (networks) or auctions (e.g. CfDs and Capacity Market) and the costs are then allocated according to rules. Capacity and functionality downstream of the meter is determined by building owners.	Generation and network capacity upstream of the meter is purchased by service suppliers, who are self–balancing. Capacity and building fabric changes downstream of the meter are determined by suppliers to meet service levels. Close out of contracts for network and generation capacity are against metered customer usage in short time periods. How long–term investments can be made is not fully defined.	Service Providers are significantly more responsible for procuring asset-based services through contracts with asset owners, including for system services. For example, the generation mix procured by a Service Provider will need to reflect the demand of their customers for frequency response and reserves, incentivising the supplier to manage demand.

	Attributes		
Feature	Business as Usual	Exemplar Architecture	Implications
Supplier ability to innovate	Most of the costs and performance elements of comfort and cleanliness are determined by the State or the customer. Suppliers can differentiate on trading, billing and responding to queries.	In principle the State can set the processes and frameworks within which commercial engagements determine the outcome through winning and satisfying domestic customers. For example, the State can set carbon intensity targets for suppliers to achieve.	Far more of the value is determined at interfaces between customers and Service Providers through the value chains. The State is more able to concentrate on outcomes and processes and less on the specifics of implementation and technology. The role of both regulators and system operators changes.
Data	A small number of data items and their access rights are determined by long and complex Codes, which apply across the whole system. The standards and ownership of key consumer data, for example on vehicle charging, are yet to be fully determined. Most data is held in proprietary formats, controlled by commercial organisations.	Systems engineering breaks down the system into domains, within which the stakeholders determine the key functional objects and the data definitions associated with them. The State sets rules about how this should occur, which enable new entrants and protect both consumers and investors. Data is owned and access controlled by asset owners. For example, consumers own and control data about their driving and what happens within their home.	This is a completely different approach for the energy and associated industries. A significant cultural, skills and governance change will be required. Without such an approach the UK will deliver far less value from the coming data revolution.

	Attributes		
Feature	Business as Usual	Exemplar Architecture	Implications
Network upgrades	Gas and electricity are provided through a regulated, predict and provide approach; charges for these networks are recovered from all customers. Heat networks, LPG and liquid fuels are provided through market mechanisms with regulation to ensure competition and provide consumer protection.	Local area energy strategies enable competition between different networks to be considered strategically, in the best interests of local businesses and residents and as part of wider socio–economic spatial planning, including for example transition to hydrogen. Transmission network strategies develop through the integration of national whole system strategies, informed by and setting the context for local strategies	A significant change to network planning is required to address the transition on a multi–vector and whole system basis. As well as considering for example a new national hydrogen transmission and storage network or CO_2 transport and offshore storage network, local distribution system investments and retirements need to be informed by spatial plans which bring together network companies, energy services suppliers and democratic representation. Once these very strategic and long–term investment plans have been developed, how the capacity is shared and costs recovered through commercial bids will require a balance between security of return on investment and performance incentives.

	Attributes		
Feature	Business as Usual	Exemplar Architecture	Implications
Location signals	A series of rules about location-based cost allocation have grown up, which significantly address transmission charges. Distribution costs vary by region and the way they are paid for varies by customer class. It is unclear how vehicle charging network investments will be justified and charged.	The data about needs by location will be available and capacity will be shared more by market mechanisms. How this will work in practise is not set out at the higher levels of the architecture and requires some policy or outcome driven objectives against which to test different options.	How vehicle charging will be enabled and managed is a very near–term and practical question for any system design, including the current one.
Optimisation of system resources	Currently centralised (TSO) becoming more decentralised (DSO)	More resources are the responsibility of energy service suppliers, in terms of the load characteristics of their customers and the characteristics of their suppliers. The object class definitions cover these system resource characteristics. The envelope and responsibilities of the TSO and DSOs is different.	This is another significant cultural and operational shift.

Table 1 – Comparison of Features

Table 1 illustrates how significant are the differences between our exemplar architecture and the current one. A systems approach has enabled us to go back to first principles and consider a way of addressing the challenges and opportunities in a different way.

If the industry believed that the current architecture and governance of the UK energy system was capable of supporting an effective transition, then the costs and risks of making more fundamental changes would not be justified. However, there is a widespread and strong belief that significant changes will be required and the proposition of this report is that it would be prudent to make these changes in a structured and disciplined way.

Changes to the architecture need to address three groups of factors:

1. A switch to low carbon energy vectors for homes, offices, factories and transport – probably significantly more electrification but including hybrid systems and other vectors such as hydrogen or district heating. Which therefore requires more than incremental investment in networks and network management on a multi–vector basis.
2. Different cost and operating structures to the supply of electricity, gas and liquid fuels, as a result of decarbonisation and unfamiliar structures for low carbon hydrogen and district heating. Which therefore requires consideration of how to match supply to demand most cost effectively and reliably.
3. Much greater levels of automation and control within homes and vehicles, as a result of the penetration of internet technologies, along with increased customer expectations to be more in control and have greater transparency and effectiveness from their suppliers. Which creates an opportunity for better information and control of the new loads but also raised expectations on the part of the consumer in an industry which is not familiar with deep consumer engagement.

Electrifying heating and vehicles will both introduce new, unfamiliar and very large load classes. We have chosen heating as the test case for stimulating thinking about systems architecture, as it is most challenging. However, charging electric vehicles is likely to put bigger demands on the system by 2030 and therefore represents a more urgent driver of change. In principle, it should be possible to provide a large proportion of charging overnight at home. This would suit both drivers and the energy system. Drivers can wake to a reasonable and cost-effective charge and existing underused generation and network capacity can attract additional revenues. This would need to be integrated with other charging opportunities, for example deferring some charging for some drivers until they are at work and making better use of PV in the summer.

The median dual fuel household in the UK currently uses 3,100 kWh of electricity. Recharging battery cars would add 3,500 kWh; providing heating and hot water with a heat–pump would add around 5,000 kWh. These are significant additional loads, especially as the charging is likely to be split between home and other new installation locations. Cars and heating will be even more variable between households than current usages. These additional services represent a huge value opportunity, provided that they are taken seriously, as new needs.

Baringa Partners have developed a number of example 2030 hourly electricity supplier cost stacks for ETI (Energy Technologies Institute, 2018). These extracts from the ones based on the National Grid 2017 Future Energy Scenarios *Two Degrees* scenario illustrate a number of the points about supply (Figure 4).

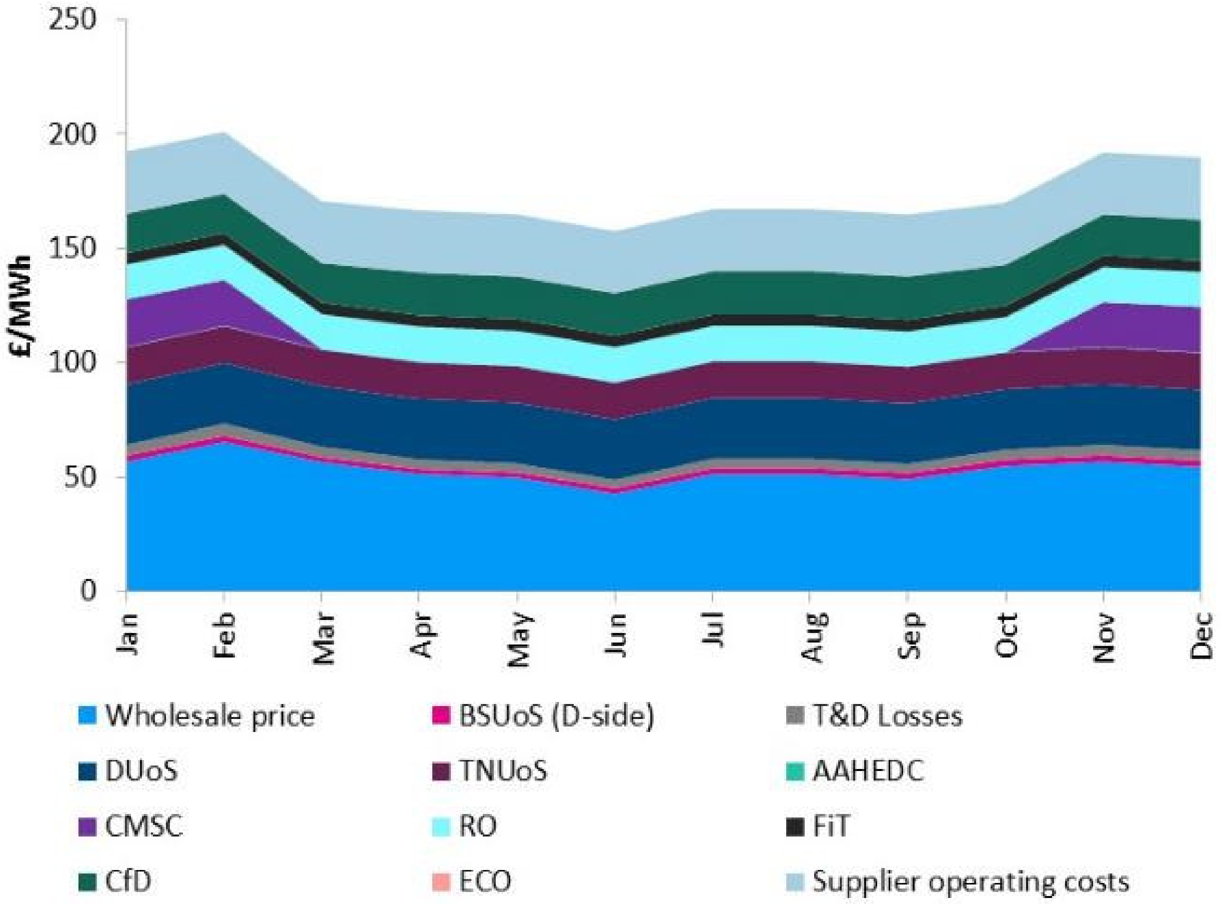


Figure 4 – Average monthly domestic retailer cost stack (Energy Technologies Institute, 2018)

The majority of the costs that retailers will pay are fixed and allocated costs, not determined by markets. Under market current rules there will be large spikes in cost, driven by transmission and capacity market costs during peak, for example (Figure 5):

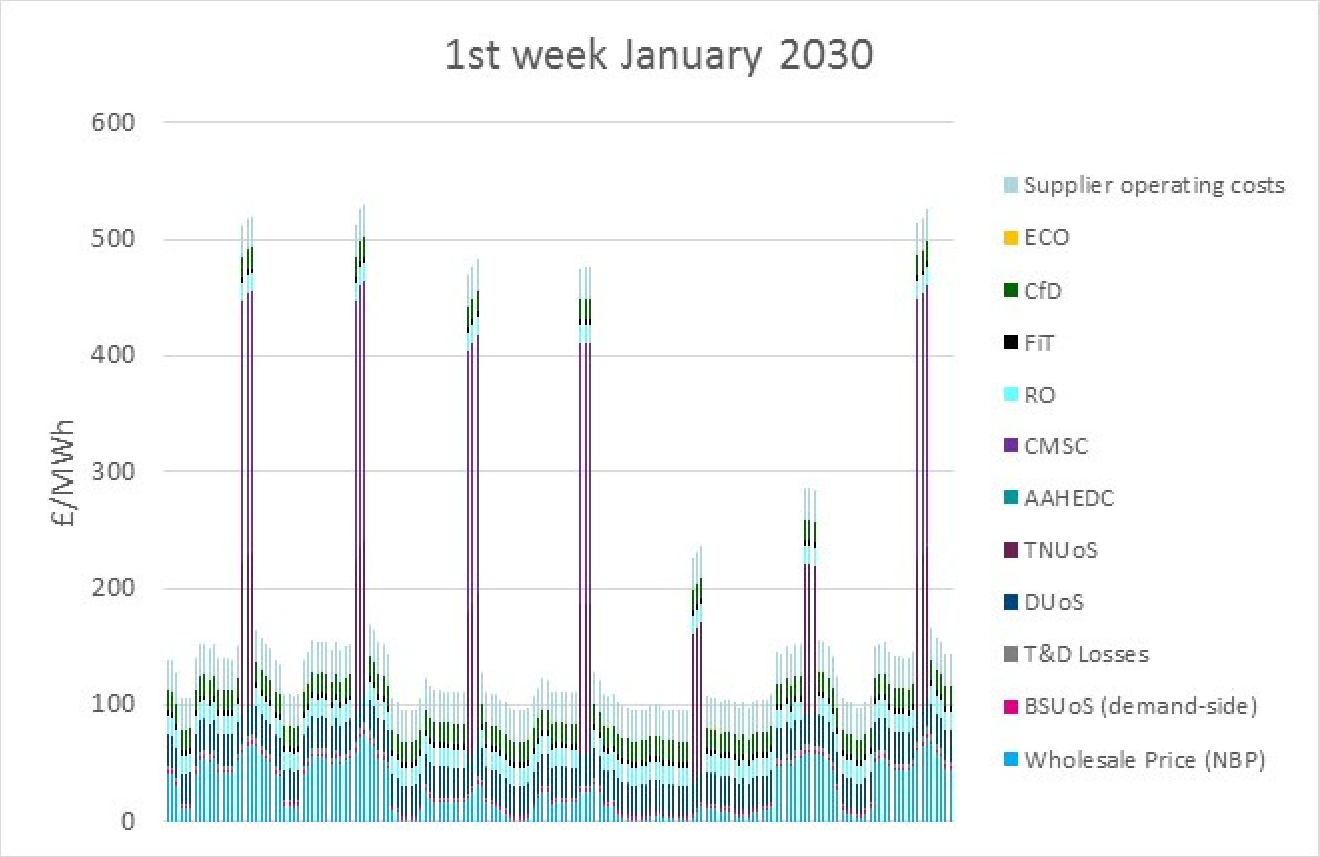


Figure 5 – Contribution to Costs (Energy Technologies Institute, 2018)

Although average wholesale costs are higher in winter than summer, there are more windy periods in winter when wholesale costs are low. Current cost signals for domestic supply do not reflect peak usage of distribution networks or periods of very low marginal cost of generation.

A further consideration is the decarbonisation benefit. Current new cars have similar emissions to battery electric cars when the electricity carbon intensity is around 600g/kWh. Electric vehicles only deliver cost effective decarbonisation where the electricity used for charging is significantly below 300g/kWh. Running more gas–turbine capacity to provide additional peak generation to meet charging loads is not an effective way of decarbonising. Baringa also estimated the carbon intensity of additional electricity supply in each hour, for example (Figure 6):

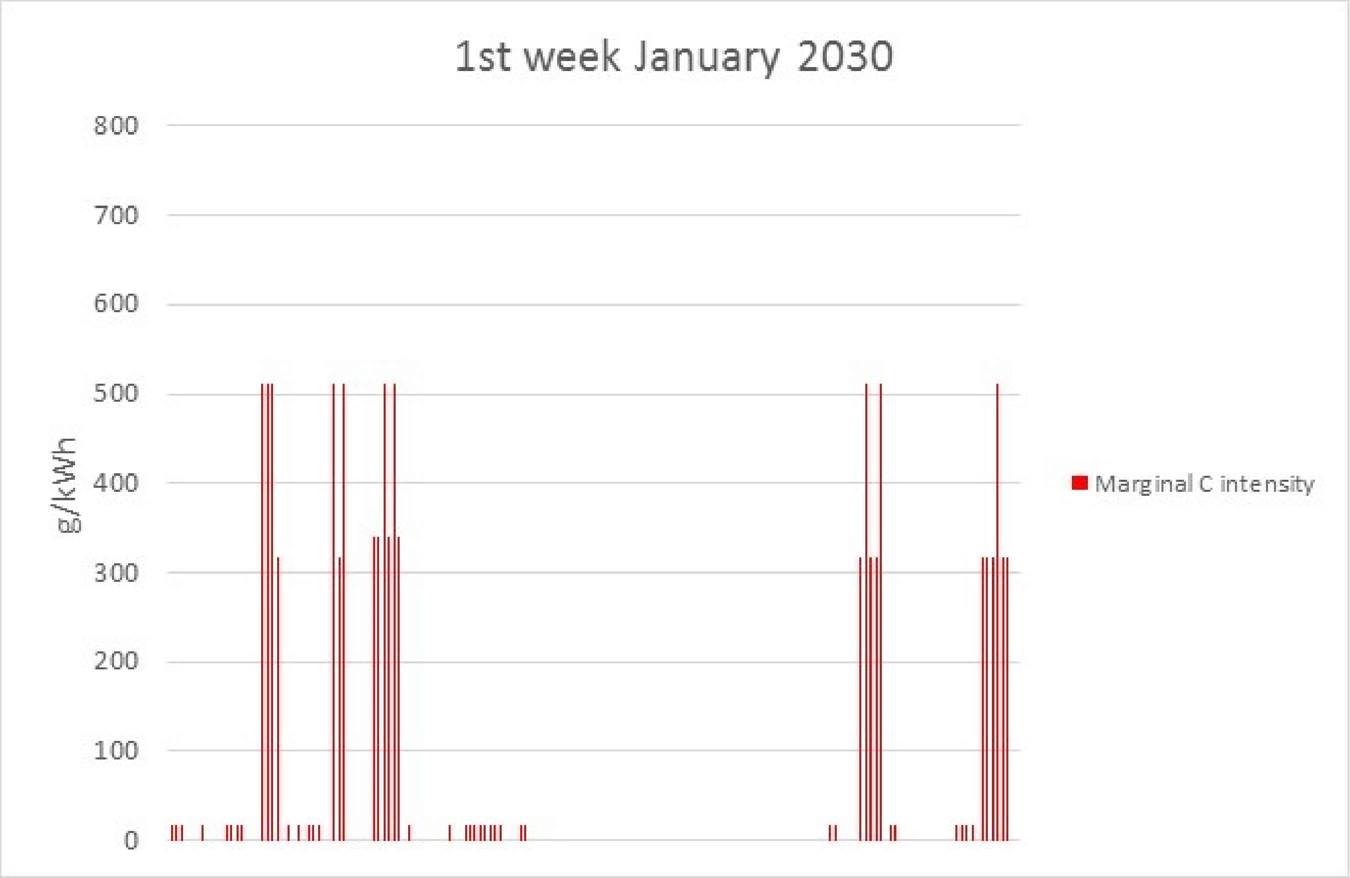


Figure 6 – Carbon Intensity (Energy Technologies Institute, 2018)

High carbon electricity supply will not always coincide with peak demand. In this scenario, it depends on the wind. In fact, wholesale prices are a reasonable surrogate for carbon content.

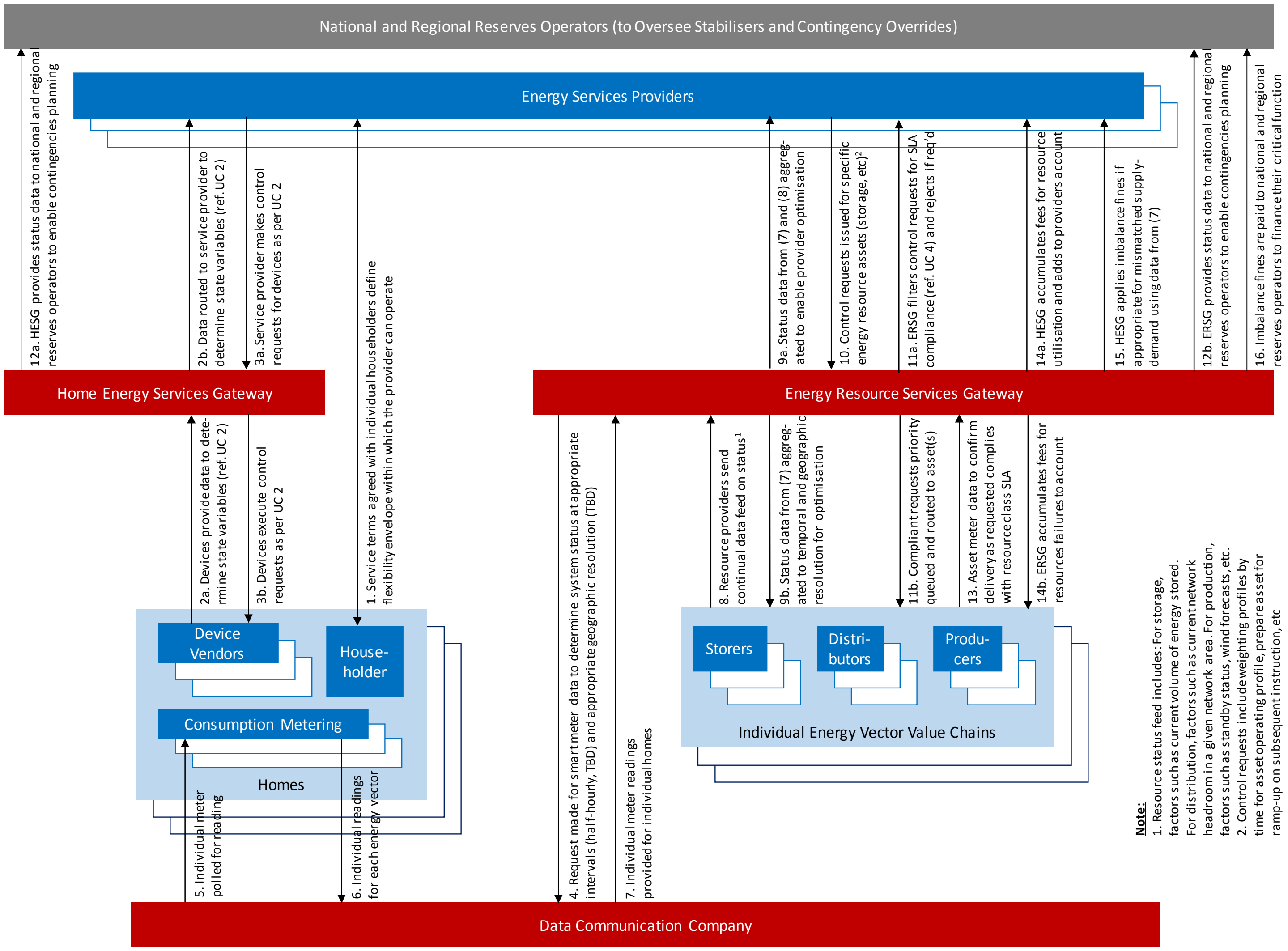
We might present the challenge of vehicle charging as:

- How will your charging service supplier be incentivised to manage and present charging to you in a way that makes best use of existing generation and network capacity and the availability of low carbon electricity?
- How will it work if your charging service supplier is managing your charging across multiple sites, including your home, and is different from your domestic energy service supplier?

Changing from our current system architecture and governance will be uncomfortable and Table 1 – Comparison of Features illustrates that there are unknowns and significant risks. This should be a prompt to adopt highly disciplined processes that have been proven to work in other industries. It also reminds us that we need to start with a number of promising architectures and design details and down select to what is implemented through a combination of analysis, modelling and real–world test validation. Typically sub–systems are validated in well–controlled experiments before they are reassembled into larger and broader tests and demonstrations. Analysis and simulation are important tools to reduce costs, time and risks in finding solutions for larger scale tests.

Having chosen large scale penetration of hybrid heat–pump and combi-gas boilers into an area as our test case, a specific supplier problem was set to think about how this would be addressed within the detailed design. This was how an Energy Service Provider will balance its own supply and demand position, using the tools at its disposal, whilst still delivering the contracted service to their customers. This use–case was used to detail out business processes and develop an EPO model to show how this might work in a specific supply situation. Each problem statement can be mapped out within the architecture as a set of high level transactions between different actors. The mapping for the chosen use–case is shown in Figure 7.

In order to develop the detailed design, this high-level mapping is developed further within Sparx EA as many hundreds of business process components, which would then enable systems designers to implement these as IT systems and human processes. It also provides the detail which enables an EPO model to be built.



Note:
1. Resource status feed includes: For storage, factors such as current volume of energy stored. For distribution, factors such as current network headroom in a given network area. For production, factors such as standby status, wind forecasts, etc.
2. Control requests include weighting profiles by time for asset operating profile, prepare asset for ramp-up on subsequent instruction, etc

Figure 7 – Case–study: ESP balances supply and demand position

3. Exploring Systems Architecture – Simulation and Analysis using EnergyPath® Operations

EnergyPath® Operations (EPO) is a simulation tool developed to enable analysis of the behaviour of the exemplar architecture for the GB Energy System.

There are other "whole–systems" tools available (such as the ETI's ESME, EnergyPath® Networks or Energy Exemplar's Plexos®) but the most significant difference with EPO is the ability to simulate future policy and market arrangements.

EnergyPath® Operations (EPO) simulates operational timescales, capturing the moment–to–moment decisions and interactions that together give rise to the system–level outcomes. As a result, the core of EPO is an extensive dynamic simulation engine that represents the exemplar architecture of the future Great Britain Energy System as described in Section 2.

Other core features of EPO include:

- The Allocation Function runs to assign appliances and occupants to houses. House sizes and types are obtained from available census and ordnance survey data and then probabilistic functions apportion appliances (e.g. heating technologies, EV, storage devices etc.), occupants (inc. usage patterns) and property improvements (primarily insulation). Additionally, the Allocation Function is able to build in the concept of diversity by randomising potential allocations which are then used to find the envelop of operations. Finally, this function can be used, standalone, to gain insight into potential clustering of appliances and usage patterns but is primarily used in EPO to allow for energy consumption to be calculated.
- The Distribution Network Model runs to calculate the voltages at nodes, losses in the network and temperatures of equipment. To minimise run–time the network models are assessed with load–flow models and those outputs are used to train a neural network which can then predict the network performance under loads in a much shorter run time.

This section outlines the functionality of the EnergyPath® Operation tool and details the analysis undertaken to address the use–case outlined in this report but more detail is available in section 10.

3.1. EnergyPath® Operations – Simulation Tool

EPO is designed to allow a skilled user to provide insights into the behaviour of a potential architecture. As currently conceptualised, this is a sequential process involving the following stages:

1. The analyst defines an Analysis Plan to address an aspect of the architecture. This is described in section 4.1, but in summary it defines one or more simulation runs (executions of the dynamic simulation engine) to be carried out.
2. The configuration specified in the plan is loaded into the tool.
3. The simulation is executed, involving multiple simulation runs if required.
4. The results from the simulation are exported in an accessible form for further analysis.

The major subsystems within EPO are shown in Figure 8. The diagram also highlights a division of the subsystems into different categories, some of which are run manually to setup data, some are run to process data after the model runs.

Further information about the function of the individual subsystems is provided in section 3.1.1 below. The diagram shows the sections within Appendix 5 in which the details of these subsystems are presented.

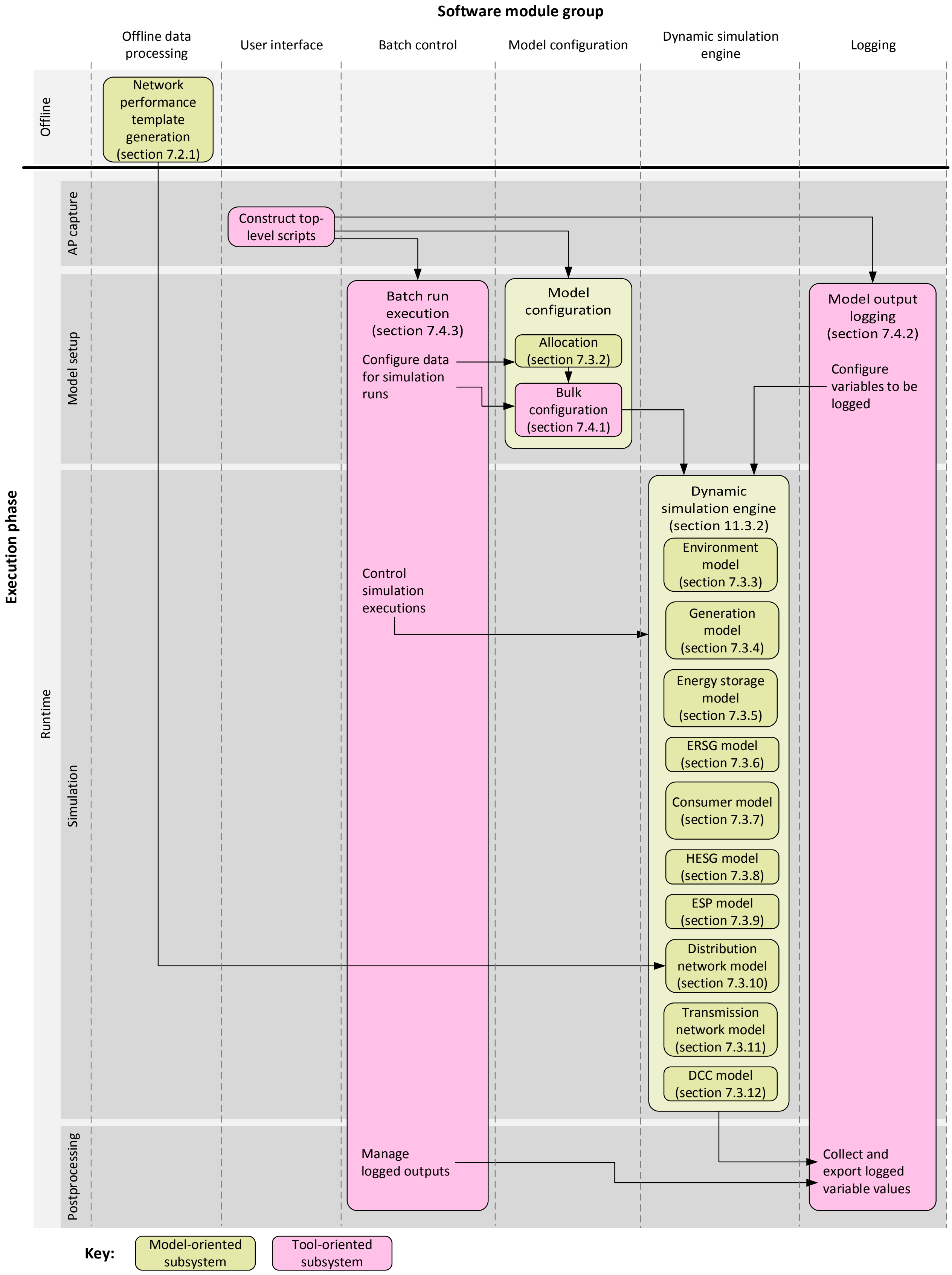


Figure 8 – Major model/tool subsystems in EPO by execution phase

A core element of the structure of EPO is the sequence of execution phases that are used to perform analysis. This is captured in Figure 8**Error! Reference source not found.** on the vertical axis indicating the order of running:

1. **Offline** (during development, before release of source code): Functions used by the operator to construct datasets required by other functions.
2. **Analysis Plan capture:** The activities which allow the operator to enter variables to perform the analysis
3. **Model setup:** Initialise dynamic–simulation model based on user's configuration
4. **Simulation:** Run the simulation in accordance with configuration
5. **Postprocessing:** Functions used by the operator to perform post–processing on results extracted from dynamic simulation

The user's interaction with the tool is framed as selecting configurations and values for model settings from predefined ranges. These may be either qualitatively–different variants within a set of available sub–models (e.g. different business processes can be chosen from drop–down menus), or numerical values within a range (e.g. the percentage of hybrid heat–pumps in a given simulation run). The key options used to configure the tool to suit an Analysis Plan are:

- **Model variants** to be used to represent each actor within the simulated energy system, from the set of (qualitatively different) variants developed
- **Parameter values** to be used to further configure the behaviour of the sub–systems of the model
- **Model variables** to be logged for subsequent analysis

The connections between sub–models are pre–determined for a given candidate architecture and the user is only required to configure the changeable attributes of the sub–models. This approach has sufficient flexibility to accommodate the currently projected range of analyses.

3.1.1. Software architecture

The software subsystems of EPO are organised into module groups, as depicted in Figure 8. A detailed description of all subsystems within EPO is included in Appendix 5, and full details are given in the corresponding EPO Requirements Specifications and/or EPO Design Documents. A brief description of their functionality is as follows:

- **Offline data processing:** At development time, prepares data required by runtime components
  - **Network performance template generation:** Constructs *network performance templates* that are computationally–efficient descriptions of the behaviour of an electrical distribution network in response to applied loads (used to reduce computational effort in the simulation)
- **User interface:** Allows user to define the desired configuration for EPO to implement the analysis plan
- **Model configuration:** Expands and combines library data and user input to generate information required by simulation engine
  - **Allocation:** Produces a description of the energy consumers in the world in which the simulation will take place, by modifying and extended real data according to user–supplied assumptions.
  - **Bulk configuration:** Loads values for model configuration parameters into simulation engine.
- **Dynamic simulation engine:** Executes dynamic simulation of actors in energy system architecture over defined time period, as specified by user
  - **Consumer model:** Inputs consumers' electricity power demand into the energy system, either generated from a non–equilibrium model of building physics with consumer comfort as the control objective or provided from standard demand profiles.
  - **Energy Service Provider model:** Dispatches flexible generation/storage to balance supply and demand of electricity.
  - **Generation model:** Provides electrical power supply, flexibly (simulating a spot market) and/or inflexibly (simulating a wind generator).
  - **Energy storage model:** Flexibly provides electrical power supply or demand.
  - **Distribution network model:** Simulates performance of electrical distribution network, through aggregating individual consumers' demands and predicting power losses and busbar voltages.
  - **Transmission network model:** Simulates performance of electrical transmission network, through aggregating distribution network demand, generation supply and storage supply/demand, and predicting power flows.
  - **Energy Resource Service Gateway model:** Relays information between Energy Service Provider model and generation/energy storage models.

  - **Home Energy Service Gateway model:** Relays information between Energy Service Provider model and consumer models and produces predictions of consumer demand.
  - **Environment model:** Inputs predefined meteorological conditions (wind speed and air temperature) into model of energy system.
  - **Data Control Centre model:** In future this will provide an alternative route for information passing from consumer model to Energy Service Provider model (currently unimplemented).
- **Model output logging:** Configures simulation components to log variables specified by user, and collate and export logged data for user analysis
- **Batch run execution:** Coordinates execution of multiple simulation runs (if required for analysis)

3.1.2. Outcomes from EPO Development

This section has described the components of the initial version of the EPO simulation tool. In summary, the tool is designed around a sequential workflow during which one or more simulation runs are carried out. The core subsystems of the software represent the models of the actors within the exemplar architecture described in section 2. Work to date has demonstrated the feasibility of:

- Modelling a candidate architecture
- Constructing a simulation which allows for different variants of subsystem models that are, themselves, configurable.
- Combining simulation of business processes, physical processes and the ICT interconnections between them in a single model.
- Maintaining traceability links between the definition of a proposed future GB energy system and the specific parts of the simulation that implement those requirements such that future changes are easy to implement.

This version of EPO is the outcome of an iterative development process. In each iteration, a goal was set for the functionality of the resulting version, defined in terms of a set of "scenarios" to be addressed. The scenarios described the actors in the exemplar architecture of the future GB energy system to be modelled and their level of complexity. Tool features to support analysis capabilities were also part of the goals of each iteration.

This approach worked in a similar way to the use of the use–case to focus the decomposition of requirements to create a design for the exemplar architecture. It aided development by focusing on a subset of the requirements from the exemplar architecture within each iteration but in such a way that each iteration created an internally self–consistent simulation model that added incrementally more complex modelling problems.

There were, however, some limitation to this development approach, which restrict the current usability of the model including:

- The user–interaction approach chosen (selecting from available options) is limited in its ability to support architectural–level changes. Although changes can be made to the behaviour within one or multiple actors handled through a 'variant' mechanism, the current set of interfaces between actor models only allows for the exemplar architecture.
- In general, the usage of the tool may involve iteration, where one configuration is simulated, the results explored and a further simulation carried out using a modification of the configuration. At present there is no functionality to support such iterative use.
- Usability–related aspects (graphical user interfaces for model configuration, support for postprocessing of simulation results etc.) have not been developed in this phase of the project.

In addition, EPO is now ready to exploit many opportunities to improve the simulation models and unlock understanding of the behaviour of different conceptual architectures, including the following:

- Expansion to represent the physical elements of the whole UK electricity system (consumers, generation, transmission and distribution), involving appropriate approximations to keep the computational effort tractable. This will allow implementations to be tested in different real physical environments, up to the scale of the UK to aid understanding of the scalability of the exemplar architecture and others.
- Inclusion of further business processes in the architecture, or more detailed representation of them to explore further behaviour of the exemplar architecture.
- Expansion to cover additional energy vectors (e.g. gas, heat networks) and applications (e.g. transport) to enable analysis of the multi–vector aspect of potential energy system architectures.

4. Analysis

Analysis using EnergyPath® Operations (EPO) is performed to provide insights into how a potential energy system architecture would operate in a specific scenario. The value of EPO comes from its ability to analyse the impacts on multiple systems and actors (organisations) simultaneously. In that way, one organisation may set a question but others who are interested in the results may learn about the impacts on their businesses and technologies.

The aim of the analysis is to demonstrate the impacts (primarily physical and financial) on the energy system in the context of choices made around the future candidate architecture (structures, policies and rules).

The analysis presented below represents a sample of the possible insights that EPO can generate. At the time of writing EPO is still a prototype so these results must not be treated as final, validated, or numerically accurate but rather they are indicative of the types of outputs that can be obtained.

The scope of analysis items is limited only by the range of questions that are asked during the analysis planning phase. The planning phase can involve multiple stakeholders deciding what they'd like to explore between them and often requires iteration after early results are obtained to change the specifics of what is reviewed.

Much data is generated and retained and it's simply the need to perform post–processing to organise and visualise the data in a way that is useful to the reader.

This section describes the configuration of the model and summarises the results that were found when the simulation was executed. More detail of the analysis can be found in section 11.

In this section, the roles and behaviours of the actors in the energy system are based on the exemplar architecture while the selected scenario defines the research question to be analysed and the boundary of operation (i.e. the level of functionality included and how it is configured). Figure 9 shows a simplified diagram of the actors implemented in this scenario and the connections between them.

Those actors included are a sub–set of all the actors identified in the development activity required for the scenario under examination but were chosen for simplicity in this prototype.

In this first analysis run we used the scenario where an Energy Service Provider is made accountable for balancing their own supply and demand position using generation and storage to meet the demands of their customers. In the next version of EPO, the ESP will also have control of demand with their customers and be able to modify both sides of the supply–demand equation together.

The EPO tool was configured in accordance with the analysis plan described in Section 4.1, which is summarised in Figure 10 to outline the analysis process undertaken. The complete analysis and results report is another of the project's deliverables. It provides further detail regarding the configuration of the model for this analysis; at each stage of the analysis, the key assumptions, decisions and methodology for performing the analysis are described. A summary of that report is provided in the sections below.

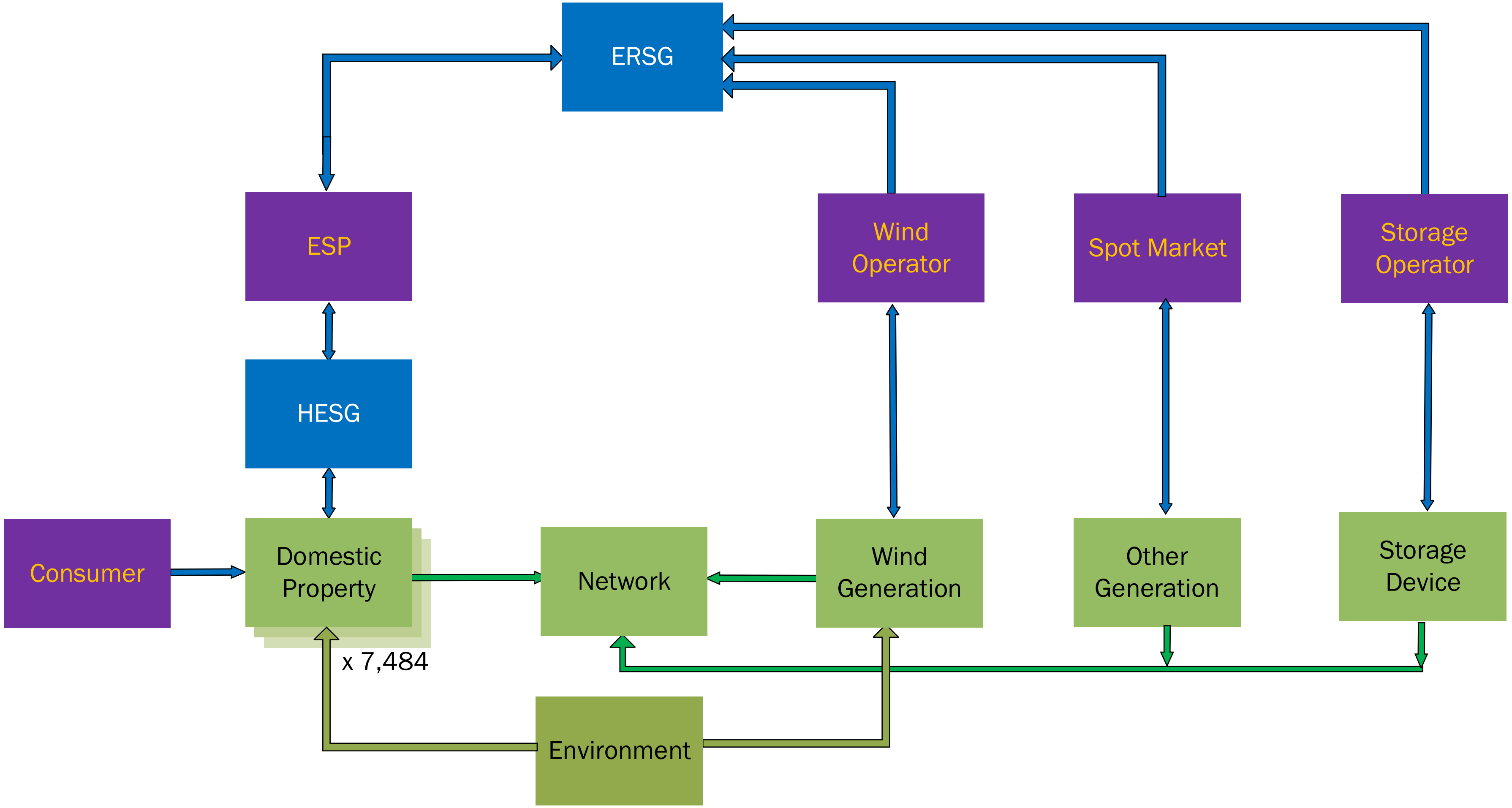


Figure 9 – Simplified View of Scope of EPO Model

4.1. Analysis Plan

4.1.1. Scenario

The scenario analyses the ability of an ESP to manage the difference between the demand for electricity and the available supply from a wind generator and through using battery storage.

A single ESP supplies a group of domestic properties with gas or electric heating according to the availability of cheap electricity (from the wind provider) and to maintain the customers' selected comfort level. The energy demand for each vector is dependent on the behaviour of occupants, the heating appliances installed and the weather conditions.

The ESP has a relationship with one wind generator, whose supply is dependent on the weather. Further to this, the ESP instructs a battery storage operator to charge when there is a surplus of generation, or to discharge when there is a deficit. The ESP can also purchase energy from a spot market (representing all the other generators) whenever additional supply is required.

Figure 10 provides an overview of the scenario and the connections between the different actors. EPO is configured to examine the problem of balancing energy supply and domestic demand from the perspective of the ESP. The distribution and transmission networks are considered to have infinite capacity (i.e. place no constraints on the system) in this analysis.

The actions of actors and the interactions between actors within this scenario, for both the physical and business representation, are outlined below (the numbering matches the numbers in square brackets in Figure 10).

1. Demand for electricity originates from a collection of domestic properties. A real geographical area is chosen as a basis, to capture the distribution of property types and to allow comparison to the national distribution. The heating appliances present in the properties are a mixture of combi–gas boilers (gas heating) and HHPs (in this case they are used for electric space–heating and gas water–heating only), defined probabilistically. In this analysis no DSR capabilities are available.
2. The ESP delivers electricity and gas to the selected group of properties. Currently there is only one ESP modelled. If that ESP has failed to provision enough supply (compared to actual demand) then a physical imbalance will result.
3. The spot market, representing all other generators, supplies electricity as requested from the ESP's forecasting. This simplification currently disregards the latency in communications which will be added in a later version.
4. The storage devices charge or discharge as requested by the ESP. There are limitations on the rate of charging and discharging. However, the storage's energy capacity is considered not constrained.

5. The ESP receives a forecast of the aggregated demand profile of their consumers from the HESG every 15 minutes, covering the period from 15 to 30 minutes ahead of the forecast issue time at 60–second intervals. E.g. at 11am the ESP receives the consumer's demand forecast for each minute between 11:15 and 11:30.
6. The wind generator forecasts generation and sends this to the ESP every 15 minutes, covering the period from 15 to 30 minutes ahead of the forecast issue time at 60–second intervals. E.g. at 11am the ESP receives the forecasted wind output for each minute between 11:15 and 11:30.
7. When the forecasted wind generation is greater than demand, the ESP requests the storage operator to take the excess.
8. When the forecasted wind generation is less than demand, the ESP requests the storage operator to provide the deficit.
9. If the deficit is greater than the maximum power available from the storage, the ESP purchases additional energy from the spot market.

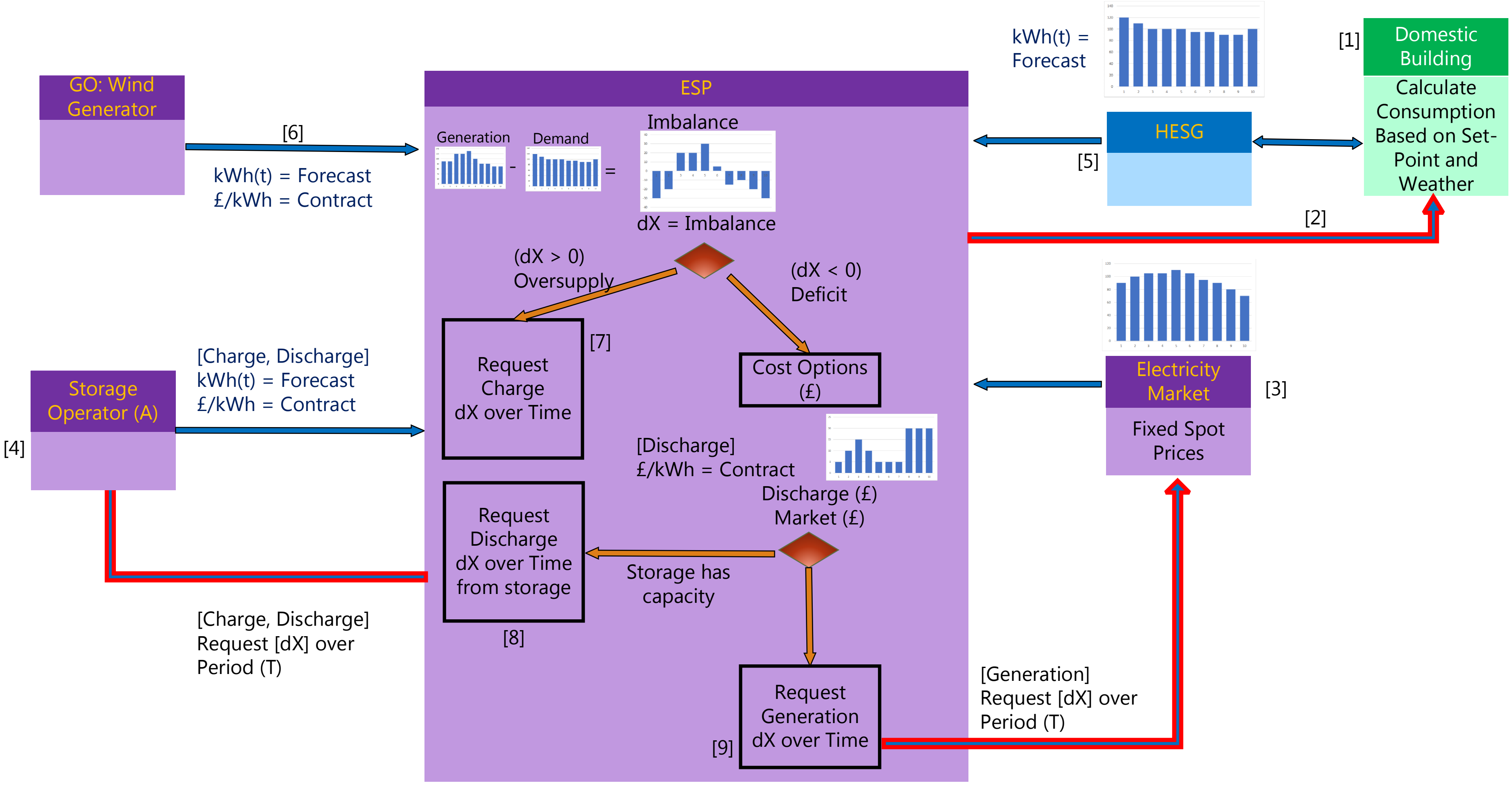


Figure 10 – Summary of key actors in EPO configuration for analysis

4.1.2. Analysis Questions

The analysis questions are framed to explore behaviour within the exemplar architecture from the selected scenario.

1. What is the cost to the ESP of supplying energy (electricity and gas)?
2. Within what limits can the difference between ESP supply (from generation and/or storage discharging) and demand (from consumers and/or storage charging) be maintained?
3. What storage capacity is required to handle the total difference between electricity demand and supply?
4. What proportion of the total energy supplied to the domestic properties comes from the wind generator, relative to spot market and gas? (This gives an indication of the decarbonisation that is achieved from this scenario.)

To provide insights into each of these questions, the corresponding key performance indicators (KPIs) in Table 2 will be extracted from the simulations performed.

Analysis Question	**KPI**	**Purpose**
1	ESP Cost	To understand whether this is an attractive financial proposition. The different prices for energy from wind generation, spot market and gas are constant (£ per kWh). The storage operator charges the ESP a fixed margin for charging / discharging energy (£ per kWh).
2	Demand Supply Imbalance	To determine whether the proposition will sufficiently balance to reduce the risk of voltage issues on the distribution network (within normal non–fault operation). This considers the imbalance in supply purchased and demand provided from the perspective of an ESP (kW).
3	Storage Capacity	This is represented as the cumulative discharge and charge (kWh) provided by the storage since the beginning of the simulation. The difference between maximum and minimum values indicates the storage energy capacity (energy) required to facilitate this proposition.
4	Energy from Wind Generation	To understand the decarbonisation of the energy system achieved. This is defined by the proportion of the total energy supplied to domestic properties that comes from wind generation (as a % of total energy consumed).

Table 2 - Summary of analysis questions and KPIs

4.1.3. Analysis Test–Case

The analysis considers a heating season running from the beginning of October to the beginning of the following April.

It was based on a region within Bridgend supplied from a single 33kV to 11kV substation. This substation supplies 7,484 domestic properties. Compared to the national average the region has slightly larger houses with fewer solo occupants and fewer flats but can be considered a reasonably typical semi–urban area.

All houses were assumed to use either a combi–gas boiler or a hybrid heat pump (HHP) for heating. In properties with a combi–gas boiler, this provides all space and hot water heating. In properties with an HHP, the heat pump component provides all space heating, while the gas boiler component provides all water heating. The rated power of the appliances and other aspects of the heating system were set to be directly proportional to the size of the house. Appliances delivering space heating were switched on and off by a thermostat based on the simulated room temperature and its corresponding setpoint.

Assuming that no flats have HHPs, HHPs were allocated to 30% of all other property types. Since it is impossible to predict which houses will purchase HHPs, appliances were allocated to properties probabilistically where the probability distribution across appliance types depends on the property type (in this case the probability of a heat pump was set to 0% for a flat and 30% for e.g. a semi–detached house). Likewise, the number of occupants and their demands for each property were determined probabilistically, dictating the temperature set points, time of use and amount of hot water required. Figure 11 shows how the appliances were allocated across properties, demonstrating how diversity is handled, across two runs of the simulation.

Figure 11 – Allocation of Heating Appliances to Properties

Some artificial choices were made for example; the number of wind turbines was chosen to approximately match the average domestic property demand throughout the overall heating season. This decision was made to ensure a range of behaviour during the simulation, varying between wind generation exceeding demand and the reciprocal situation.

As another example the battery charge/discharge rate limitation was selected so the storage operator can take all output from the wind generator, i.e. there is no need to curtail wind power, but peak demand can still exceed the peak storage output which leads to a reliance on the spot market (and all other generation).

Table 3 summarises the different test–cases investigated in terms of the factors varied.

Test–case 1 is the baseline where all heating is provided by combi–boilers.

Test–case 2a replaces 30% of combi–boilers with heat pumps. Test case 2b introduces the limits on the charge and discharge rates of batteries. Test–cases 2a and 2b were run multiple times with different allocations of heating appliances and occupants to ensure that a range of results was obtained to account for the uncertainty around energy usage in each dwelling. To reduce simulation run–time the multiple runs of the offline consumer model were executed over a short time period. The configurations with the lowest, median and highest electricity consumption (denoted "LowC", "MedC" and "HighC") were identified and then re–run for the full–time period. Test–case 1, meanwhile, was only executed once since the only electricity consumption was background demand which would not be expected to vary significantly.

Test–case	Heating Appliance	Storage Power
1	All Gas Heating 100% Combi–Gas Boilers	Unrestricted charge/discharge rate
2a	Mixture of Combi–Gas and HHP 70% Combi–Gas Boilers 30% HHP	
2b		Restricted 10 MW max charge/discharge rate

Table 3 – Test Run Summaries

4.2. Results

Detailed results are presented in section 11 but a summary, provided here should be sufficient to illustrate the possibilities to most readers.

The following results have been generated to provide insights to Energy Service Providers of:

a) the variability of demand given the unknowns in consumer behaviour and appliance choices
b) the impact of demand on the local electricity network
c) their cost to serve (cost of purchasing power / energy to deliver outcome to consumer)
d) their supply–demand imbalance (which leads to balancing services costs)
e) the capacity of storage required to balance out other control decisions (though demand side controls have not yet been implemented.
f) the trade–off of forecast accuracy against supply–demand imbalance (which might provide an investment case for better sensors and measurement versus balancing service costs)

Whilst some of these may be of interest to other actors, e.g. distribution network owners on the variability of demand and impact on the electricity grid or the systems operator in terms of supply and demand imbalance, this summary focuses on the ESP's perspective.

4.2.1. Variability of demand

As described earlier the allocation of appliances to properties and then the use of those appliances by occupants cannot be accurately predicted. Figure 12 illustrates the electricity demand of the simulated houses over a day. The line illustrating the range of possibilities in a given hour.

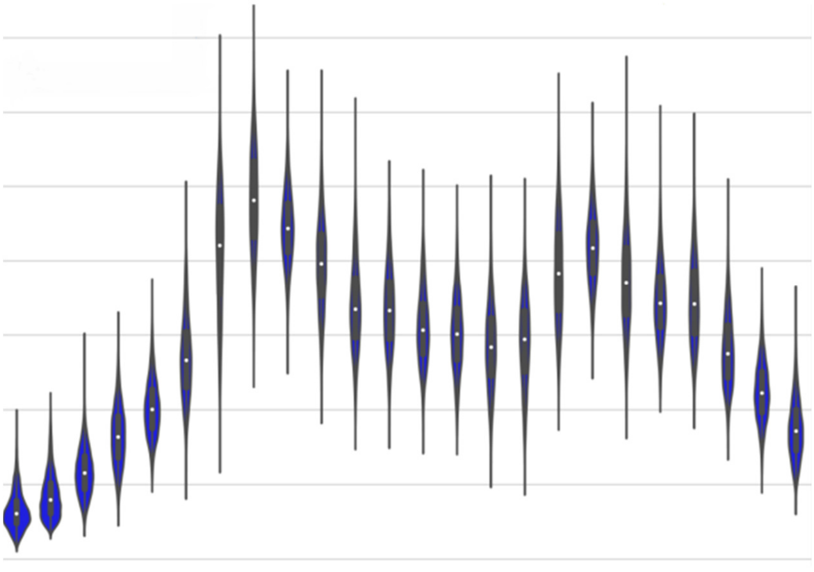


Figure 12 – The Variability of Electricity Demand over a Day (given variance of occupants and appliances)

4.2.2. Impact on Electricity Distribution Network

For a given simulation run the load–demands (gas and electricity) of each house are aggregated (summed) together as illustrated in Figure 13.

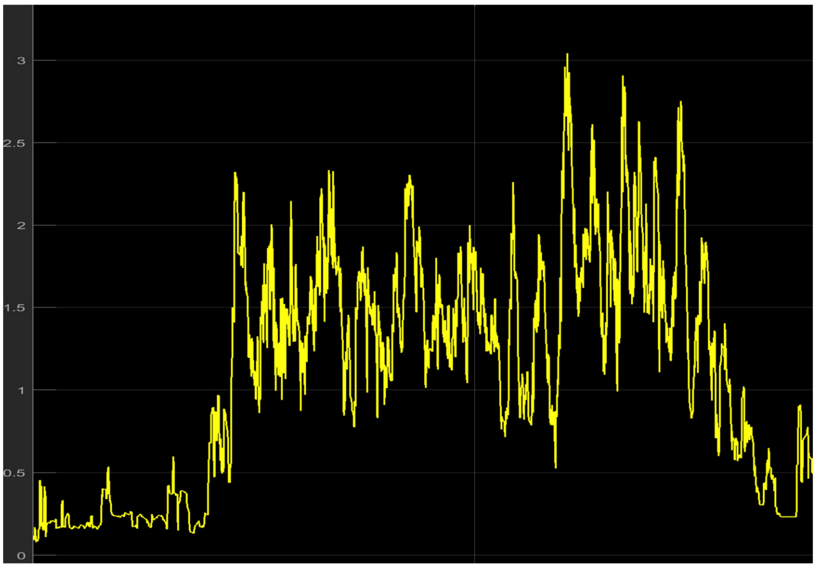


Figure 13 – One Day Electricity Demand Curve (given 30% HHPs)

These curves are then fed through the network model to provide the predicted voltages on whichever feeders are under investigation, as illustrated in Figure 14. Note that losses, temperatures are also able to be generated but only voltages are shown. At a national level frequency is also calculatable in the prototype software.

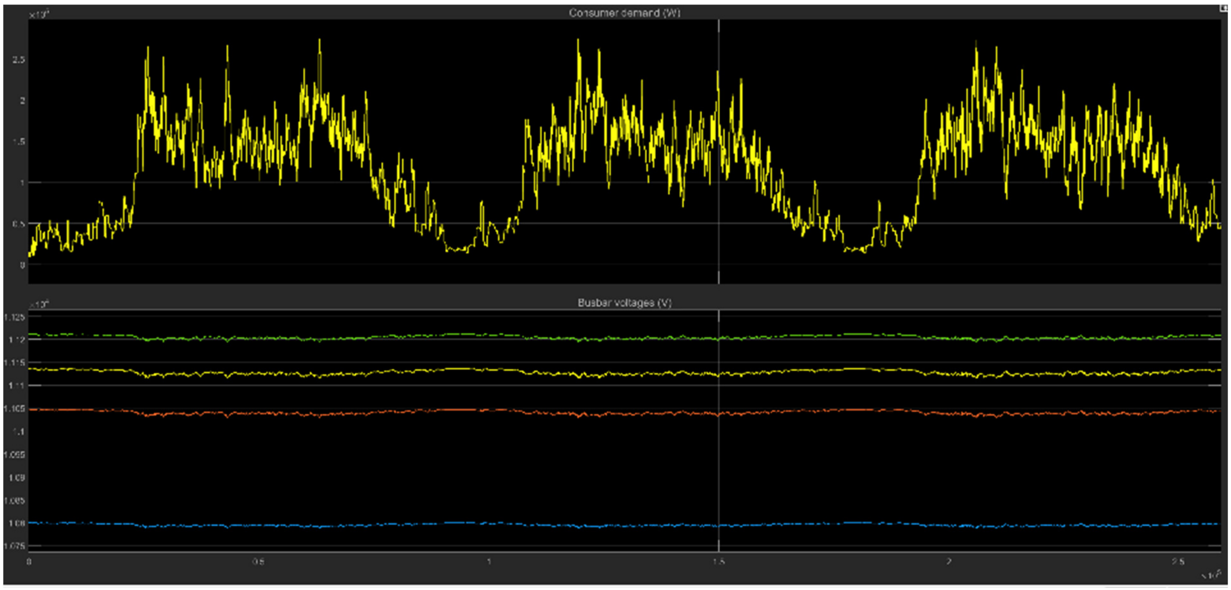


Figure 14 – Voltages on 4 Buses given a Demand Profile

4.2.3. Consumption of Energy and Cost to Serve

In a given simulation run the amount of energy, and correspondingly the cost of that energy is calculated providing the ESP with the information on the variable components of their costs (Figure 15). In future versions of EPO demand–side controls will allow for more efficient use of energy at different times (responding to variable pricing).

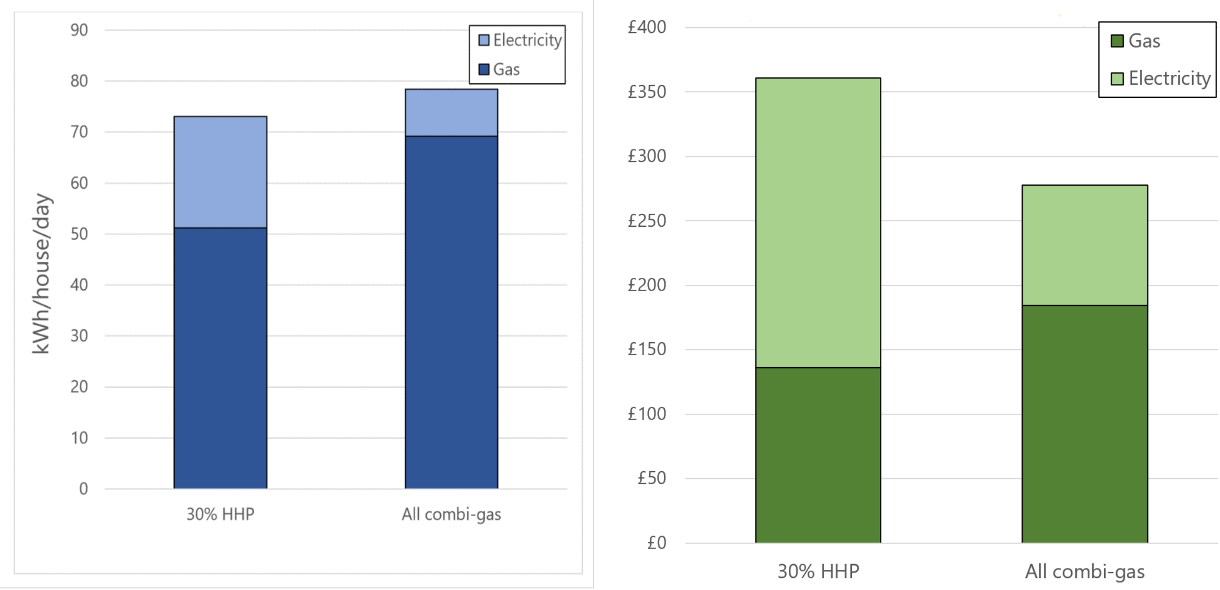


Figure 15 – Energy Consumption and Wholesale Energy Cost (ave per home)

4.2.4. Supply–Demand Imbalance

Figure 16 illustrates the imbalance of supply vs demand given the ESP operating model. The absolute values are not relevant in this case given the simplifications that were required in the prototype, however, in future versions of EPO it is expected that this type of output will be useful for understanding the capability to offer flexibility and to balance supply and demand to avoid system imbalance charges.

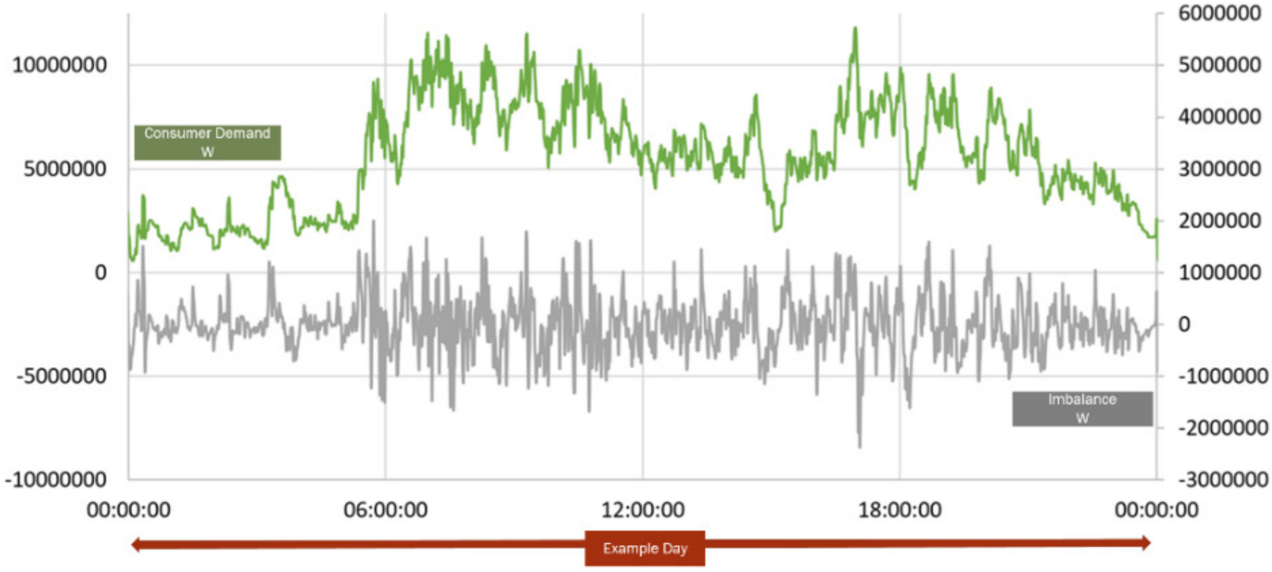


Figure 16 – Consumer Demand and Supply–Demand Imbalance over an Example Weekday (30% HHP)

4.2.5. Storage Capacity

The centre graph in Figure 17, below, illustrates the contribution of batteries (positive = discharging to grid, negative = charging battery) to an ESP's portfolio, whilst the occasional yellow spikes in that centre represent the need for spot–market transactions to still address the demand (since the battery rate of delivery is exceeded). Again, the absolute numbers are not as important as the fact that different strategies for purchasing energy from storage devices, and their capacities can be explored against one another (and in later versions of EPO contrasted with demand side strategies).

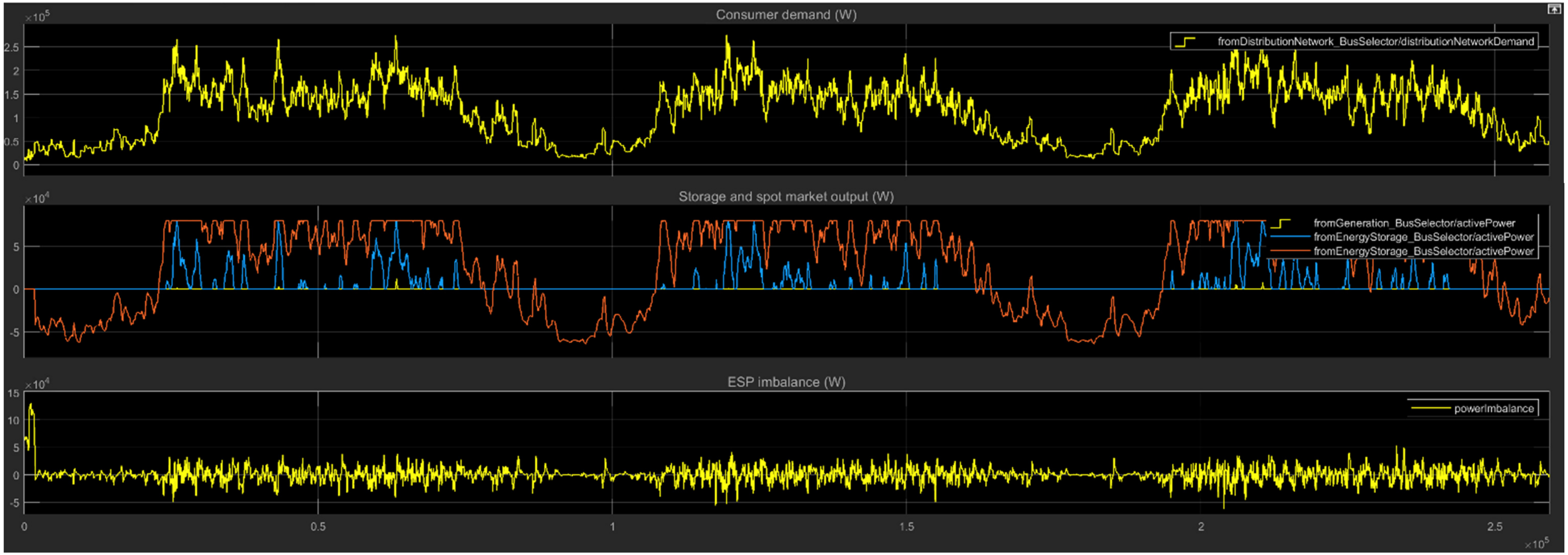


Figure 17 – Use of Storage to Balance Supply–Demand Position

4.2.6. Forecast Accuracy

The forecast accuracy i.e. the accuracy of which a forecast of future energy consumption can be made has a direct bearing on the cost of balancing services.

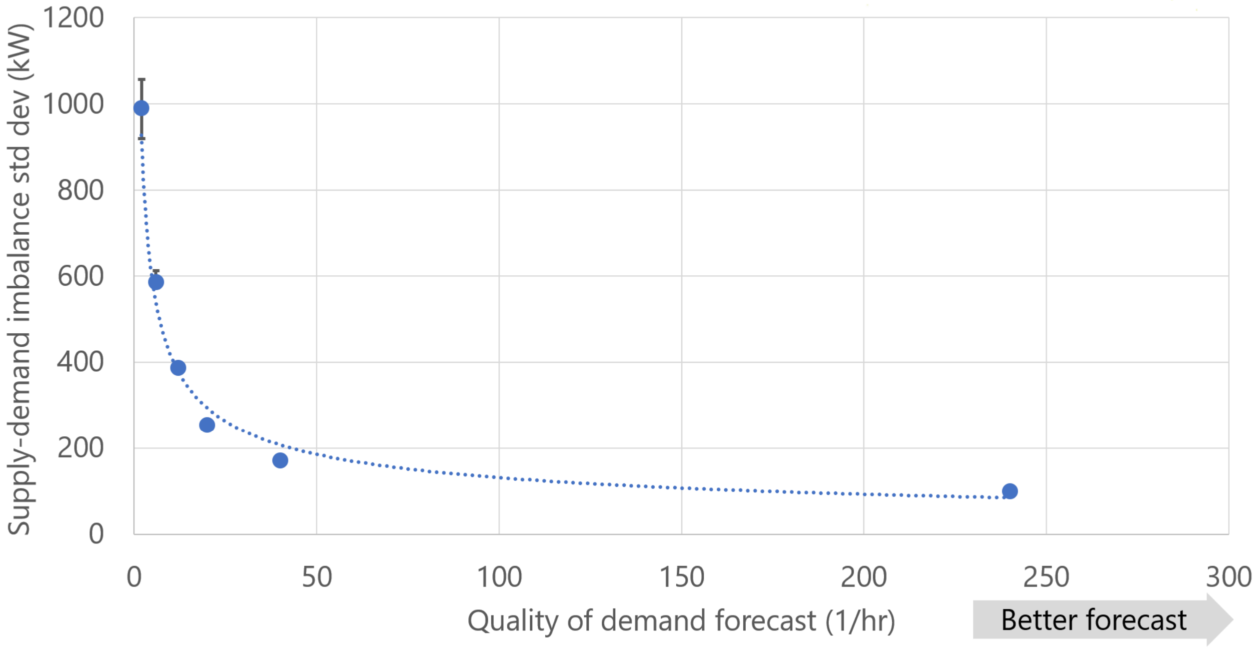


Figure 18 – Forecast accuracy Impact on System Imbalance

Figure 18 shows how the amount of demand–supply imbalance decreases as a function of forecast accuracy and indicates, as the ESP evolves its business models, where it might be worth investing in modelling, AI and/or sensors and measurement equipment to better reduce its operating costs.

Similar models can be explored around other capital expense, for example, how much capital to spend on insulating a house versus the reduction in cost to serve but only the forecast accuracy has been explored to date.

5. Key Insights

The intention of this report was to highlight the potential of the architectural and simulation capability developed in SSH1 WP3.

The work undertaken has developed and tested a methodology for developing system architectures and requirements for implementation with a focus on making it an engaging, stakeholders' needs driven process.
The uniqueness of the future GB Energy System and EnergyPath® Operations project output is that, in the future it can offer:

1. The architecture process allows for a range of energy system actors to be proactive in shaping the operation of a future GB Energy System. Looking at the relationships between many actors to design efficient ICT implementations (shared and proprietary), designing commercial agreements which can unlock the value–chain and formulating the possible market and trading arrangements, driving decarbonisation as a result.
2. The modelling tool, EnergyPath® Operations, allows for multiple actors to simulate the physical and financial aspects of their proposed future businesses and how they interact with other businesses with complimentary or competing ideas prior to a scaled demonstration and commercialisation.

It is envisaged that the main users of this capability are future Energy Services Providers; Energy Market Policy Makers/Regulators; Electricity and Gas Network Operators and Consultancies and digital IT companies. The exact make–up of future energy market structures is currently unknown and the ESC believes that a future GB Energy System will be the result of many organisations developing integrated energy networks and service offerings. The collaboration of many energy system actors which will inform future energy policy and unlock value for energy providers and end–users – while prioritising least–cost, low–carbon transition pathway.

At the start of the process, it was understood that pursuing architectural transformation would carry significant risk in terms of the complexity considering the breadth of scope, the possibility of pursuing dead–ends, the scale of the unknowns inevitable with such work, the conflicts between competing stakeholders etc. but the developed process has led to an understanding of how to control such issues and make them manageable.

An example development of a slice through a Conceptual Architecture, to develop out the level of detail to allow for implementation and/or simulation has been completed and is contained within the Enterprise Architect® repository.

The Conceptual Architecture requirements development has created the simulation capability to help industry participants tackle the chicken–egg problem of developing retail business models, network business models, etc in parallel. This capability has been demonstrated across a complete end–to–end value chain within the Energy System over a narrow use–case to illustrate the methodology and modelling capability. The Use–case for this analysis focused on how an Energy Service Provider might balance energy supply and demand.

The analysis into the system helped to identify some of the dynamic behaviour of the system. The following aspects of the exemplar architecture simulated in the EnergyPath® Operations tool were:

- The cost to the Energy Service Provider of supplying energy (electricity and gas).
- The tolerance to which the different between Energy Service Provider supply (from generator / storage discharge) and demand (from houses / storage charge) can be maintained.
- The storage capacity required to handle the total difference between electricity demand and supply.
- The total energy supplied to the domestic properties that comes from the wind generator, relative to spot market and gas.

The operating costs to the Energy Service Provider are higher when HHPs are introduced in comparison to consumers using conventional combi–gas boilers which are supplied by contracting energy from the day ahead market. This is dependent on the future price of wind relative to gas, and the storage margin. Further work is required to look at aspects of the architecture to make the deployment of HHPs economically viable.

The imbalance in supply and demand is significant particularly during peak heating times when consumer demand is significantly volatile. To improve the supply and demand imbalance, the forecast time step needs to be decreased. However, this increases the cost to the Energy Service Provider as they must be more reactive to the demand as the forecast timestep decreased. The tolerance of the imbalance would need to be agreed by the actor whom it is likely to be most impacted, presumably the network operator. There would need to be an incentive, (based on this tolerance), to the Energy Service Provider that would be greater than the cost of using additional storage to manage short term volatilities in demand.

The insights gained from the analysis feed back to the exemplar architecture requirements decomposition process to critique the requirements and allow for improvements in the architecture.

The end–to–end process of tracing the development of architectural ‘slices’, through successive layers of abstraction and then simulating those design ideas, using the EnergyPath® Operations tool to explore use–cases, has demonstrated the capability to provide insight directly linking back to stakeholders' needs and hence to inform architectural choices which work across multiple actors in the value–chain.

6. Appendix 1 – Glossary, Acronyms and Bibliography

6.1. Glossary

Term	Description
Actor	A defined role within the system of systems. It may be an individual, an organisation, a part of an organisation or a collective entity.
Device Vendor	Device Vendors provide a variety of primary appliances such as electric vehicles, heat pumps as so on; and secondary devices such as advanced home automation systems. These devices are made available to Energy Services Providers via the Home Energy Services Gateway. The Home Energy Services Gateway provides a set of standard device class Service Level Agreements that define: how that class of device should perform (e.g. to switch off within three minutes of a request); how Services Providers are permitted to use it (e.g. not cycling an electric vehicle battery); and any fees payable. The Home Energy Services Gateway provides governance to add, modify or retire classes.
EnergyPath® Operations	A simulation capability to enable different Shared Ecosystems to be codified into a simulation environment where a wide range of Individual Actors can input representations of their own business model, processes and systems to obtain insight on emergent behaviours due to interaction with others.
Energy Services Provider	The Energy Services Provider is a broad class of business models where the retailer takes responsibility for ensuring agreed service outcomes are delivered to Householders. They assemble the required supply chains and optimise their day–to–day operations to drive–up customer satisfaction while driving–down costs. They are not tied to a distribution network, so they must compete with one another. They design, market and deliver highly tailored services to Householders.
Gateways	One of the two types of Enabling Platform, specifically for the purposes of enabling market competition and/or cooperation between Individual Actors. Gateways are first and foremost business entities, owned and run in the collective interest to enable interoperability; any software or hardware is simply an element of what that business entity must do to perform its function. Gateways establish technically open 'pipes' but with

	commercially controllable 'taps' such that Individual Actors can decide when and where there is mutual value in interaction; in a similar manner to the way mobile phone roaming works.
Governance	How collective decisions are made, which may be involving a group of people representing their own corporate interests or a group of people selected to act impartially on behalf of the sector. It encompasses how the rules, standards and market actions are structured, sustained, regulated and held accountable.
Home Energy Services Gateway	A specific Gateway (one of the two types of Enabling Platform) to enable interoperability between any Household to any Energy Services Provider; and any Energy Services Provider to any device from any Device Vendor. Interoperability between the former pair involves a shared language to describe services and standard data schemas; interoperability between the latter pair involves standard device class Service Level Agreements, Governance to add/modify/retire device classes, data/control routing and data/control rights management.
Householders	Generally, Householders are likely to buy outcome-based services from Energy Services Providers as opposed to input commodities. However, if a Householder wants to remain directly exposed to input commodity pricing then undoubtedly there would be offerings from Energy Services Providers to cater for that. Consumers' needs and preferences vary enormously, so Energy Services Providers need to work to understand, shape and bound expectations. The conditions and constraints of their homes also vary enormously, so Energy Services Providers need to use extensive data to price meeting expectations.
ICT	Information and Computing Technology.
Individual Actors	The individuals or organisations that cooperate and/or compete within the Shared Ecosystem. They are codified in this report using light blue blocks.
Service Attribute	A descriptor for one of the elements of a service. It may be for a consumer agreement (e.g. number of hours a home will be warm for), or it may be for a supply chain agreement (e.g. ramp–up rate for electricity production).
Service Level Agreement	A specific combination of Service Attributes and Performance Levels for each Attribute, which may be negotiated bilaterally or may be selected from a set of standard classes to further reduce transaction costs between Actors.

6.2. Acronyms

Abbreviation	**Explanation**
BSUoS	Balancing Service Use of System
CfD	Contracts for Difference
CREST	Centre for Research, on Evolution, Search and Testing
DSO	Distribution
DUoS	Distribution User of System
EA	Enterprise Architect®
EPO	EnergyPath® Operations
ERSG	Energy Resource Services Gateway
ESC	Energy Systems Catapult
ESP	Energy Service Provider
ETI	Energy Technologies Institute
FiT	Feed–In Tariff
HESG	Home Energy Services Gateway
HHP	Hybrid Heat Pump
IP	Intellectual Property
KPI	Key Performance Indicator
MBSE	Model based systems engineering
SGAM	Smart Grid Architecture Model
SoSA	Systems of Systems Approach
SSH1	Smart Systems and Heat Programme Phase 1
SysML	Systems Modelling Language
TOGAF	The Open Group Architectural Framework
TSO	Transmission
WP3	Work Package 3

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7. Appendix 2 – Change Management and Traceability

7.1. Configuration and Change Management

Configuration and Change Management (CCM) provides the mechanism for the creation, modification and reuse of unique architecture elements within one or more modelled systems. It satisfies two important purposes:

1. To ensure that the architecture definition is known and documented, with changes managed and controlled.
2. To allow stakeholders to change, reuse and extend any available architecture element and modelled system that exists (including previous and latest versions) and understand its requirements, functionality, and compatibility with other elements.

CCM comprises the following steps:

1. Identify the architecture elements that require configuration management.
2. Define the set of architecture elements that comprise the next architecture baseline (the set of aligned elements for a specific purpose).
3. Manage and control changes to architecture elements and baselines under configuration management.

This provides two major advantages: first, each architecture element that forms part of the approved baseline is formally recorded and managed, as is the baseline itself; second, proposed changes are always assessed for impact before they are agreed and implemented, to allow changes to be optimised, prioritised and scheduled, or rejected if appropriate. Figure 19 provides an overview of the end to end approach.

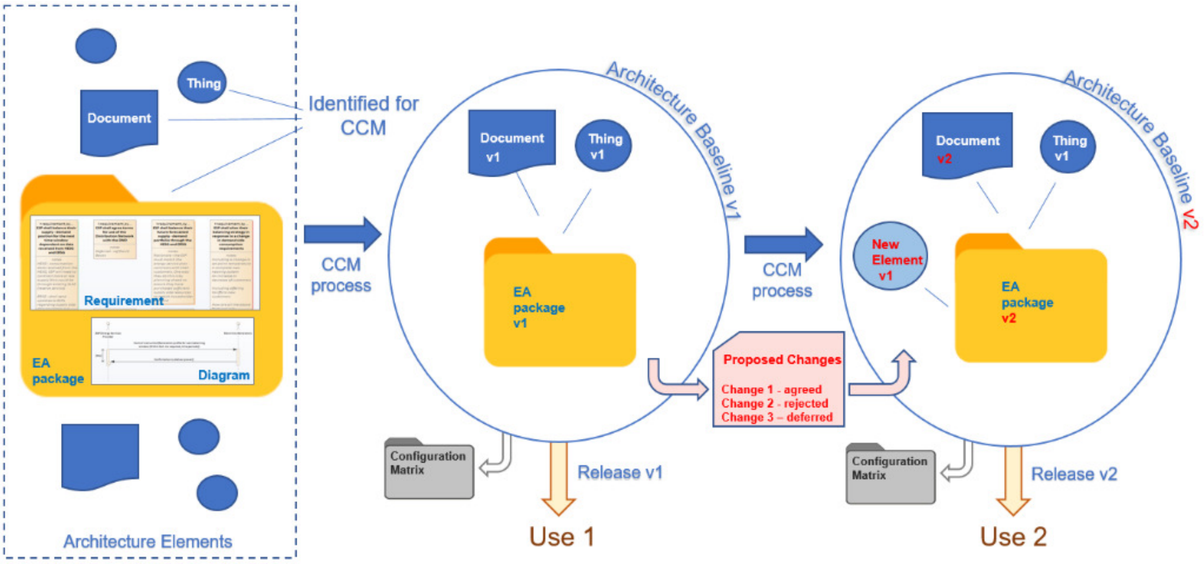

Figure 19 – Configuration and Change Management Approach

Architecture elements under configuration management are those Enterprise Architect® (EA) model packages and model exports that define the energy system architecture under development. Examples include:

- Requirements, from stakeholder to system to actor, through level zero (L0) to level three (L3) derivations
- Behavioural diagrams e.g. use–cases, sequence and activity diagrams, business models
- Structural diagrams e.g. block definition, internal block and interface diagrams
- Functional Requirements Specifications (FRSs), which inform EPO Tool development

Architecture baselines are captured in a configuration matrix, which lists all the architecture elements application for the defined release and end use.

The EA model and CCM approach are designed so that new elements or changes to any existing element are easily accommodated and managed, whether they are introduced by internal change (e.g. peer review or model analyses) or external change (e.g. different requirement or business model from a new or existing stakeholder). This removes the need to develop an entirely new set of interfacing elements or wider architecture every time a different need, objective or end use is identified.

7.2. Traceability

Relationships between architecture elements are recorded using tools and process to ensure traceability of decisions and justifications, and to support development activities such as:

- Requirements engineering and management
- Change management
- Architectural, functional and logical design
- EPO Tool development
- Stakeholder IP management

For architecture elements under CCM, traceability helps support change impact considerations e.g. to understand the impact on the functional design of an ESP if a new business model is incorporated; or to understand the impact on the EPO Tool if a change is proposed to the energy system architecture being modelled.

EA provides built in traceability by using relationships that are created between model elements during architecture development. These relationships can also be used to support model maturity and completeness assessments.

Traceability to EA exports, such as the ERS, is achieved by using unique requirement identities that transcend the different tool formats, and a configuration matrix that contains the content of each architecture baseline, which includes the EA model packages and exports. This ensures that it is always possible to determine the set of architecture elements and applicable architecture baseline(s) for any defined use. Figure 20 summarises the flow between elements.

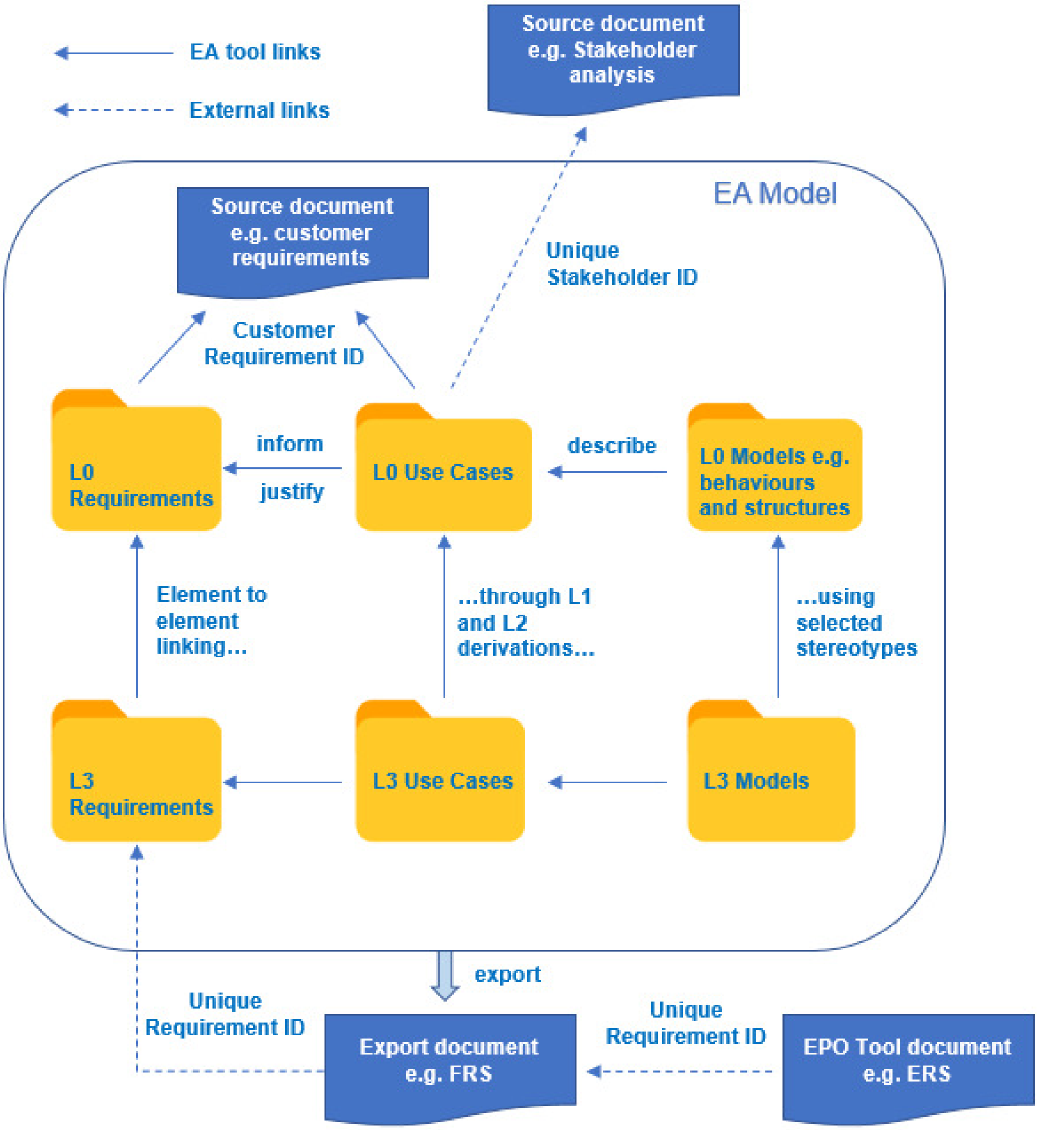

Figure 20 – Traceability Flow

8. Appendix 3 – Requirements Capture

The following functions were identified as important for the software tool that was required to capture the detailed design of business processes that underpin any high-level function implied by a chosen architecture.

- Multi–stakeholder requirements capture (i.e. how multiple stakeholders can all have input to specify problems and then facilitate compromises across any conflicting ideas)
- Facilitate a cross–cutting view of requirements (i.e. how you can look at the impact on changing one element with items that it affects)
- Integrate with other tools to allow traceability of requirements (specifically here we mean how energy system designs can be moved into the modelling domain and where problems are identified, traced back the origin for discussion and/or how changes in one area can be communicated effectively).
- Requirements engineering and management (i.e. how are requirements captured and worked with textually, as diagrams, and as interactive models)
- Change management
- Architectural, functional and logical design (i.e. how can you view the problem at different granularities for different stakeholder purposes)
- Stakeholder IP management

8.1. Alternatives

Some consideration was given to the use of SGAM (Smart Grid Architecture Model) for both requirements capture and presentation of results however there are some limitations. From a requirement capture perspective SGAM is currently electricity focused only and the work carried out on this project is multi–vector. Furthermore, this work requires the development of multiple levels of complexity (abstraction) to a level at which implementation is possible. The assessment of SGAM was that it would be very difficult to articulate some of the more detailed views needed. For this reason, it was decided to develop textual requirements in parallel with the conceptual views which, to some extent, informed the use of the chosen development tool (SparxSystems® Enterprise Architect®). In terms of presentation, SGAM outputs tend to look at problems in isolation rather than developing a cross–cutting view. There is no feasible way that the whole system can be visible in one view and so SGAM was not deemed appropriate for our uses. On the other hand, there is a plug–in for the SparxSystems® Enterprise Architect® application which can produce outputs in the SGAM format. This has been explored and could be utilised in the future to automatically generate outputs, ensuring consistency with other projects.

For Enterprise Architecture in other businesses TOGAF (The Open Group Architectural Framework) is well utilised to capture and describe organisational, data and control structures and relationships.

TOGAF was considered on this project too, but again, there are limitations. TOGAF is most–often deployed on single enterprise models i.e. within one business.

This application requires that many businesses are involved and many of the requirements within each of those businesses may not be explicitly stated externally (due to IP, trade secrets, business strategies etc). In most enterprise level developments, the physical asset and the business and operational processes are loosely coupled. In most industries the rate of manufacture of goods and the sale of those goods are not tightly linked (stock can sit on shelves in a supermarket for examples). With electricity this is not the case, data (e.g. how much power is required) is always slower than the actual manufacture and consumption data and so other, more tightly coupled, system definitions and simulations were deemed to be required.

8.2. Comparison of Tools

The development of the architecture uses a model-based systems engineering approach (MBSE)[16] using Systems Modelling Language (SysML)[17]. The approach focuses on using graphical representation to support the requirements capture, analysis, design and verification of a complex system design.

An MBSE approach supports decomposition of high level stakeholder requirements down to a level of detailed design that can be used for implementation. This is the first known application of these tools to explore the evolution and functions of a whole energy system, based on an explicit choice of a system architecture framework. These tools were applied to the problem statement (Use Case) outlined above.

This approach demonstrates the interfaces between multiple, competing, complementary and/or conflicting business models and technologies within the whole system architecture. This has the advantage, compared to examining a single value proposition or function within a vacuum, that the implications for the whole system are considered. Any individual element has to fit within the rules and capabilities of the wider architecture, or the architecture as a whole needs adjustment.

Through full contextual analysis, stakeholders can understand what interfaces exist that need supporting and what processes they need to exercise. Scenarios are then developed that guide the user through their design, challenging the assumptions which have been made.

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[16] See INCOSE (systems engineering governing body) publication https://www.incose.org/docs/default-source/delaware-valley/mbse-overview-incose-30-july-2015.pdf

[17] See http://www.omgsysml.org/

SparxSystems® Enterprise Architect® was chosen as the tool to support the capture of detailed business process design at a whole system level. It is capable of:

- Integrating of business process modelling notation (BPMN)[18]
- Supporting dynamic coding to represent physical models
- Modelling databases
- Managing textual based requirements (to support implementation and testing)
- Flexibly presentation results; including whole system and cross–cutting views for visualisation
- Integrating with other tools for future exploitation (such as DOORS and MATLAB)
- Enabling change control and management processes
- Capturing of multiple layers of requirement and interface resolution
- Tracing requirements within the tool and by linking to external sources

This results in a capability which not only delivers a full system analysis but also one which can be flexed and altered depending on stakeholder's initial and developing requirements. SparxSystems® Enterprise Architect® can also manage multi stakeholder requirements through the traceability and change management features of the tool, facilitating the options for a future Shared Ecosystem. More detail on this selection and the requirements is provided in Appendix 4.

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[18] http://www.bpmn.org/

Tool	**Requirements**	**Strengths**	**Weaknesses**
SparxSystems Enterprise Architect	Multi–stakeholder requirements capture Facilitate a cross–cutting view of requirements Integrate with other tools to allow traceability of requirements Requirements engineering and management Change management Architectural, functional and logical design Stakeholder IP management	Allows development of textual requirements alongside full model–based systems engineering (MBSE) SysML and UML support Dynamic Modelling BPMN support Plug–in for SGAM available Plug–in for ToGAF available Provides built in traceability using relationships that are created between model elements Cost effective	Manual entry of for traceability when moving into software development Harder to recruit users
IBM Rational DOORS		Massive industry acceptance Strong baseline management Provides built in traceability using relationships that are created between model elements	Expensive Significant administration overhead

9. Appendix 4 – Exploring Systems Architecture

A high–level system architecture choice creates the framework within which the interplay of social and economic forces will lead to the development of an actual functioning system. As the system evolves, various issues will arise which may have easy solutions or they may not. There will be alternative solutions, which will compete for investment, customer attractiveness and policy support. Having chosen an exemplar architecture and the implementation of a particular technology as a test–case, the next stage is to explore how the architecture might evolve, especially to solve the enduring challenge of heating – seasonal demand variation and major within–day peaks.

The commercial, informational and physical future Energy System implementation implications are tested by exploring the requirements of each of the actors within the example systems architecture through a focused use–case.

This section outlines the use–case for framing the exploration of the exemplar architecture as well as describing the tools and process used to manage the decomposition. It is also framed in the context of how a wide range of existing industry participants and new entrants might engage with the process. Many businesses with experience of internet-based business processes are evaluating the opportunities that new energy systems might present to them. For further detail regarding the actors and interactions within the example systems architecture, please see the SparxSystems® Enterprise Architect® repository[19],[20].

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[19] There is a free viewer for Sparx EA - https://www.sparxsystems.eu/enterprisearchitect/ea-lite-edition/

[20] The repository is available on the ETI Knowledge Zone; search for "Sparx EA repository"

9.1. The Use–case

The overall issue regarding the mass deployment of hybrid heat pumps is too large to consider as one question. An initial use–case[21] was established to focus on a specific problem to frame the decomposition of the example systems architecture. The initial use–case for this project was:

> *How could an Energy Service Provider (ESP) balance their supply – demand position by having a relationship with providers of energy and consumers of energy with a large penetration of consumers with hybrid heat pumps in a local area?*

In the exemplar architecture, the Energy Service Provider aims to balance their portfolio by increasing domestic consumption, through influencing appliances within their customer's homes when they have purchased an abundance of affordable energy and reducing consumption when they have constraints. They can also request changes to the output of power sources i.e. generators and storage providers. This also includes providing and managing some of the system services that are currently managed by the Electricity Systems Operator (ESO). Once very large demands, such as charging vehicles and heat–pumps, can be controlled by energy service suppliers, it is almost impossible for the ESO to respond to supplier actions. They therefore need to take responsibility for their own actions, a quite different model of system balancing from today.

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[21] A Use Case describes a problem statement from a user, that is explored using the tools described in this report

9.1.1.1. Architecture Visualisation

SparxSystems® Enterprise Architect® has the functionality to create cross–cutting templates to engage with different stakeholder audiences. This is an important aspect of the tool as it allows the requirements from the architecture decomposition to be exported in different formats, depending on the audience. This could be a high–level view detailing the goals and capabilities for senior management, as depicted in Figure 21 or a detail design view which could be used to implement a specific function within a process, as shown in Figure 23.

This feature furthers the objective to explore options for a future Shared Ecosystem, as it invites different stakeholder audiences to understand the requirements of the systems architecture, thus facilitating their input to its development.

Below are several views for example stakeholder audiences that can be exported from the architecture.

High level: This example displays the goals and current or future capabilities of a stakeholder. Senior management could use this view to gather an understanding at a high level of what capabilities they currently have and what capabilities they will need if they wanted to transition to a different business model. Other users would start their journey here to understand the highest level of abstraction.

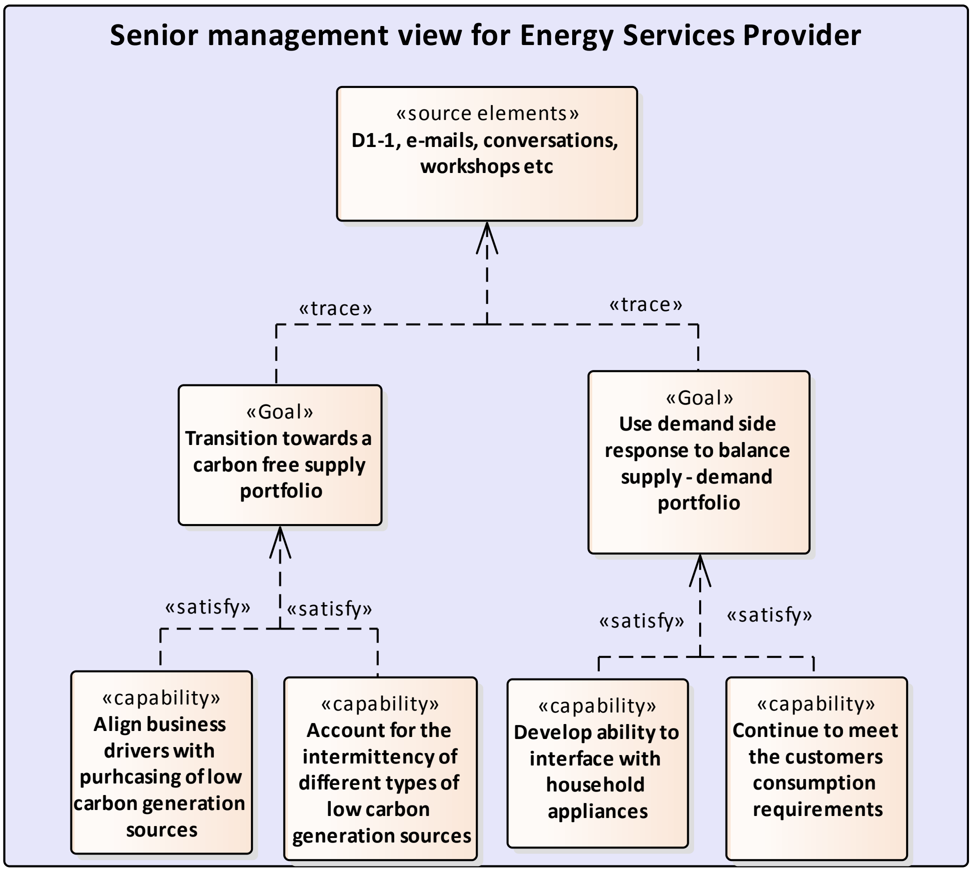

Figure 21 – Example High Level View

This high-level view should not come as a surprise to senior management, but it shows how every capability being developed within the design is aligned with the organisation goals. It enables senior management to check that the design is addressing the issues and capabilities that they expect.

Functional Level: The functional level view details what functions a business is either performing or desires to perform. This enables stakeholders with key insight, but not necessarily the deep technical knowledge, for example business development people, to understand what functions the business currently has or soon will have. It is important, especially during transition, that stakeholders such as business development understand the current and future offering to improve communication with external stakeholders regarding what they can or will be able to offer as a business.

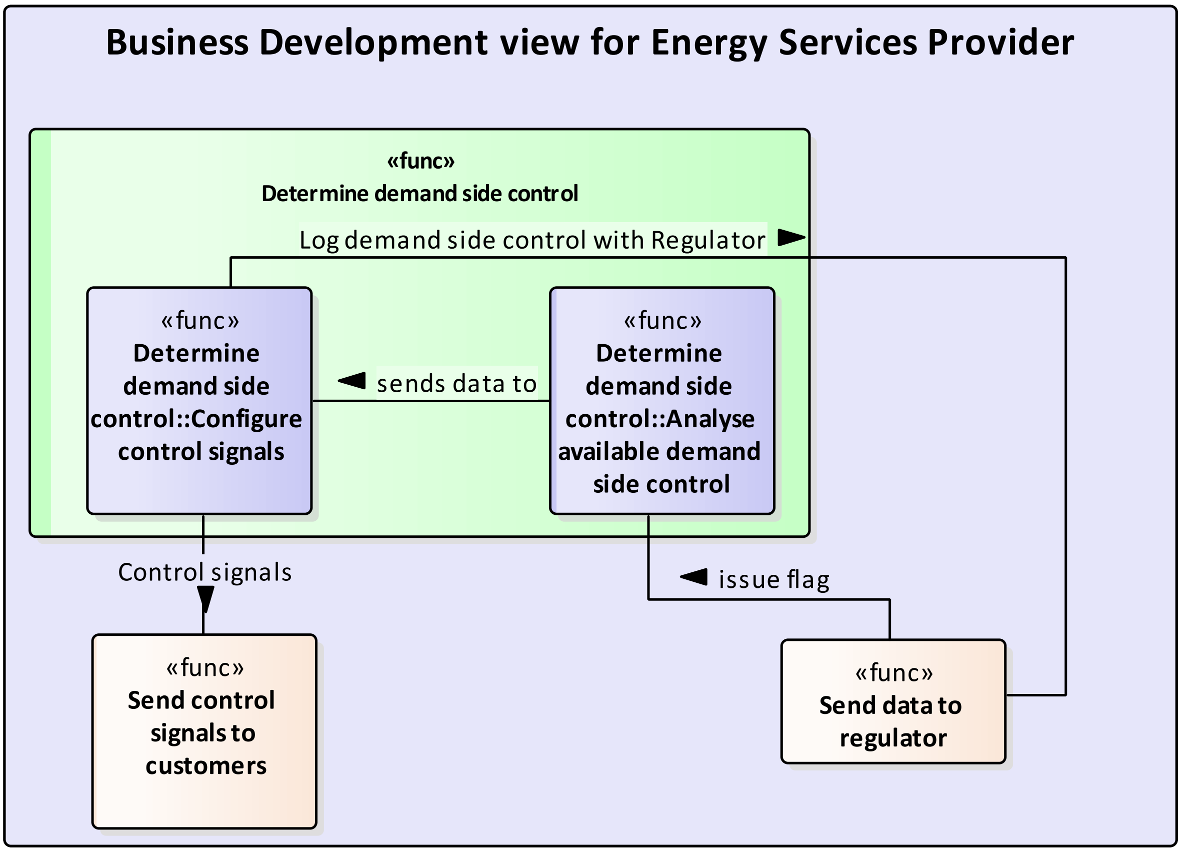

Figure 22 – Example functional level view

Implementation: The detailed design level details the necessary information required for implementation. This level graphically represents the behaviour within each function. Each function can be associated to several different behavioural views (i.e. one particular approach to a function) to enable different options to be modelled and tested. This level could be applicable to a software developer who is building algorithms for a function. The developer can understand how the function is expected to behave and the details within the interfaces required to support the function.

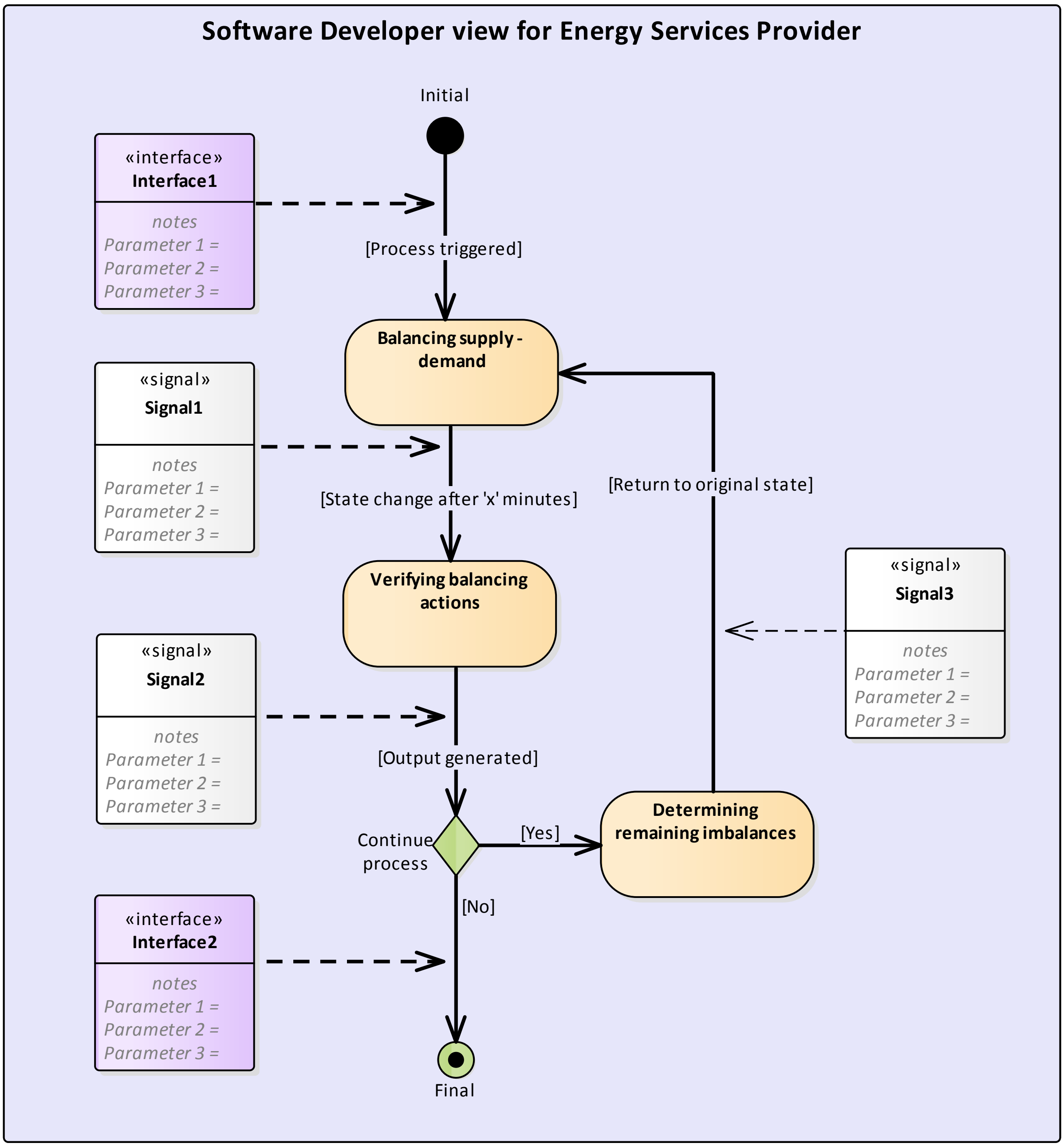

Figure 23 – Example implementation level view

9.2. Development Approach

The process for decomposing initial requirements can be as detailed or high level as desired. It allows for a flexible and industry standard approach to be taken towards full system analysis. The process starts with understanding a stakeholder's business model and how the value–chain is constructed around their goals.

Through collaboration with the stakeholder, the requirements can be developed from high level, ambiguous requirements into a set of detailed requirements. This detail can be achieved in the form of graphical representations of system behaviour and functional interfaces between actors to develop a full analytical view of an idea or problem. As different multiple parts of the system are designed then different levels of detail identify whether different ideas and behaviours are compatible or not. This enables new learning to be fed back into the architecture at any level of detail; traceability ensures any associated requirements are also considered when making changes. The flexibility of the approach enables new functions to be added and existing functions to be changed to give an understanding of what effect they have on the system, not just for a specific stakeholder, against an architecture baseline.

These requirements are then used as the basis for EnergyPath® Operations development to gain a better understanding of the dynamic behaviour of the proposed energy systems architecture.

The steps described below outline the process for decomposing initial requirements, down to a sufficient level of detail framed within the example of an Energy Services Provider, an actor in the example Conceptual Architecture.

Initial phase: The stakeholder will have an idea, question, value proposition etc which they wish to explore, in this case the use–case discussed in Section 2. High level requirements are initially gathered through several source elements. These can range from released documents, e–mails, workshops, external research etc. The idea is to generate an overview of the current environment and all information regarding the future, desired environment which they wish to transition to.

This high–level understanding of their business model will produce several goals which they would like to achieve.

Goals: As shown in Figure 24, the goal is a high level, ambiguous statement of what the stakeholder would like to achieve.

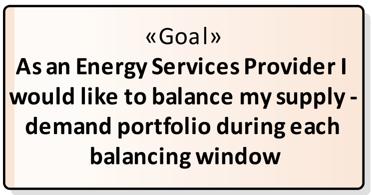

Figure 24 – Example Goal template

Capabilities: The next stage is to understand what capabilities the stakeholder requires to achieve these goals (Figure 25). These are traced back, through links, to the high–level goals.

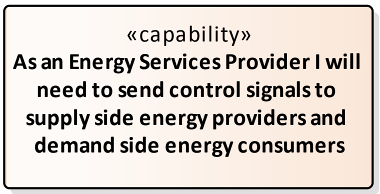

Figure 25 – Example capability

Use–cases: Several high–level (Level 0) requirements are then generated through a use–case analysis (Figure 26). This analysis looks at the goals and capabilities from many stakeholder contexts and scenarios. The use–cases are traced to any requirements which are generated from the analysis.

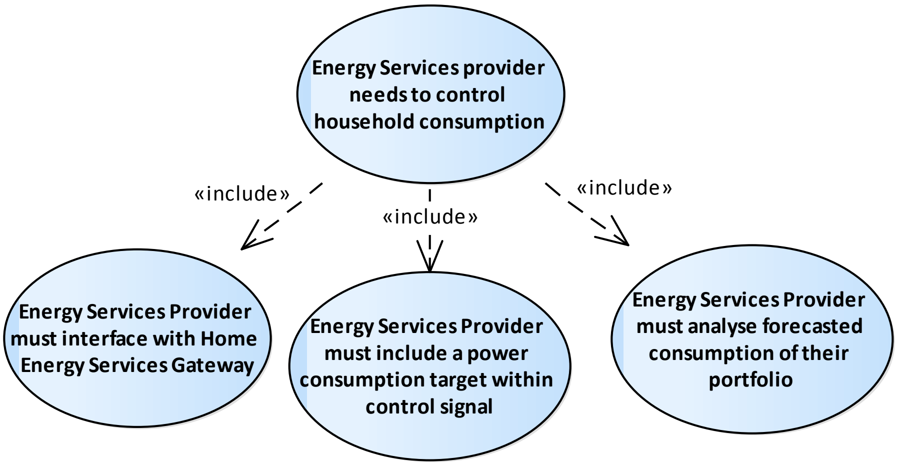

Figure 26 – Example Level 0 Use–case analysis

Requirements: These requirements help identify, at a high level, the initial capabilities and goals of the stakeholder (Figure 27). The requirements are directly linked to the capabilities and goals so the reasoning behind them can be traced.

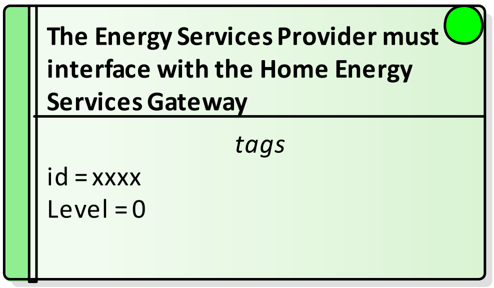

Figure 27 – Example high level requirement

Detailed Use–cases: Once the high level (Level 0) requirements have been generated, another use–case analysis is performed on each of these requirements (Figure 28). The aim is to look at each requirement from all relevant contexts and scenarios to help the stakeholder understand what they will need to do to achieve the high–level requirements, including aspects of the system they had not previously considered.

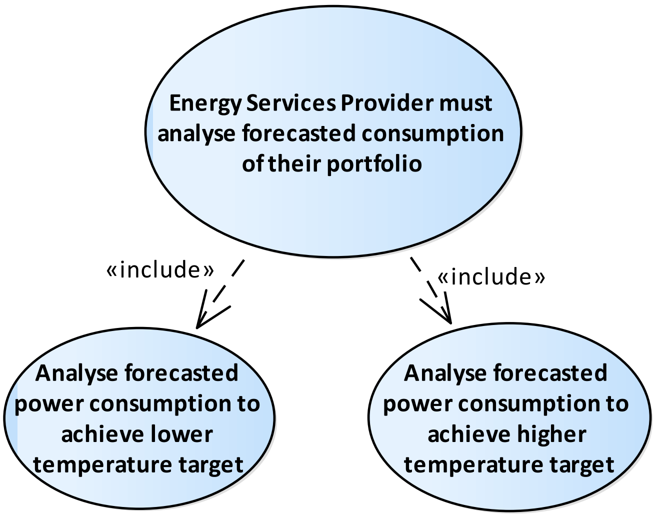

Figure 28 – Example Level 1 Use–case analysis

Detailed requirements: From this more detailed use–case analysis, many lower level (Level 1) requirements are generated and traced back to their parent Level 0 requirement, enabling the stakeholder to fully understand the use–cases, parent requirements, goals and capabilities involved with producing each requirement at any level (Figure 29).

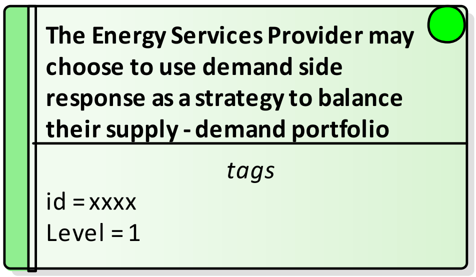

Figure 29 – Example Level 1 requirement

The functional level (Level 2): can be analysed based on the Level 1 requirements (Figure 30). This involves producing several functional interface diagrams to describe what functions each actor will need to perform and the internal and external interfaces required to satisfy the Level 1 requirements.

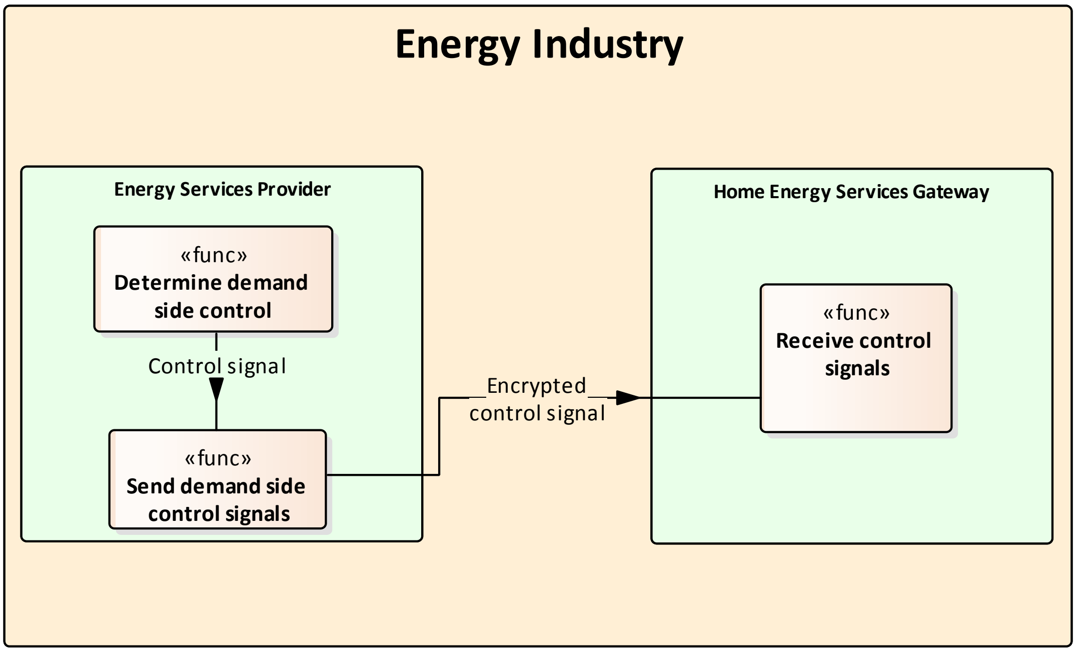

Figure 30 – Example functional interface diagram

Once these functional interface diagrams have been produced, the Level 2 written requirements can be generated as a result (Figure 31). Each function must have at least 1 input requirement, 1 behavioural requirement and 1 output requirement. The requirements trace back to both their Level 1 parent requirements and to the functional diagram directly.

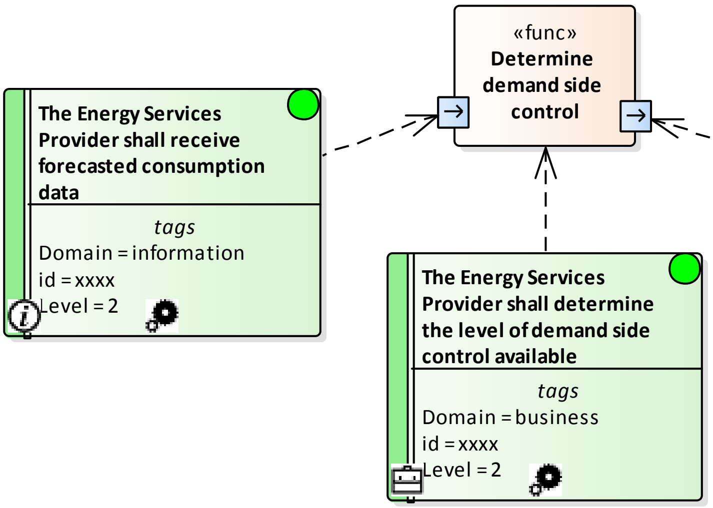

Figure 31 – Example requirement to function traceability

Detailed design (Level 3): The next stage is to define the behaviour of the functions (Figure 32). For example, this can take the form of state machines, activity diagrams or sequence diagrams. dependent on the type of view required. Any supporting/validation material at Level 3 traces directly back to the relevant function and requirements. The purpose behind this is to add sufficient detail for implementation.

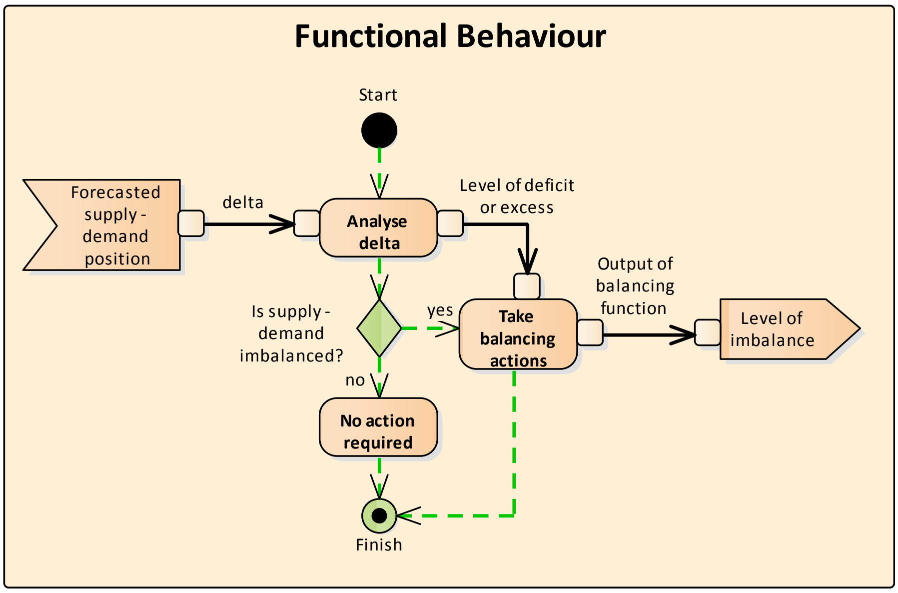

Figure 32 – Example behavioural diagram

9.3. Outcomes of Architecture Development

The work process and tool selected allow the decomposition of detailed design requirements for the exemplar architecture to outline a single, potential implementation option for the future energy system (by implication for GB, i.e. the scope of the NETSO). It also facilitates the input of multiple stakeholders simultaneously, even if they have conflicting views, through traceability and change management processes; further detail on these aspects of the work process can be found in Appendix 2. Furthermore, the traceability and library object approaches allow for baselining, meaning that a stakeholder can come back to their setup and analysis months or years after the event and enrich their analysis, try new ideas, and see what upgrades have been made since their last work (and decide if to incorporate those changes or not).

The MBSE approach can be rigid, therefore adaptions have been made to the approach to make it more flexible. This has enabled functions to easily be changed, replaced or new ones introduced without having to re–design the whole architecture as new and existing stakeholders explore ideas.

The whole approach supports a full decomposition of a system architecture rather than just a detailed analysis of a sub–system or stakeholder. This enables participants in the work process to identify not just what any individual actor is doing but also how they interface with the rest of the system.

The method described approaches the energy system in a profoundly different manner to the way it works today where businesses need to study many codes and rules to be able to participate in energy markets. Instead, this method aims to highlight structures and interfaces of interest, which will improve focus on core business areas, reduces complexity and removes barriers to participation.

Finally, this method allows for the functionality of the conceptual system architecture to be tested with multiple stakeholders. One objective of WP3 was to explore options for facilitating co–creating an architecture. This will allow stakeholders, in a group, to explore how the functionality of the energy system can change as a whole, as well as examining the impact of their specific innovative functions and processes within the energy system.

The detailed requirements of the actors of the Conceptual Architecture developed within the use–case can be found within the Enterprise Architect® repository, some examples of the requirements explored are outlined in Section 9.2.

10. Appendix 5 – EnergyPath® Operations Technical Detail

This appendix provides technical details on the development of the EnergyPath® Operations simulation tool described in section 3.1. Section 10.1 includes a detailed version of the block diagram from Figure 16 showing subsystems and information communicated between them. Sections 10.3 and 10.4 outline some of the major components of the tool based on the descriptions introduced in section 3.1: section 10.2 describes offline data processing, Section 10.3 describes the runtime model–oriented subsystems and section 10.4 describes the runtime tool–oriented subsystems. Section 10.5 describes the key processes involved in carrying out development. Finally, section 10.6 describes future work.

For further details on any subsystem, please refer to the corresponding EPO Requirements Specification (ERS) and/or EPO Design Document (EDD).

10.1. Detailed block diagram

More detail on the subsystems present and their interactions, in the form of a high–level block diagram, is embedded in the document here:

Adobe Acrobat
Document

10.2. Offline Data Processing

10.2.1. Network Performance Template Generation

10.2.1.1. **Purpose**

Network performance template generation constructs “templates” that describe the responses of sections of the electrical distribution network to the instantaneous loads at different nodes within the network. These templates are used by the Distribution Network Model within the dynamic simulation engine to predict the state of the network (voltage levels at different nodes in the distribution network and power consumed by network feeders) based on the power demands calculated by other subsystems (chiefly the Consumer model).

10.2.1.2. **Achievements and next steps**

A performance template for one Medium Voltage (MV i.e. 11kV) network has been constructed in the form of an appropriately trained Artificial Neural Network (ANN), using realistic data on a real MV network located in Bridgend in Wales. Since the template is specific to this network, accurate predictions of the performance metrics may be obtained. However, this approach does not as it stands cover other geographical areas, and limited work has been performed on mechanisms to use a template obtained from one network to predict the behaviour of other "similar" networks. In addition, the performance of Low Voltage (LV, i.e. 415V) networks has not been considered, and all analysis has assumed "forward" power flows i.e. from primary substation to secondary substations, ignoring potential effects of distribution–connected generation.

The current process is relatively scalable (thanks to automation of process steps) to any network across the 415V to 33kV levels, allowing for analysis of effects at these levels – however detailed data and non–negligible effort is required for each network to be simulated.

As a precursor to the work described, a scoping exercise was pursued with leading UK universities as well as an external consultancy to understand the use of network templates. This identified limitations in the previous approaches for our purposes, and so the approach described in this section was followed.

10.2.1.3. **Design overview**

As described above, the performance template encapsulating the behaviour of the chosen MV network takes the form of an Artificial Neural Network (ANN). The inputs to the ANN are values of real and reactive power demand (P_i and Q_i respectively) at each of the chosen network's 117 bus–bars, while the outputs are the voltage magnitudes (V_i) at each busbar and the real power losses (P_{Li}) and reactive power consumption (Q_{Li}) in each of the network's 8 feeders. A set of weights connect the inputs to the hidden layer neurons which encode the trained behaviour of the ANN. The hidden layer size has been optimised to give a good generalisation ability and avoid overfitting.

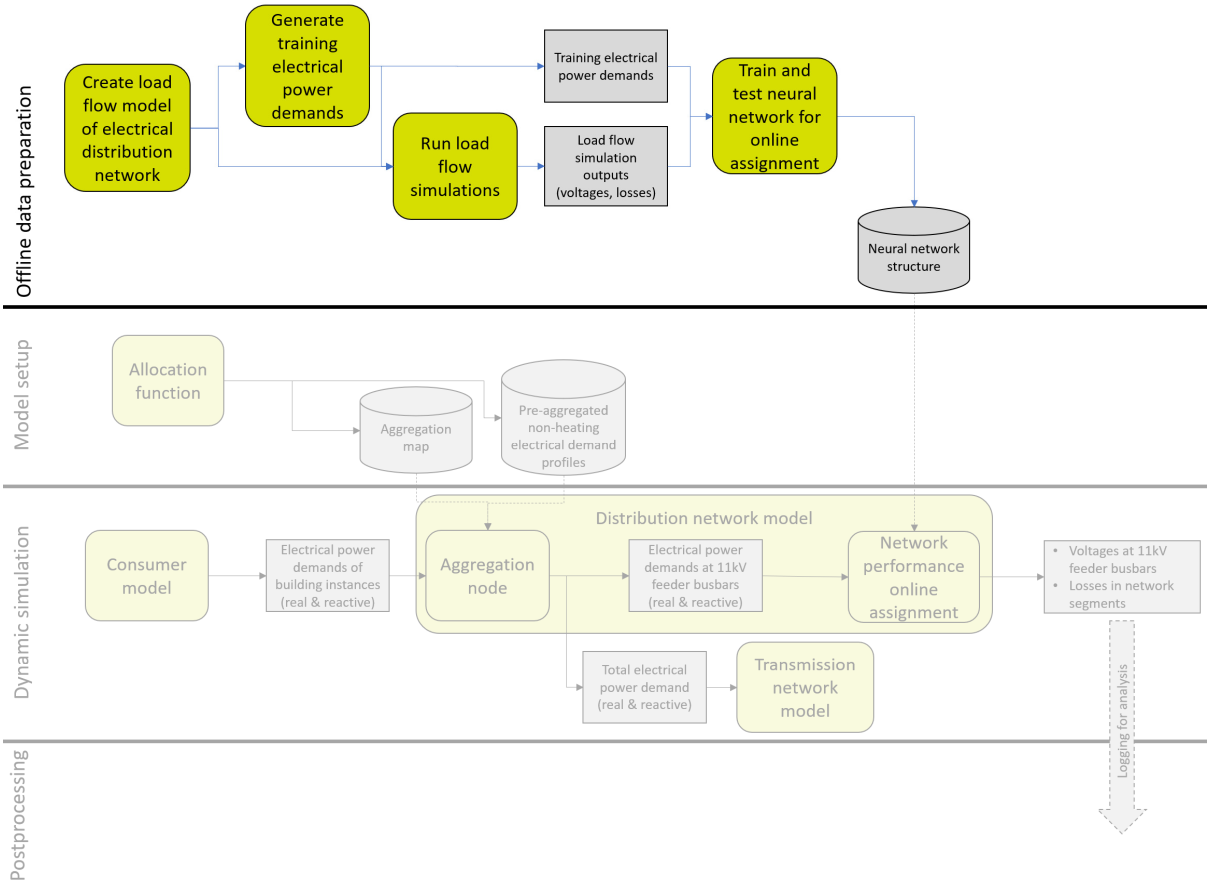

Figure 33 – The offline process for network performance templates with link to the distribution network model in the simulation

Figure 33 shows an overview of the process used to construct this ANN:

1. **Create load flow model of electrical distribution network:** The 11kV network chosen, associated with primary substation ID 560024, was selected as it was the largest MV network in Bridgend. GIS data was obtained for this network (shown in Figure 34), alongside the corresponding network parameters such as line and transformer capacity and impedance properties. This was used to construct the electrical network in a load flow program (IPSA) as an 8–feeder system with load balanced across the phases.
2. **Generate training electrical power demands:** To cover the possible range of demands at each secondary substation arising during the simulation of the full EPO model, sets of demand values were chosen from a uniform distribution up to 1.5 times the rated apparent power of the transformer and from a power factor between 0.9 and 1.0.

3. **Run load flow simulations:** Load flow analysis was performed on the network model with the demand values from the previous step. Over ten thousand simulations were performed in ca. 30 minutes.
4. **Train and test ANN:** This involved searching across a range of learning algorithms and numbers of hidden layers and neurons within the hidden layer to find the best prediction accuracy.

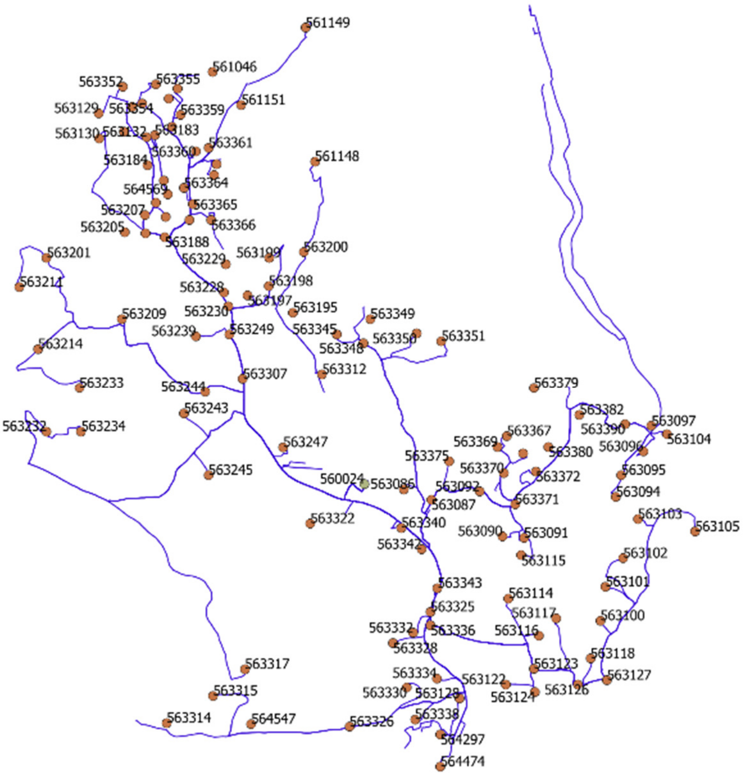

Figure 34 – A geographical view of the MV network used (primary substation ID 560024), depicting all secondary substations with their IDs

In general, due to the high dimensionality of the problem the demand values used to train the ANN will not cover all possibilities of load values. Therefore, the set of loads calculated by the consumer model during the simulation may not have been seen by the ANN during training, and so it is not possible to guarantee that accurate predictions will result.

10.2.1.4. **Data and IP**

Item	**Source**	**Used for**	**IP status**	**Limitations and mitigations**
EPN data sets for Bridgend	ETI/ESC	Electricity network topology and electrical parameters	Licensed for EPO use in accordance with SSH Framework Agreement	Only covers the Bridgend area. Mitigation: pursuing further data sources covering wider geographical area. Does not specify electrical connectivity between busbars. Mitigation: geographical information used to derive realistic connectivity.

10.2.1.5. **Validation**

When tested on unseen data, the goodness of fit of both voltage magnitude and losses reported an R^2 value close to unity. Testing the network on a different data population that was used in the test will be important together with pruning the network with a view to checking for overfitting.

10.2.1.6. **Impact**

Inclusion of electrical network modelling within EPO allows assessment of the types of networks most likely to need reinforcement in the face of future demands from low carbon technology, as well as the data, control and commercial models that can mitigate the severity of the problem most successfully and the financial implications of those decisions. This might also allow for exploration of differing business models: for instance, while the network operator may perceive an overloaded transformer as a threat, a DSR provider might use this as an opportunity to sell electricity downstream of the transformer to alleviate the threat.

A computationally lightweight model of distribution network behaviour (using network performance templates), combined with appropriate methods to estimate both demand and distribution–connected generation, could also provide value outside of EPO. It might be able to inform stakeholders such as planning and policy with respect to the costs, environmental impacts and technical issues of operability of the distribution networks. More commercially, it might also be of interest to DNOs looking to transition themselves into distribution system operators (DSOs). This impact would be magnified if it becomes possible to expand such a lightweight model to cover wider geographical areas (regional scale); potential methods for doing so are described in the following section.

10.2.1.7. **Future work**

The approach described in this section differs from the standard technique of using a load–flow solver such as IPSA (TNEI Services Ltd, 2016) to calculate voltages and losses in an electrical network. Given the anticipated scale of EPO simulations, tightly coupling a load–flow solver to the dynamic simulation engine might make prohibitive the computational cost of performing computations for all networks in the simulation, and thus the choice has been made to prepare reduced–complexity "templates" during tool development to be used online. However, this may be reconsidered during future work as described below:

Functionality	**Impact**
Analyse datasets of real networks to identify classes of similar networks (e.g. rural overhead lines) and exemplars of those classes (*representative networks*). Generate performance templates of those representative networks, to be used to predict performance of all instances of that class of network in the dynamic simulation.	Distribution network simulations can expand to wider regional–scale geographical areas for acceptable computational effort, at the cost of reduced accuracy.
Expand templates to include response of networks to integrated control mechanisms including OLTCs, energy storage, network reconfiguration and static synchronous compensation.	Allows for richer representation of DNO/DSO business process within dynamic simulation.
Expand templates to consider reverse power flows due to distribution–connected generation.	Allows simulation to explore architecture's response to (and control of) such generation.
Investigate incorporating online load–flow–style solver in place of ANN, including variations such as reduced–order load flow or multi–vector load flow model.	Reduced development complexity and increased accuracy, potentially at the cost of increased computation time.

10.3. Model Features

10.3.1. Top level Simulink model structure

10.3.1.1. **Purpose**

The top–level model structure provides the overall framework to simulate the Conceptual Architecture. It transfers signals between actor models, handles variants and instances and allows for imperfect ICT simulation.

10.3.1.2. **Achievements and Next steps**

The model developed to date is sufficiently flexible to represent the Conceptual Architecture and the different scenarios that may wish to be simulated within that framework. It communicates signals between actor models and allows multiple instances of a given actor to be simulated. The structure enables different variants of an actor to be represented and easily changed.

The current framework assumes the actors communicate instantly between each other and between the business and physical parts of their internal models or do so at a constrained rate. A more realistic implementation would represent additional dynamics of the communications systems that might contribute to the viability of the Conceptual Architecture in the specified scenario (e.g. message latency, throughput limits, data corruption etc.).

10.3.1.3. **Design Overview**

The top–level model is written in Simulink and includes all the actors in the Conceptual Architecture. A diagram is shown in Figure 35. It consists of 10 high–level *actor models*, shown as rectangles, each corresponding to the collection of all of one type of the actors in the Conceptual Architecture. Lines connecting the actor models correspond to flows of information or physical phenomena between them.

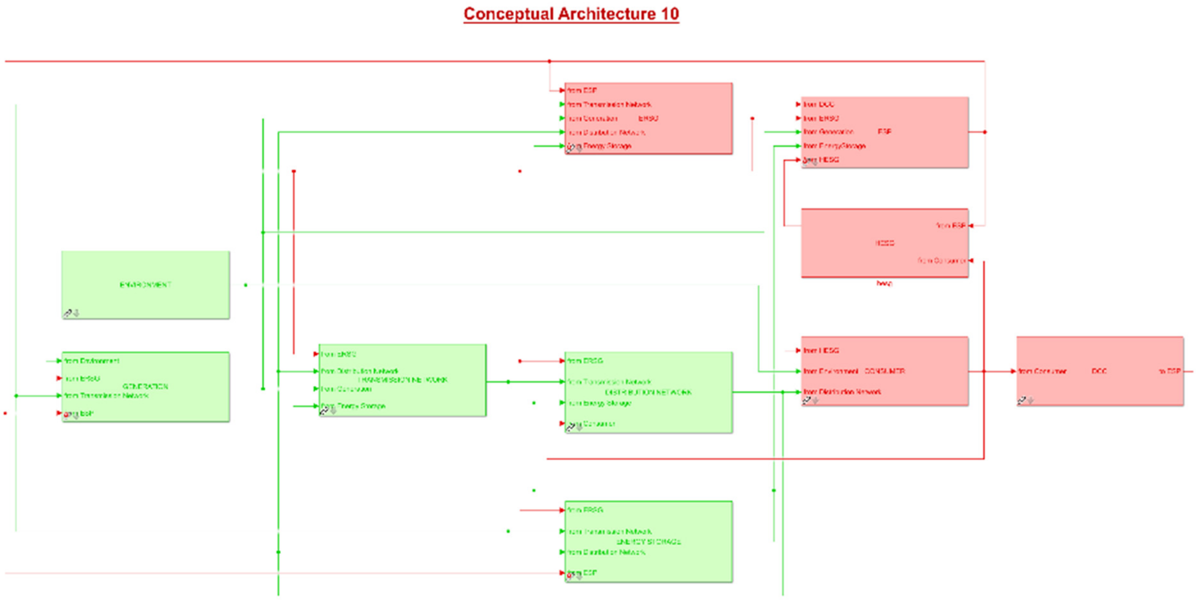

Figure 35 – Top–level Simulink model

Each actor model is constructed as a *group* of *instances* as shown in Figure 36 for the generators (with two separate generation instances modelled). Each instance can be configured separately, and communicates independently with others, to allow for the modelling of multiple actors in each architecture–level role.

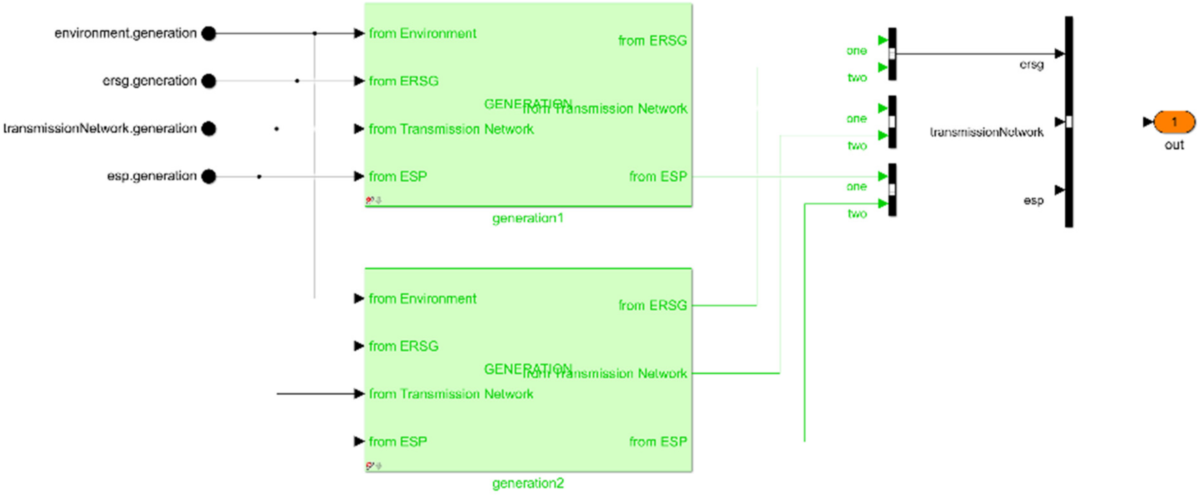

Figure 36 – Generator actor group

The physical and business processes of an actor are modelled separately within the actor itself (see Figure 37). The physical behaviour of the system is calculated within its own individual subsystem, as is the behaviour of the business process. The I/O interface enables the two subsystems to exchange information (a sensor measuring physical behaviour and making it available to the business process for example).

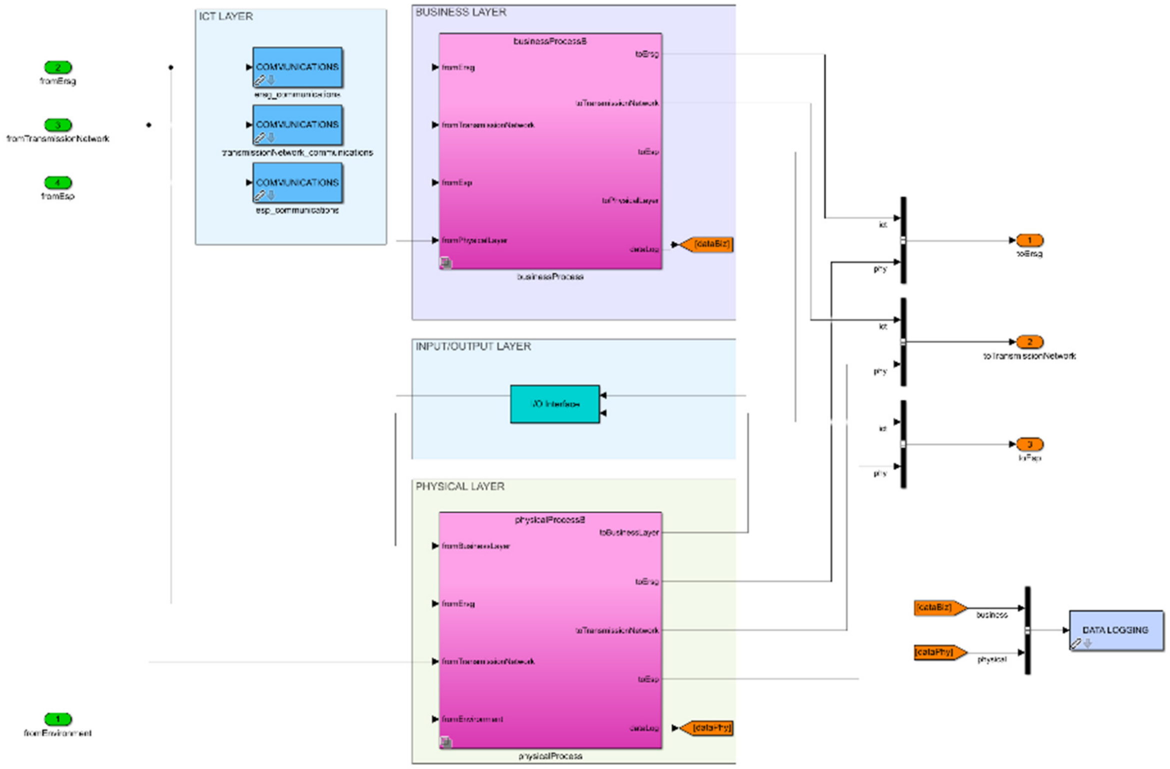

Figure 37 – Physical and business processes

A strict signal naming convention is in place whereby the bus structure meets a robust protocol[22]. Multiple variants of both the business and physical process can be defined and are selectable by the user.

In addition to the single top–level model, the individual actor models may be reused in simpler models dedicated to supporting specific analysis tasks. An example is the consumer demand model which includes solely the Consumer model (see section 10.3.7), portions of the Environment model (see section 10.3.3) and the aggregation node from the Distribution Network model (see section 10.3.10).

10.3.1.4. Data & IP

There is no data and background IP associated with the top–level Simulink model structure.

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[4] "Business and ICT Modelling Structure"

10.3.1.5. **Impact**

As the model has been written to be flexible, it enables most of analysis relating to the Conceptual Architecture to be done in a single model, with that model configured and parameterised as required.

The actor group structure and the signal routing approach enables the model to represent multiple instances of any actor, handling many–to–many communication paths. This combined with the variant–selection mechanism allows for the representation of heterogeneous instantiations of the Conceptual Architecture, playing off different business processes against each other in direct competition.

The structure also enables efficient development through expansibility and debugging.

Use of separate physical and business models allows the physical and business aspects to be changed independently, without the need for an unnecessarily large number of subsystem variants. The use of variants also allows different business (and physical) processes to be evaluated quickly.

10.3.1.6. **Validation**

The structure has not undergone formal validation, however significant time has been spent to ensure the model is able to support both current and potential future scenarios within the Conceptual Architecture. The model has also been used successfully for initial analysis work as described in section 4, giving confidence in the implementation.

10.3.1.7. **Future Development**

As noted in section 3.1, a key distinguishing feature of the EPO simulation is its fine time resolution while modelling the whole energy system – distinguishing events occurring at spacings of less than 1 second. This is needed to understand the transactive behaviour and physical dynamics of a proposed energy system architecture. Amongst simulations with such close relationship to time, the main subclasses are discrete event simulations, dynamical systems models, agent–based models and spatial models (i.e. finite–element simulations); these may overlap and a given simulation may exhibit characteristics of multiple categories. At present, EPO uses a combination of discrete–event simulation (for business processes) and dynamical systems simulation (for physical phenomena e.g. the consumer model); spatial variations of parameters are not explicitly considered at this stage, although this is a development direction for the future (discussed in more detail in association with relevant subsystems).

Development directions for the current top–level model approach include:

Functionality	**Impact**
More realistic communications model	Allows assessment of sensitivity of business processes to factors such as message update rate, message latency, data corruption, data throughput limits, finite measurement resolution or maximum number of simultaneous accesses
Additional points where variants may be introduced, within business/physical processes	Allows scalability of modelling to increased numbers of variants while minimising overhead of maintaining large numbers of variants
Alternative implementation constructs	Enhances efficiency of model development and of analysis workflow
Adaptability to other architectures beyond the Conceptual Architecture, either through additional top–level models or genericising a single top–level model's interconnections	Allows expansion of simulation capability to address alternative energy system architectures

10.3.2. Allocation

10.3.2.1. Purpose

The allocation function outputs a table of data describing the population of energy consumers (or producer–consumers) in the simulation and their connections into the energy networks. This output forms the basis for simulating the demand profiles for energy usage (in combination with other factors e.g. weather). In order to construct the table, the allocation function allows the user to provide data on the consumers and to specify the probability distributions that are used to allocate other characteristics to these consumers, covering: building type, physical location, network topology, socio–economic status of occupant, occupancy statistics (when a person or persons are at home), appliances installed and used within the home (including low–carbon technologies), appliance usage profiles and commercial links to energy suppliers. The probability distributions may be based on established modelling of future scenarios (for example, the probability of any occupant owning a PEV increases between now and 2050) or may be user–defined to explore what–if scenarios.

10.3.2.2. Achievements and Next steps

Functionality has been developed to allow the stochastic assignment of occupant demand profiles and heating appliances to, a real dataset of domestic buildings developed as part of the EnergyPath® Networks project (Energy Systems Catapult, forthcoming) based on the Bridgend local area (a small town). Refinements to reduce computational effort have also been implemented.

The probability distributions currently implemented are as follows:

- Heating appliance types based on:
    - Building type (detached, terraced etc.) only
    - Building type, building age and geographical area
- Occupants' demand profile (from a finite set) based on:
    - Floor area only
    - Floor area, building age and geographical area

This restricts the factors that can be considered when defining the distribution of types of heating appliance and occupants' demand profiles across the population of buildings.

Additionally, each building is assigned a weekday occupant demand profile and a weekend–day profile. This means that multiday simulations show unrealistic repeating patterns for (e.g.) consecutive weekdays. However, this is alleviated during the simulation by variations in other factors (e.g. weather).

Geographical areas beyond Bridgend are not currently included in the dataset, hindering the ability to simulate other geographies (e.g. dense urban).

10.3.2.3. Design Overview (Input – Output)

The allocation function is implemented in Python. Figure 38 shows its key inputs and outputs.

Inputs:

1. **Configuration:** Data sources to use and other options, e.g. filtering of energy producer–consumers by electricity network segment.
2. **Probability distributions for allocation:** Probabilistic relationships between variables, e.g. probability that a house will have a specific type of heating system as a function of its type (flat, terraced, detached etc.), age and size. Distributions included at present are heating system type and number of occupants.

Data sources:

1. **Population of energy consumers (raw):** Table of individual energy producer–consumers that may be included in the simulation, prior to any modifications.
2. **Electricity network topology:** Connections between nodes in the electricity distribution network, including buildings, feeders, and primary and secondary substations.
3. **Building physics parameter values:** Parameters defining the thermal behaviour of different building archetypes, based on factors such as type (e.g. flat, terrace, detached), age and size.
4. **Time–profiles of demand:** Predefined curves representing occupants' demands on a building against time, including room temperature setpoint, hot water temperature, hot water usage, radiator temperature setpoint and non–heating electricity consumption.

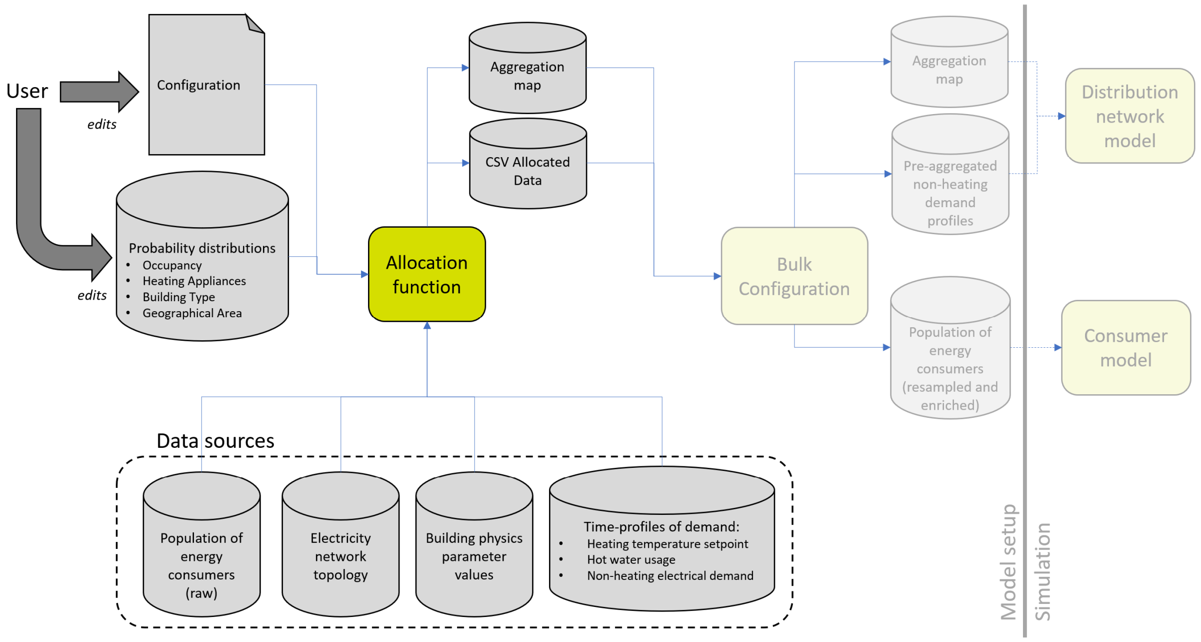

Figure 38 –Black–box diagram of allocation function

Outputs:

1. **Population of energy consumers (resampled and enriched):** Table of individual energy producer–consumers to be included in the simulation, with attributes modified/augmented according to the probability distributions in the input data.
2. **Time and demand tables:** Tables of non–heating energy demand over a given period, on Feeder Substation and Building level
3. **Aggregation map:** Tables showing how lower level nodes in the electricity network (e.g. consumers) are connected to higher levels nodes (e.g. LV substations).

The user sets up the probability distributions for appliances and occupancy for different building types etc. as required. This data will then be processed by the allocation function to assign the relevant additional characteristics to the original information. Mapping tables maintain data integrity.

For computational efficiency in the simulation:

- Building instances may be filtered to only those connecting to a certain higher–level node in the electricity network, focusing the simulation on a certain area
- Building instances may be clustered, by grouping instances connected to the same electricity network segment with identical characteristics into a single instance with an associated multiplier
- Non–domestic–heating demand data can be pre–aggregated at nodes at different levels in the electricity network

The Allocation function outputs the adjusted data, including both scalar parameter values and time–varying parameter values for each building instance, as CSV format. This CSV data is then read in by the Bulk Configuration function (see section 10.4.1) to be used by the dynamic simulation.

10.3.2.4. **Data & IP**

The key pieces of data utilised by the allocation function to generate output are as follows:

Item	**Source**	**Used for**	**IP status**	**Limitations and mitigations**
EPN data sets for Bridgend	ETI/ESC	Population of energy consumers (raw), electricity network topology, demand time–profiles (domestic)	Licensed for EPO use in accordance with SSH Framework Agreement	Only covers the Bridgend area. Mitigation: investigating Census data covering whole UK. Space heating demand time–profiles assume gas/oil boiler – usage of other heating systems may be different.
Cambridge Housing Model	Cambridge Architectural Research	Building physics parameter values	Licensed for EPO use	Values as presented lead to excessive heating energy consumption but scaling approach across archetypes was used with adjusted values.
CREST domestic demand profiles	Loughborough University	Demand time–profiles (domestic)	Licensed for EPO use	Space heating demand time–profiles assume gas/oil boiler – usage of other

				heating systems may be different.
CaRB2 industrial and commercial demand data	UCL	Demand time–profiles (commercial and industrial)	Licensed for EPO use	Data is limited to annual total energy use and peak power consumption by area for a given activity class, and profile type (flat or weekday–daytime). Assumptions used to convert these to power vs time profiles.

10.3.2.5. **Impact**

Using data that represents the inherent diversity of individual energy consumers, with or without stochastic re–allocation of characteristics, improves the ability of the simulation to capture real–world demand phenomena compared with assuming homogeneity of consumer characteristics. This may include combinations of characteristics that would be eliminated or rendered highly improbable if uniformity was assumed.

The data structures and processes are chosen to be straightforward to update if novel information comes to light or an expansion of the simulation capabilities is required.

All stochastic processes are designed to use pseudo–random sequences, with a controlled random seed. This allows for repeatability of a given allocation run, facilitating repetition and expansion of prior work later.

In addition, the allocation function has a broad capability of predicting the spread of low carbon technologies over a network given probabilities and stimulated by user scenarios. This might be used by network companies, outside the main EPO simulation, to gain insight into the localised effects of penetration of multiple technologies and services. For example, a domestic connection may only cause a significant issue where reverse flows from a battery and PEV are combined simultaneously and the allocation function may indicate where clusters of these probabilities are most likely to occur on the distribution network.

10.3.2.6. **Validation**

Validation of the results of the allocation function represents one of the most challenging areas within EPO, since its output constitutes a projection of the state of energy consumers in an indefinite future under the assumptions included in the user's input. Nonetheless, the following validation has been carried out for aspects of the data in particular:

- EPN data sets for Bridgend: These have been validated as described in (Energy Systems Catapult, forthcoming).
- CREST domestic demand profiles: These were drawn from the model of (Richardson, Thomson, Infield, & Clifford, 2010) and were validated as described in their work. Since only the non–heating components of the electricity demand profiles were used, the lack of validation for the heating component of the electricity demand is not a concern for this project.
- Building physics parameter values: See the EPO Analysis Plan and Results document for a description of how these have been validated in combination with the full building model described in section 10.3.7.

10.3.2.7. **Future Development**

The current state of the Allocation function represents an initial demonstration of the ability to stochastically predict future populations of energy consumers. Accordingly, aside from the outstanding features described in section 10.3.2, the Allocation function is expected to expand to include the following functions and capabilities:

Functionality	**Impact**
Consumer characteristics related to non–electric energy networks (gas, heat networks etc.)	Allows simulation of these energy vectors and multi–vector/vector–switching service delivery.
Probability distribution representation: more sophisticated (e.g. as Bayesian networks)	Improves transparency of modelling assumptions and may allow use of probabilities deduced from analysis of consumer data.
Probability distribution representation: precise location as a factor	Allows representation of spatial clustering of characteristics to enable correct inclusion of otherwise uncommon combinations of characteristics.
Probability distribution libraries	Allows user to select from prior research results supplied as libraries along with EPO as well as defining their own distributions.

10.3.3. Environment model

10.3.3.1. Purpose

The environment model outputs information on the environmental conditions for use by other actor models within the simulation. The consumer model, for example, uses the ambient temperature produced by the environment model to determine the heat loss from a building. Similarly, the generation model uses the wind speed to determine the power generated from a wind farm.

10.3.3.2. Achievements and Next steps

The environment model reads data directly from a spreadsheet and can be configured to output data from any start date and time.

Currently the model only outputs wind speed and temperature. As other actor models in the system are expanded to enhance their fidelity, the environment model will need to be updated accordingly to simulate other environmental conditions.

10.3.3.3. Design Overview

The design of the environment model is simple, using real historical data imported from an external spreadsheet. This enables the environment model to provide realistic weather data without the computational overhead of running a complex model online (see Figure 39).

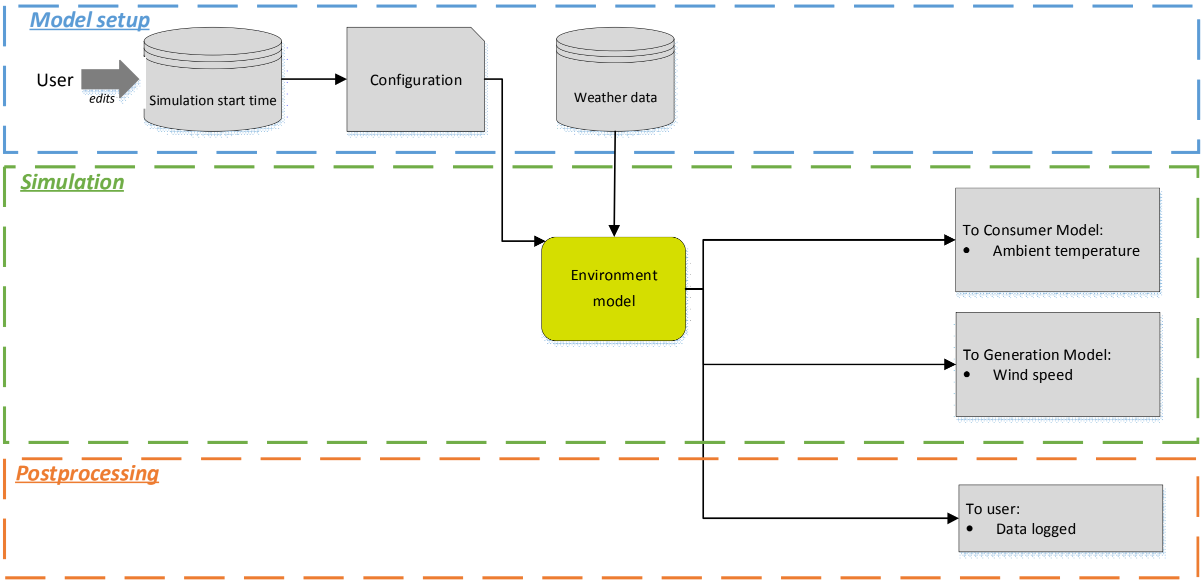

Figure 39 –Environment Model key inputs and outputs

Inputs:

1. **Start time of simulation within weather dataset:** If the provided dataset contains a lengthy sequence of data, the user can set the start time of the simulation within this period

Data sources:

1. **Weather data**

Outputs:

1. **Weather conditions:** Instantaneous wind speed and temperature

10.3.3.4. Data & IP

Item	Source	Used for	IP status	Limitations and mitigations
Cardiff Weather Data set	(Eames, Kershaw, & Coley, 2011)	Weather data	Licensed for EPO use	Wind speed and temperature are semi–synthesised so real–world correlations between the values are not preserved. Mitigation: Identify a raw data set containing both variables. Wind data is provided at 60min resolution and is linearly interpolated to finer time resolution. Mitigation: Investigate techniques for adding synthetic short–term variations (De Tommasi, Gibescu, & Brand, 2010).

10.3.3.5. Impact

Using historical data enables realistic simulation of environmental conditions. This is particularly useful when studying the response of the system architecture to variation in wind speed, a key aspect of the example scenarios analysed to date.

The ability to specify different start times and dates enables evaluation of system architectures at different times of the day and seasons of the year. Also, as the model is flexible to import data (simply by changing the source spreadsheet), a range of weather conditions can be studied (unseasonable cold, low wind and sun together etc.).

10.3.3.6. Validation

Use of a historical dataset means that the values and dynamics of the temperature and wind data are representative of real conditions.

10.3.3.7. **Future Development**

The Environment model as currently developed presents a limited capability for representing the environment's effects on the simulation. As well as the outstanding features in 7.3.3.2, the environment model is expected to expand to include the following functions and capabilities:

Functionality	**Impact**
Spatial variation of weather	Enables the effect of weather diversity across the UK to be studied.
Characteristics of weather forecasts	Enables investigation of the dynamics between the weather forecasting and other business processes. E.g. if the weather forecast predicts high winds that do not materialise, how does an Energy Service Provider resolve the resulting power shortfall?

10.3.4. Generation model

10.3.4.1. **Purpose**

The generation model is designed to represent the power generator units in the energy system. The main role of the generation model is to supply the electricity to meet the demanded power from the consumers.

10.3.4.2. **Achievements and Next steps**

To date two types of generator models have been developed based on their production capabilities: an inflexible generation model representing mainly renewable energy power plants which cannot alter their power production and output the all the power captured, specifically in this case a wind farm model whose power output depends on the wind speed; and a flexible generation model which represents conventional power plants which can alter their power production based on requests from external parties, specifically an aggregated representation of all the generators available in the spot market. All the generator models are directly connected to the transmission network model.

By aggregating all spot market generators into a single entity, the simulation is not able to explore the ability of an ESP to choose between them based on characteristics such as price or CO_2 intensity. Future versions should include the capability to represent the market generators as multiple entities with distinct offerings.

10.3.4.3. **Design Overview**

The generation model exists as part of the EPO tool and it is designed and developed in Simulink. It provides two "instances", each of which can operate in any one of 3 modes: the two types of generation described in the previous section, and an "inactive" mode with no output. Figure 40 depicts the key inputs and outputs of the generation model, summarised below.

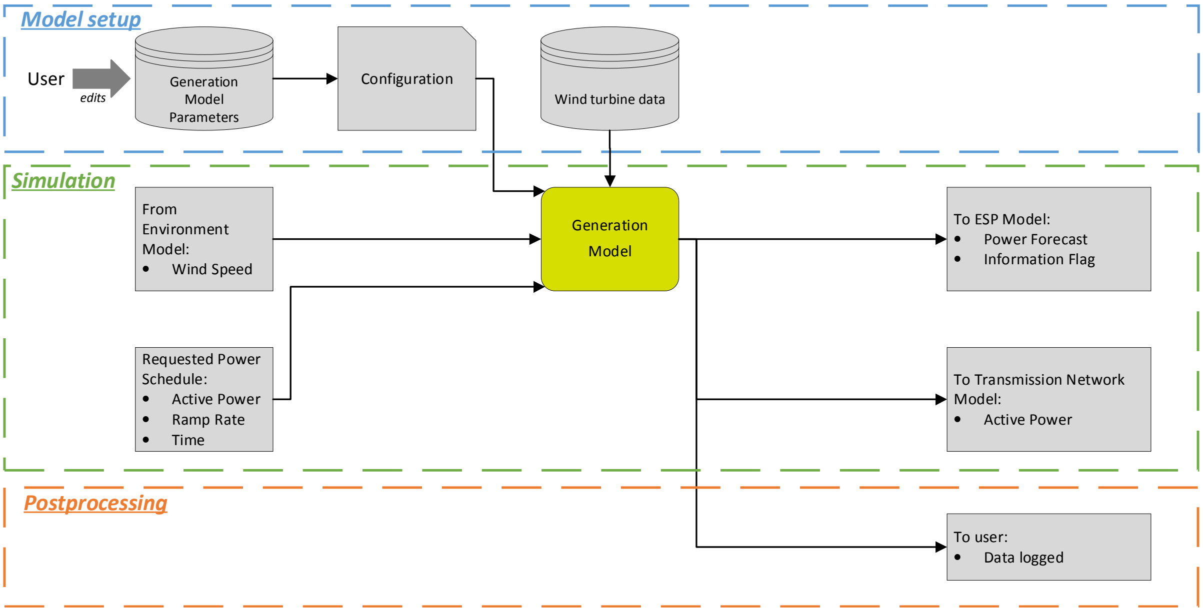

Figure 40 –Generation model key inputs and outputs

Inputs:

1. **Model parameters**: User defined data required during initialisation which is used to define the model operation, e.g. rated power.
2. **Wind speed**: Wind speed is received from the environment model and is used by the wind farm generation for definition and calculation of power production and forecasted power respectively.
3. **Requested power schedule**: The requested power schedule from the Energy Services Provider (ESP) model is received via the ERSG model and contains the active power, ramp rate and time definition that the generator model is requested to alter its power output to the requested values.

Data sources:

1. **Wind turbine data:** Power curve for the specific wind turbine simulated.

Outputs:

1. **Production forecast**: Forecasted active power production range over a pre–defined time period, sent to ESP model via ERSG model.
2. **Information flag:** Used to inform the ESP model whether a request to the generators has been accepted or rejected, sent via ERSG model.

3. **Active power**: The calculated active power production, sent to the transmission network model to be added to the total supply – demand calculation.

In the case of the wind farm, the model receives power schedule requests from the ESP model and rejects any request, as it is an inflexible generator and cannot alter its output and updates the information flag accordingly. The wind turbine physical representation is modelled as a power curve.

In the case of the spot market, the model receives power schedule requests from the ESP model and checks whether the required schedule is within the user defined contract terms. If the power schedule is within the contracted terms then the generation model accepts the request and informs the ESP model of its acceptance, or if the power schedule is outside the contracted terms then the generation model rejects the request and informs the ESP model of its rejection.

10.3.4.4. Data & IP

Item	Source	Used for	IP status	Limitations and mitigations
Siemens SWT–2.3MW–101 wind turbine power curve	(Siemens AG, 2012)	Wind farm generation model power curve	Publicly available	Represents only a single type of wind turbine. Mitigation: Include further data as a library in future versions.

No data is used by the spot market generation model as all parameters are supplied by the user.

10.3.4.5. Impact (including novel features)

The model allows the inclusion of not only the properties of the physical generation plant, but also the business processes of a power plant operator. It has been designed with expansibility to accommodate greater complexity in the future.

The model allows for the representation of real–world constraints on power production, specifically rated power and rate of change of power limits, and for the simulation of inflexible generation – both of which make balancing the network harder to achieve, which allow for realistic assessment of the ESP model's ability to control supply–demand imbalance.

10.3.4.6. Validation

The method used here to model a wind farm as a set of power curves, neglecting the complex system dynamics, is a simplified approach which has been used by industry in the past which provides sufficient information for the expected power production of a wind turbine (Uluyol, Parthasarathy, Foslien, & Kim, 2011) (Johansson & Thorson, 2016). The power curve is also used by industry for the assessment of the operational condition of individual turbine power production (Wood Group, 2018). The spot market generator model includes all the basic generator constraints, such as positive/negative ramp rates and rated power but also neglects the power system integration dynamics (Kundur, 1994).

10.3.4.7. **Future Development**

The Generation model as currently developed is sufficient for initial analysis but has the potential for expansion to cover the outstanding features in 6.3.4.2 as well as the following:

Functionality	**Impact**
Improve wind farm model physical representation to cover different wind turbine generator models e.g. Squirrel–Cage Induction Generator (SCIG), Doubly–Fed Induction Generator (DFIG), Fully Rated Converter Permanent Magnet Synchronous Generator (FRC–PMSG)	Allows assessment of ability of architecture to handle diversity of generation types and their effects on power system dynamics (e.g. SCIG consumes reactive power, DFIG provides rotating inertia, FRC–PMSG can provide synthetic inertia)
Improve spot market model physical representation to include complete synchronous generator model	Allows assessment of ability of architecture to handle diversity of generation types, including strategies based on control units such as governors and excitation systems for synchronous generators and controllable power converters for asynchronous generators. Required to assess power system stability.
Expand range of types of generation represented, e.g. solar PVs, tidal, nuclear, hydro etc	Improves simulation accuracy and allows for the investigation of the effect on the power system of new technologies.
Expand generation model business strategies and logic	Allows investigation of the effect of the choice of business strategy on the system stability and electricity price.
Represent purchase of services beyond active power supply by Distribution Network/System Operator (DNO/DSO) and Reserves Operator (RO)	Allows assessment of ability of architecture to maintain power system stability.
Full GB power system generation representation	Allows for a realistic representation of the synchronised generators of the British power system.

10.3.5. Energy Storage model

10.3.5.1. **Purpose**

The energy storage model is developed and designed to simulate the business and physical capabilities of energy storage units in the energy system. The main role of the energy storage model is to be utilised to generate and/or store electricity to allow the ESP model to balance supply–demand.

10.3.5.2. **Achievements and Next steps**

The energy storage model has been designed for power production or storage based on signals received from the ESP model, allowing for increased flexibility on power system balancing. The energy storage model allows for limits representing physical constraints on the rated power for producing and storing electricity and on the rate of change of power produced/stored. As a flexible energy provider, it is analogous to the conventional power plant model described in section 10.3.4 with the added functionality of energy storing. The energy storage units are directly connected to the transmission network model.

At present the energy storage model is designed with unlimited energy capacity for either production or storage, which is representative of pumped hydro. Future versions of the energy storage models will include capacity limitations, which can represent battery capacity limitations.

10.3.5.3. **Design Overview (Input – Output)**

The energy storage model exists as part of the EPO tool and it is designed and developed in Simulink. It provides two “instances”, each of which can operate in either an “active” mode or an “inactive” mode with no output. Figure 41 depicts the key inputs and outputs of the storage model, summarised below.

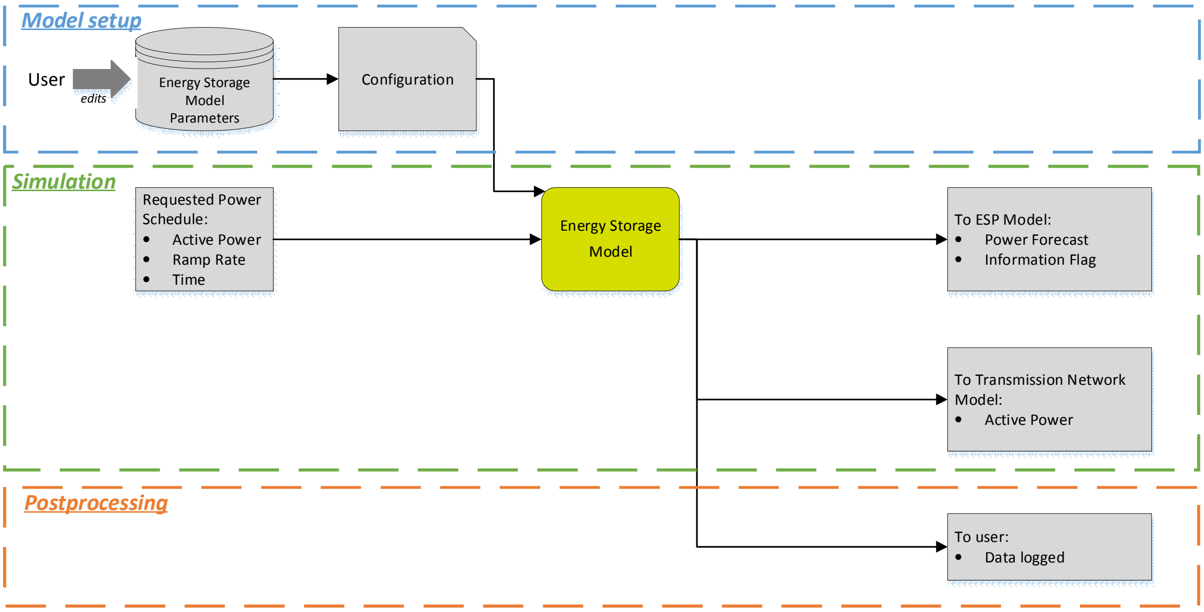

Figure 41 – Energy storage model key inputs and outputs

Inputs:

1. **Model parameters**: User defined data required during initialisation which are used to define the storage model operation, e.g. rated power.
2. **Requested power schedule**: The requested active power, ramp rate and time definition for the energy storage model to output, received from the Energy Services Provider (ESP) model via the ERSG model.

Outputs:

1. **Production forecast**: Forecasted active power production range over a pre–defined time period, sent to ESP model via ERSG model.
2. **Information flag:** Used to inform the ESP model whether a request to the energy storage model has been accepted or rejected, sent via ERSG model.
3. **Active power**: The calculated active power produced or stored, sent to the transmission network model to be added or subtracted respectively to the total supply – demand calculation.

The energy storage model receives power schedule requests from the ESP model and checks whether the required schedule is within the user defined contract terms. If the power schedule is within the contracted terms then the energy storage model accepts the request and informs the ESP model of its acceptance, or if the power schedule is outside the contracted terms then the energy storage model rejects the request and informs the ESP model of its rejection.

10.3.5.4. **Data & IP**

No data is used by the energy storage model as all parameters are supplied by the user.

10.3.5.5. Impact (including novel features)

The representation of energy storage units is important for modelling of the energy system and is expected to become essential as more storage units are connected to the network. The energy storage model includes the physical and business layers of the storage power plant and allow for the investigation that different business strategies might have on network stability, through operating as a dispatchable unit allowing the ESP model to manipulate its capabilities to produce and store energy. The inclusion of constraints regarding the rated power for producing and storing energy and the positive and negative ramp rates allows for realistic assessment of the ESP model's ability to control supply–demand imbalance.

10.3.5.6. Validation

The storage energy model includes all the basic generator constraints, such as positive/negative ramp rates and positive/negative rated power, but neglects power system integration dynamics (Kundur, 1994).

10.3.5.7. Future Development

Building on initial developments to date, the energy storage model may be expanded in future to include the following functions and capabilities:

Functionality	**Impact**
Improve model to represent energy storage control units such as controllable power converters	Allows better assessment of effect of integrating more energy storage plants into the power system and potential impact on power system operation regulations
Expand business strategies and logic	Allows investigation of the effect of different business strategies on system stability and electricity price.
Include more energy storage types e.g. flywheels, pumped hydro and (solid state and/or flow) batteries along with their physical constraints and limitations	Improves simulation accuracy and allows for the investigation of the effect on the power system of new technologies.
Represent purchase of services beyond active power supply by Distribution Network/System Operator (DNO/DSO) and Reserves Operator (RO)	Allows assessment of ability of architecture to maintain power system stability.
Full GB power system generation representation	Allows for a realistic representation of the synchronised storage units of the British power system.

10.3.6. ERSG model

10.3.6.1. **Purpose**

The ERSG model acts as a communications gateway between the ESP model and the different energy producer models (energy storage providers, wind farm and spot market).

10.3.6.2. **Achievements and Next steps**

The ERSG has been modelled as an ideal gateway, enabling communications between the relevant actors, thus facilitating simulation of the overall architecture.

10.3.6.3. **Design Overview**

The ERSG model routes signals from the ESP model to the generation and energy storage models (and vice versa), as shown below in Figure 42.

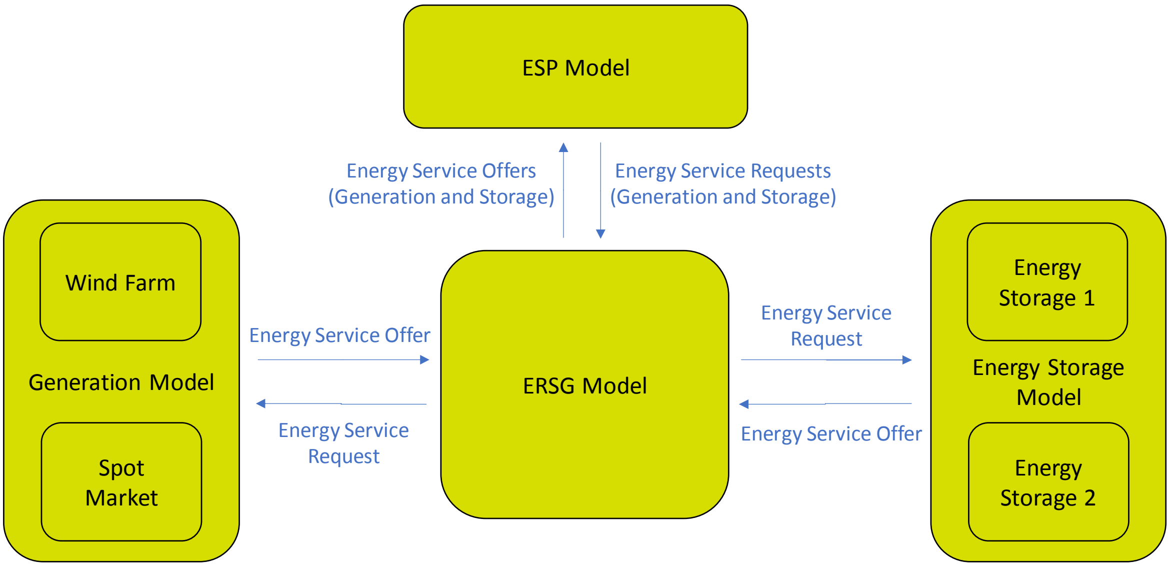

Figure 42 – ERSG model interface

The generator model and energy storage provider model send an Energy Service Offer to the ERSG model, which is forwarded on to the ESP model. The ESP model responds with an Energy Service Request which is received by the ERSG model and then sent on to the relevant energy producer.

10.3.6.4. **Data & IP**

There is no data or background IP stored in the ERSG model.

10.3.6.5. **Impact**

The ERSG model enables business interactions between the ESP and energy producers to be simulated.

10.3.6.6. **Validation**

The ERSG model is particularly simple and has been validated through inspection.

10.3.6.7. **Future Development**

The ERSG model as currently developed is sufficient for initial analysis but has the potential for expansion to cover following functions and capabilities:

Functionality	**Impact**
Additional Conceptual Architecture mechanisms: database of Energy Service offers, purchaser query/results and purchaser bid/response mechanisms	Allows assessment of ability of other actor business processes to accommodate/exploit realistic ICT constraints and commercial mechanisms
Represent ERSG Operator Business Model	Allows assessment of economic sustainability of architecture

10.3.7. Consumer model

10.3.7.1. **Purpose**

The consumer model provides power consumption values and thermal behaviour to the ESP model (via the HESG model) that is representative of domestic energy consumption, to represent the demand that must be satisfied by the ESP’s business processes. It also provides representative domestic electrical power consumption values to the distribution network model, to exercise distribution network states which require action to be taken by the network operator.

10.3.7.2. **Achievements and Next steps**

Two variants of the consumer model have been implemented: the “Full Building Model” variant that simulates the thermodynamics of a collection of buildings, and the simple “Pre–defined Curve” variant that uses consumption data imported from an external data source (used as a computational simplification in cases where the responsiveness of demand to other factors in the simulation is not required).

The Full Building Model has been developed as a generic model that can represent a range of different building types of model parameters. The implementation is simple while retaining the key physics required to capture the important thermal (and resulting electrical) behaviour. Several heating appliances have been modelled including: a combination boiler, conventional boiler, hybrid heat pump, electrical radiator, immersion heater and solar water heater. Hot water usage and non–heating electrical loads are also modelled. The model does not currently include solar gain, whereby the room heats directly due to solar radiation, which can have a significant impact on the thermal dynamics. It also does not currently include an appropriate interface for the HESG model to manage the building model's energy usage.

10.3.7.3. **Design Overview**

The consumer model is implemented in Simulink. Figure 43 depicts the key inputs and outputs of the storage model, summarised below.

Inputs:

1. **Pre–defined electricity demand profile**: Dataset of electricity demand against time, used for the pre–defined curve variant.
2. **Population of energy consumers**: Parameter values required for the Full Building Model variant, including building thermal parameters, appliance thermal parameters and occupant demand profiles (temperature/hot water).

Outputs:

1. **Real–time electricity consumption**: Forecasted active power production range over a pre–defined time period, sent to ESP model via ERSG model.
2. **Room temperature**
3. **Gas consumption:** This is not used within the simulation at present.

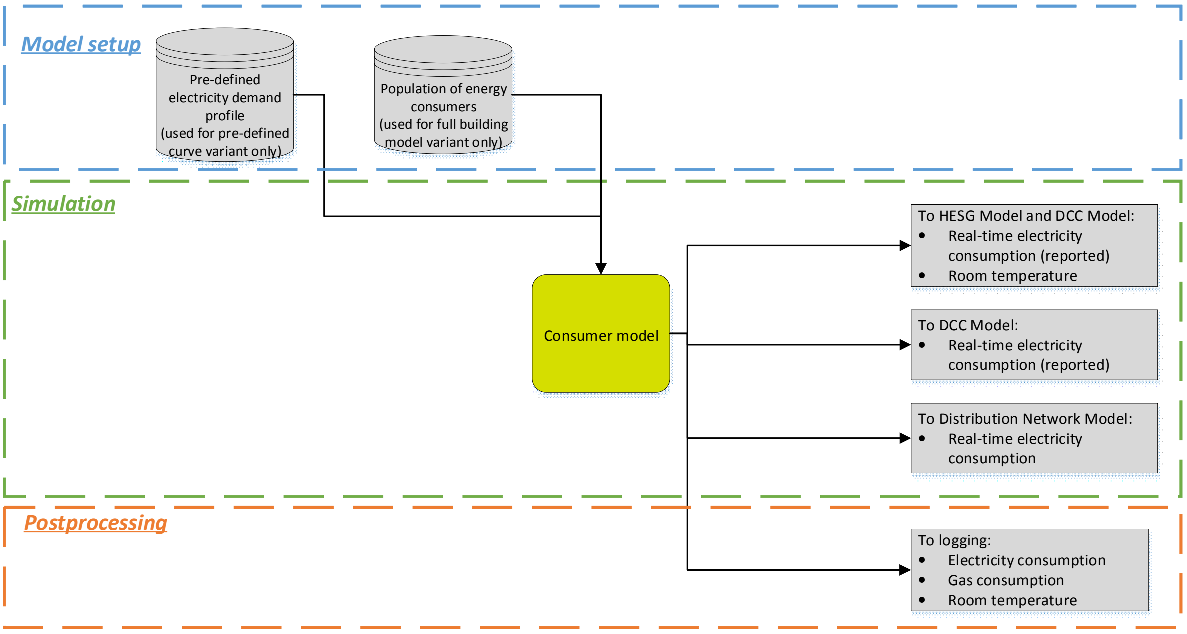

Figure 43 –Consumer model showing key inputs and outputs

The full building model variant simulates the thermal behaviour of a house as well as the behaviour of its occupants. Physically the house is represented similarly to the work of (Bacher & Madsen, 2011): all rooms are combined into a single lumped–parameter volume containing a hot water tank, radiator and several heating appliances, under the control of a thermostat governed by the occupant's setpoint demands (see Figure 44). The radiator, internal air and building fabric are all modelled as thermal masses, as is the hot water cylinder. The model has been produced in a modular form using a series of reusable library functions and can represent any number of houses by using vectors for the parameters, state variables and signals, with the number of elements in the vector corresponding to the number of buildings to be simulated.

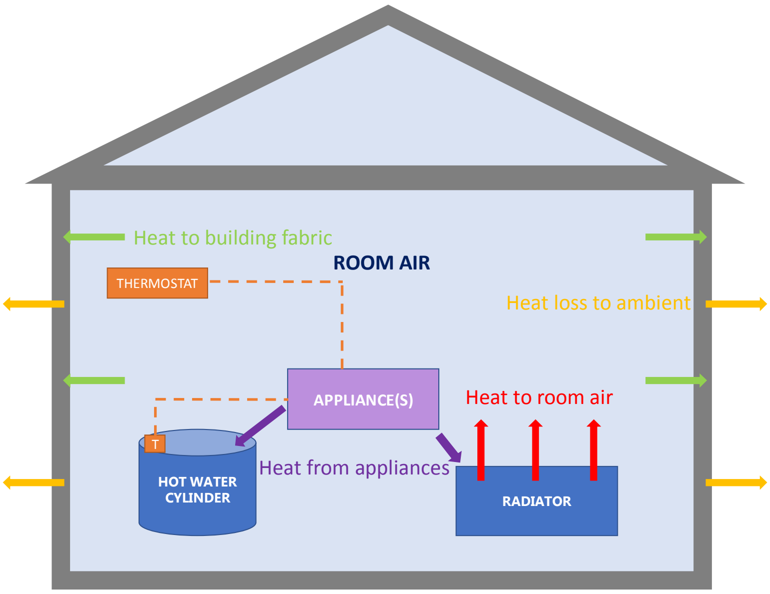

Figure 44 –Building thermal model

A selection of heating appliances can be used for space and water heating. Each building instance contains all possible appliances, with the appliance only enabled if the allocation function assigned that type of appliance to that instance (as described in section 10.3.2) – otherwise the appliance simply outputs zero power. The occupant behaviour interfaces with the thermal model through time–profiles for the setpoints of the system and other parameters: room temperature setpoint, radiator temperature setpoint, hot water temperature setpoint, hot water mass flow rate and other (non–heating) electrical consumption. These profiles are also produced by the allocation function.

The pre–defined curve variant uses a time–profile of electricity demand that is imported from an external data source and "played back" over the course of the simulation. This enables the model to provide realistic electricity consumption data without the computational overhead of running a complex model online. The approach is identical to that used in the Environment model (see section 10.3.3).

10.3.7.4. **Data & IP**

There is no data and background IP stored directly in the consumer model itself.

10.3.7.5. **Impact**

The full building model enables the simulation to capture both the electrical loads on the distribution network (average and peak) and the behaviour of the supervisory control systems in response to household temperature changes. The use of a modular, library–based approach enables efficient testing and future expansibility, while the relatively simple mathematical approach taken minimises computational loading when scaling to represent many buildings.

The pre–defined curve variant reduces the computational overhead of the simulation in contexts where the full building model is not required, improving the throughput of the analysis capability.

10.3.7.6. **Validation**

The assessment of the accuracy of the building model, in conjunction with the parameter values used in the allocation function, is described in the EPO Analysis Plan and Results document.

10.3.7.7. **Future Development**

It is recognised that the building model presented here is significantly simpler than others previously developed. The model used in EPO for the physical component of a building (i.e. excluding the internal dynamics of the heating system) has 3 state variables and 6 parameter values, whereas within the lumped–parameter paradigm (Bacher & Madsen, 2011) present a selection of models with up to 5 state variables and 13 parameter values, and other models such as the IEHeat model (Energy Technologies Institute, n.d.) have significantly more detailed modelling. Beyond this, finite–element simulations of heat flow and air movement allow still greater complexity of simulation behaviour. However, the key design choice driving the selection of this model has been the computational efficiency of the model, since each additional building instance requires an additional set of calculations to be carried out and the intention is to scale the simulation to cover significant numbers of building instances.

Nonetheless, and in addition to the outstanding features in 10.3.7, there is potential to develop the consumer model in future in the following aspects:

Functionality	**Impact**

Improved model structure to capture further thermodynamic effects, if comparison against other models show significant discrepancies	Electricity demands used to exercise business processes and other physical model components (e.g. distribution network model) better represent realistic demands for the relevant building types
Optimisation of computational run–time by refinement of numerical solver and/or introducing approximate models for large populations of buildings	Ability to expand simulation to very large numbers of building instance to model large–scale collective dynamics
Occupant behaviour responsive to other factors in the model, e.g. more likely to stay at home and use heating during poor weather	Allows better assessment of system performance under correlations between factors that might not be as strongly emphasised under the assumption of fixed occupant behaviour

10.3.8. HESG model

10.3.8.1. Purpose

The Home Energy Services Gateway (HESG) model is designed to simulate the business and physical capabilities of the HESG actor in the energy system, including both the cloud and in–home parts of the HESG actor. The main role of the HESG model is to be utilised to transfer information between the ESP model and the consumer model.

10.3.8.2. Achievements and Next steps

The in–home part of the HESG model passes electricity demand information to the cloud part of the model. The cloud part then aggregates and passes on the real–time consumption data to the ESP model and calculates a demand forecast. At present the forecast is constructed by “looking ahead” in a predefined demand–time profile read from external data, as used for the predefined–curve variant of the consumer model (see section 10.3.7). Additionally, the model does not allow for controlling signals from the ESP model to reach the in–home HESG model and manage the consumer’s energy usage. This limits the model to contexts where the demand does not respond to actions taken by other objects within the model. Future versions will include both control from ESP model to consumer model, and demand forecasting based on real–time consumption data.

10.3.8.3. Design Overview (Input – Output)

The HESG model exists as part of the EPO tool and it is designed and developed in Simulink. Figure 45 depicts the key inputs and outputs of the HESG model.

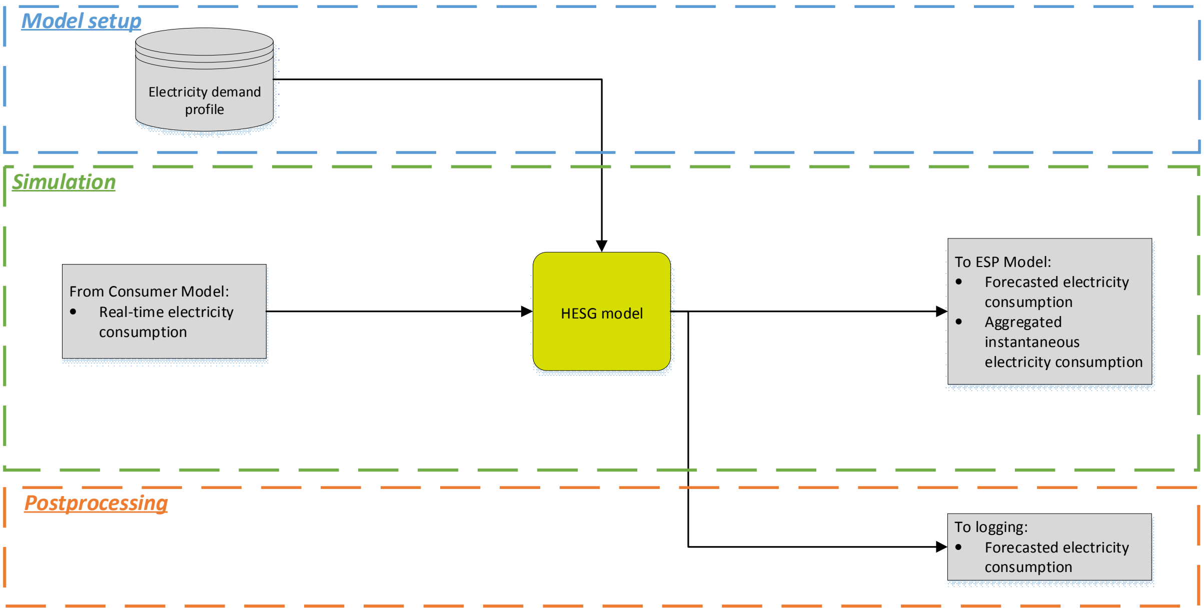

Figure 45 – HESG model key inputs and outputs

Inputs:

1. **Electricity demand profile:** predefined dataset of electricity demand against time
2. **Instantaneous electricity consumption**: electricity consumption from the consumer model per building instance.

Outputs:

1. **Aggregated instantaneous electricity consumption**
2. **Forecasted electricity consumption:** forecasted aggregated energy demand over a time period.

10.3.8.4. Data & IP

The HESG model does not require any data to be used in an EPO simulation.

10.3.8.5. Impact (including novel features)

The HESG model allows the simulation to represent the communication of status information from homes to the ESP. The division into in–home and cloud sub–models, with corresponding partitioning of functionality between them, allows simulation of the impact of communications faults on the energy system (e.g. home broadband outages in a local area).

At present, the perfect forecasts of the consumer model's consumption provided by the HESG model allows the ESP model to accurately calculate the power required to balance supply and demand, even for a small period ahead of time.

10.3.8.6. Validation

The HESG model has not been validated relative to other existing models, since it represents an actor that currently does not exist, and the simulation of its capabilities could prove the potential for further investment in this sector.

10.3.8.7. Future Development

The HESG model as currently developed is sufficient for initial analysis but has the potential for expansion to include the following functions and capabilities:

Functionality	**Impact**
Realistic (imperfect) demand forecasts	Allows assessment of capability of architecture to deal with residual supply–demand imbalances after ESP purchasing.
Alternative domestic heating system control schemes for management of energy usage, and corresponding options for energy management request structure	Allow exploration of different control schemes and their impact on energy system behaviour

10.3.9. ESP model

10.3.9.1. Purpose

The role of the Energy Services Provider (ESP) model is to request energy production or consumption from actor models with flexible capabilities, taking account of forecasts from those with inflexible production or consumption, to attempt to balance of electricity supply and demand.

10.3.9.2. Achievements and Next steps

The ESP model balances supply and demand by treating demand as inflexible, taking account of inflexible contracted generation, and then requesting appropriate power production from its contracted and available power portfolio. It utilises initially its contracted flexible generation and storage, prioritising the most cost–effective solution first. If the contracted generation and storage are unable to meet the demand, the ESP utilises the available generation from the spot market to purchase additional capacity.

To date, a single ESP model is simulated and the model is not designed to utilise flexibility on the demand side, but future versions of EPO will allow the ESP model to manipulate the electricity demand by managing the energy usage of domestic heating systems.

10.3.9.3. Design Overview (Input – Output)

The ESP model exists as part of the EPO tool and it is designed and developed in Simulink. Figure 46 depicts the key inputs and outputs of the ESP model.

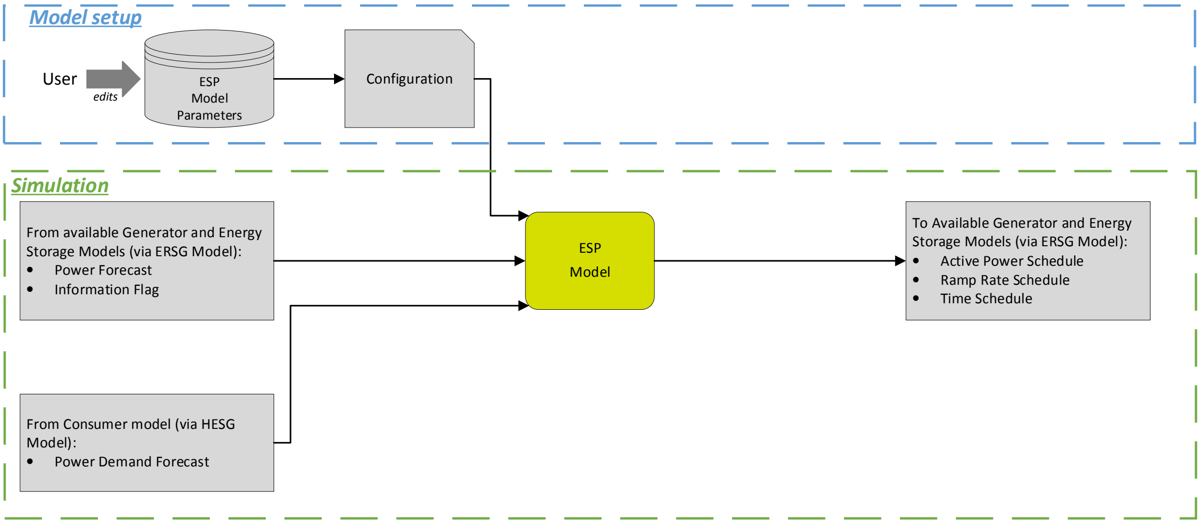

Figure 46 – ESP model key inputs and outputs

The ESP model provides two different options: "Variant A" represents the scenario where a wind farm generator and an energy storage provider are available to the ESP, and "Variant B" represents the scenario where a wind farm generator, two energy storage providers and spot market generation are available to the ESP.

Inputs:

1. **Model parameters**: User defined data required during initialisation which are used to define the ESP model operation, e.g. contracted capacity.
2. **Power demand forecast:** The aggregated power demand forecast from the consumer model is received, via the HESG model, and is used by the ESP model to compute the required power schedule to balance supply – demand.
3. **Power forecast**: The power forecast of available generation and energy storage models is received, via the ERSG model, and is used by the ESP model to compute the required power schedule to balance supply and demand.
4. **Information flag**: The information flags from available generation and energy storage models are received, via the ERSG model, and inform the ESP model whether its requested power schedule has been accepted or not by the corresponding generator and/or energy storage model.

Outputs:

1. **Requested power schedule:** The requested power schedule is sent, via the ERSG model, to the available generation and energy storage models.

The requested power schedule is simply computed by calculating, for each forecast point within the forecast window, the difference between the demand forecast and the inflexible generation forecast (from the wind generator model). This difference is then divided between the available flexible power portfolio (energy storage model(s) and spot market model) according to their power capacity and ramp rate limits and sent as the requested schedule.

10.3.9.4. **Data & IP**

No data is used by the ESP model as all parameters are supplied by the user.

10.3.9.5. **Impact**

The role of the ESP model within the overall architecture model allows for the assessment of different ESP business processes, for example prioritising purchases based on price or CO_2 emissions. The physical constraints of the power producing and storing units are also considered, allowing for a more accurate simulation of the power system physical constraints.

10.3.9.6. **Validation**

The ESP model has not been validated relative to other existing models as it represents an actor that currently does not exist, and the simulation of its capabilities could prove the potential for further investment in this sector.

10.3.9.7. **Future Development**

While currently limited in detail, the ESP model may be developed in future to add the following capabilities:

Functionality	**Impact**
Expand business strategies and logic	Allows investigation of the effect of the choice of different business strategies on the system stability and electricity price.
Online definition of contracts between ESP model and available capacity	Allows assessment of further forms of ESP business process (e.g. buy–early vs buy–late) and their impact on overall system performance
Account for detailed dynamics of different types of power providers (e.g. real or synthetic inertia)	
Multiple competing ESPs	Allows performance assessment of different business strategies between competing ESPs and their effects on profitability and overall system behaviour

10.3.10. Distribution network model

10.3.10.1. Purpose

The distribution network model calculates the electrical power flows at different points in the electricity distribution network, and the performance of the distribution network – specifically the voltages at nodes and the power losses in network segments. It also simulates the response of the Distribution Network/System Operator to those conditions.

10.3.10.2. Achievements and Next steps

Three different components of the distribution network model have been developed to date:

1. **Basic aggregation node:** This simply sums the electrical power demand of each energy consumer in the simulation, calculating the aggregate electrical demand on the network.
2. **Full aggregation node:** This calculates the electrical power demand on nodes at different levels in an electrical distribution network (i.e. on each secondary substation, on each 11kV feeder and on each primary substation), using information describing the topology of the network and the electrical demand of each electricity consumer.
3. **Network performance online assignment model:** This predicts the voltages at each busbar on an 11kV network, and the power losses in the network segments, from the real and reactive electrical power demands at each secondary substation on that network (as supplied by the full aggregation node) using network performance templates as discussed in section 10.2.1.

To date only the basic aggregation node has been integrated with the other subsystems of EPO. This allows simulations of the full energy system architecture to assess overall system supply–demand balance but does not allow assessment of stress on the distribution network. Additionally, as noted in section 10.2.1 the online assignment model has only been developed for a single exemplar 11kV network and thus simulations will be restricted to this region until the dataset is expanded.

Next steps include:

- Integration of the full aggregation node and the online assignment model into the full architecture simulation, to understand the state of stress of the network under these conditions.
- Extension of the full aggregation node to handle “clustering” of the building model in the allocation function (as described in section 10.3.2).
- Extension of the full aggregation node to include power losses predicted by the online assignment model into the calculation of power demands in the network.

10.3.10.3. Design Overview

The distribution network model is a Simulink model that interacts with other components of the simulation model. Figure 47 shows an overview of the model and its interactions with other subsystems, including the offline data preparation process for network performance templates.

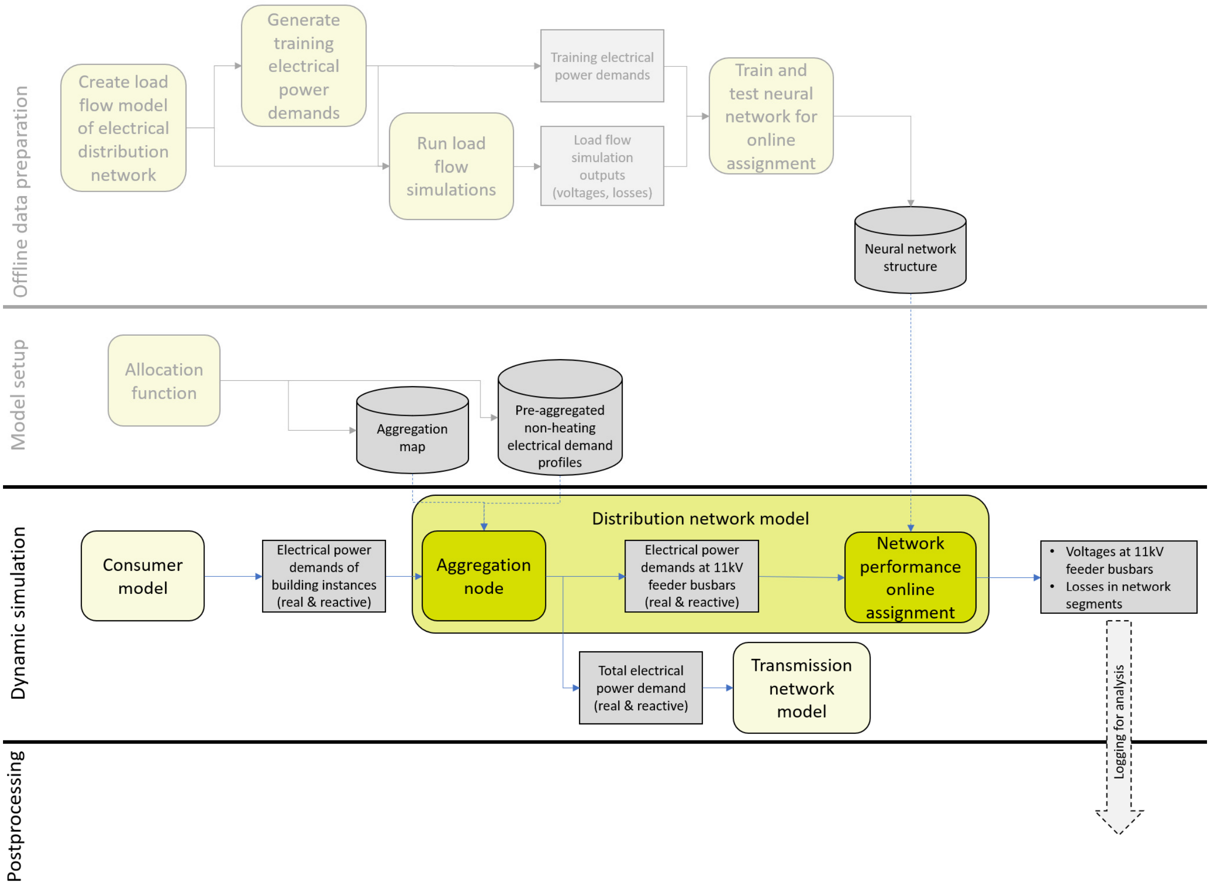

Figure 47 –Diagram of distribution network model showing inputs, outputs and downstream affected subsystems.

The model has the following inputs:

1. **Aggregation map:** A data structure encoding the topology of the lowest layer of the distribution network, specifically the connections between specific building instances and specific LV substations.
2. **Pre–aggregated non–heating electrical demand profiles:** For computational efficiency in the dynamic simulation phase, electrical demand profiles in the energy system that will not be affected by factors elsewhere in the system (i.e. domestic non–heating electrical load and industrial/commercial load) may be pre–aggregated by the allocation function as time profiles of the total predetermined load at each LV substation.

3. **Neural network structure:** The structure (connections and weights) of a neural network trained (during offline data preparation) to predict voltages at points in the 11kV network and losses in the network from corresponding demands.
4. **Instantaneous electrical power demands of each building instance** (excluding non–heating–related loads if these have been pre–aggregated).

The outputs are as follows:

1. **Total electrical power demand**
2. **Voltages at 11kV feeder busbars and losses in network segments:** These values are logged for subsequent analysis.

The basic aggregation node sums the instantaneous electrical power demands to compute the total real electrical power demand on the distribution network. This version does not compute voltages at 11kV busbars.

The more advanced distribution network model (currently not integrated with other simulation components) uses the aggregation map to calculate the real and reactive power demands at each LV substation, which are assumed to be equal to the power at those substations' connection point to the 11kV distribution network. Those power values are then used by the online assignment neural network to estimate the voltages at those connection points on the 11kV distribution network and the losses in the network. The overall total electrical power demand is also computed.

10.3.10.4. Data & IP

No data is used directly within the Distribution Network Model.

10.3.10.5. Impact

The ability to predict network performance enables the EPO simulation to detect failure modes of an actor's business process that may not be apparent from simple consideration of supply–demand balancing, for instance if a demand management scheme for electric heating does not distribute the electrical demand across all network segments but rather concentrates the load in a localised portion of the network. Moreover, it enables the future representation of the reactions of the network operator to the instantaneous state of the electricity network.

The pre–trained neural network represents a concise and computationally efficient mechanism for predicting busbar voltages and losses on a specific 11kV network from power demands on that network, which may be independently applicable beyond the EPO simulation.

10.3.10.6. Validation

Use of appropriately trained neural networks as surrogate models is a standard approach in engineering. In this specific case, the neural network used for the online assignment component of the model has been tested using synthesised data as discussed in section 7.2.1.5. However, its ability to generalise to demand values from the consumer model has not yet been confirmed. This will be possible once the full aggregation node and online assignment model have been integrated with the full simulation model.

10.3.10.7. **Future Development**

The distribution network model currently represents an initial demonstration of the prediction of electrical behaviour of such networks and excludes important aspects of the complete system (principally commercial considerations). Aside from the outstanding features described in section 10.3.10, the following expansion points, if pursued, would mitigate these shortfalls:

Functionality	**Impact**
DNO/DSO business process simulation	Allows validation of architecture requirements regarding processes and communications of DNO/DSOs, and provides a more realistic prediction of the degree to which HESG control actions will be required
Online detection of network conditions outside NN's previously trained values, and load flow simulation/retraining of NN to improve prediction (see Figure 48). Filter involves 2 passes: (1) Check all aggregated loads fall within previously trained range (see section 7.2.1.3); (2) Check combination of loads between nodes. If filter does not reject loads, losses and voltages are predicted by closest matching ANN. If filter rejects loads, full load flow results are compared with closest ANN predictions, and filter is updated and/or results are cached for subsequent ANN retraining.	More robust network performance predictions

Performance prediction of other distribution network tiers (415V, 33kV and upwards)	Allows more realistic prediction of losses to be made up and system's mechanism for doing so
Distribution network capacity limits	Allows simulation of energy system response to extreme events leading to overloading of asset capacity
Use of representative networks to approximate actual networks	Geographical scope of simulation can be increased to cover more combinations of network type, energy consumer and other factors, further increasing ability to detect unusual circumstances

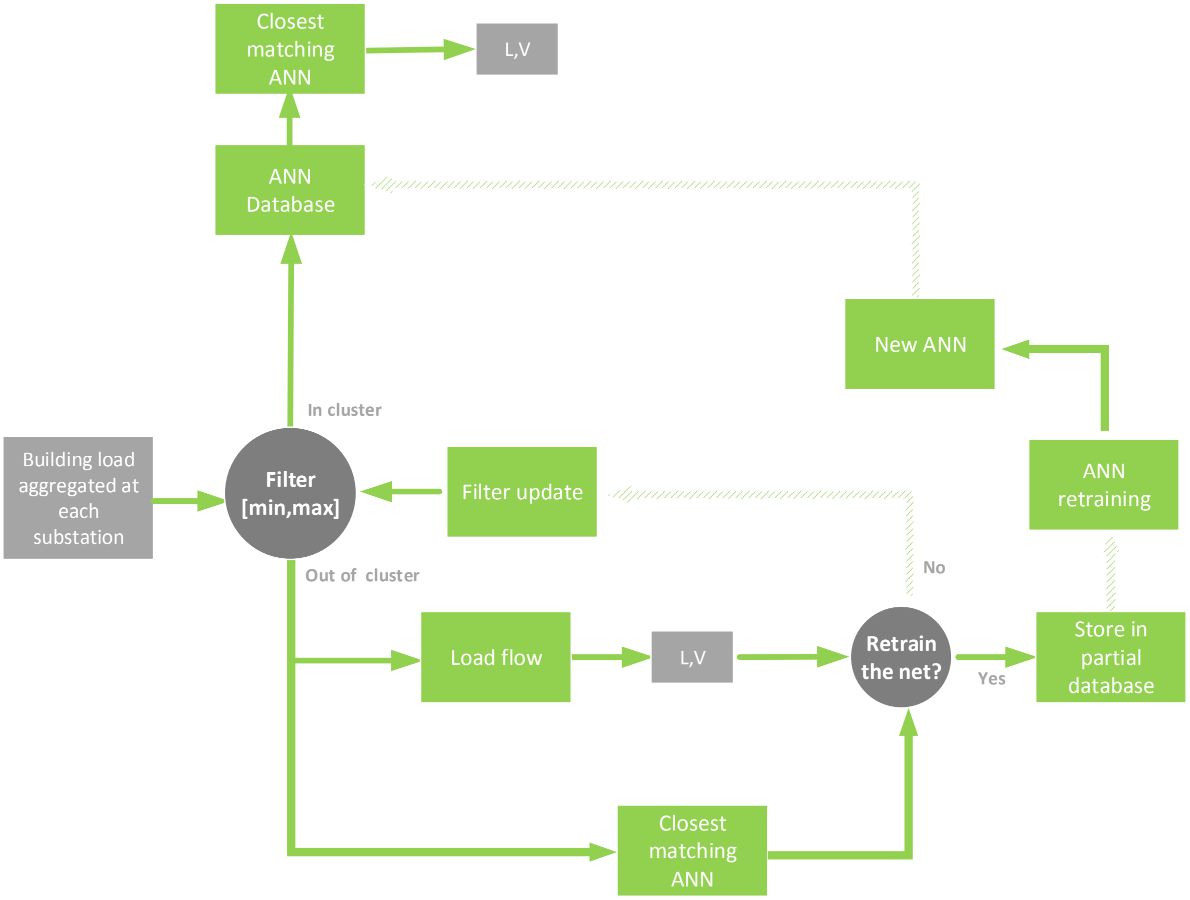

Figure 48 – Control sequence for retraining ANN online in response to network conditions outside previously trained values.

10.3.11. Transmission network model

10.3.11.1. **Purpose**

The transmission network model represents a simplified version of the transmission grid. It calculates overall supply–demand balance and system frequency and represents the behaviour of the Reserves Operator in response to these conditions.

10.3.11.2. Achievements and Next steps

Two different variants of the transmission network model have been developed to date:

1. **Basic system imbalance calculator:** This sums the electrical power demand of energy consumers (from the distribution network model) and the power produced/consumed by the generation models and the energy storage models, to calculate the overall electrical supply–demand imbalance.
2. **System frequency model:** This allows the simulation of the effect of time–varying synchronised rotating inertia on grid frequency.

At present, the transmission network model has not been integrated with the other subsystems of EPO. This allows simulations of the full energy system architecture to assess overall system supply–demand balance but does not allow assessment of the impact on the system frequency or the behaviour of frequency–responsive assets. Future EPO versions will integrate the frequency model.

10.3.11.3. Design Overview

The transmission network model exists as part of the EPO tool and it is designed and developed in Simulink. Figure 49 shows the key inputs and outputs of the transmission network model.

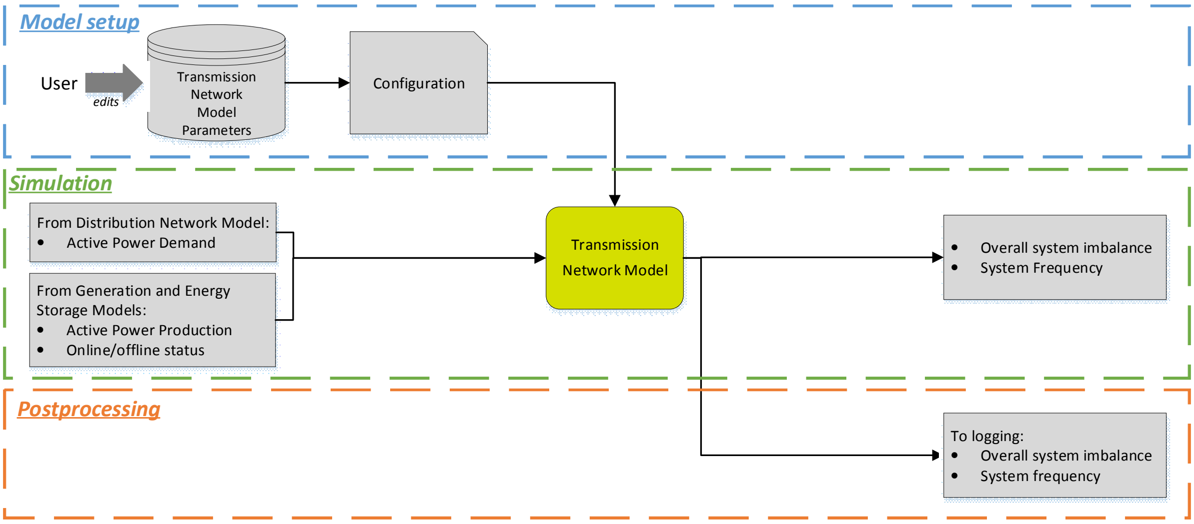

Figure 49 –Transmission network model key inputs and outputs

Inputs:

1. **Model parameters**: User defined data required during initialisation which are used to define the transmission network model operation, e.g. MVA ratings of connected units.
2. **Active power production/demand**: The active power flowing through the transmission grid.
3. **Generator online/offline status**

Outputs:

1. **System electrical supply–demand imbalance**
2. **System frequency**

The system frequency calculation is based on a simplified network representation. The GB transmission network is represented by two synchronous generator models. The first generator provides primary frequency response services, and the second generator provides both primary and secondary frequency response services. The parameters of these two generator models are calculated from the parameters of all generation models that indicate they are online at that time.

10.3.11.4. Data & IP

No data is used directly within the Transmission Network Model.

10.3.11.5. Impact (including novel features)

The transmission network is essential for the assessment of the effect of different business strategies on system stability. The model is designed to be flexible with varying machine inertia, allowing for investigation of different scenarios with time–varying synchronised inertia.

The synchronised equivalent system inertia is a function of synchronous and non–synchronous (i.e. behind converter generators) generation, and the transmission network model allows for frequency calculation with time–varying system inertia.

10.3.11.6. Validation

The transmission network model is based on the mathematical formulation presented by Cheng et al (Cheng, et al., 2016) and Huang et al (Huang, Wu, Infield, & Zhang, 2013).

10.3.11.7. Future Development

The transmission network model at present is primarily a sufficient piece of infrastructure needed to enable complete simulations and neglects the true dynamics of this part of the energy system. Future developments therefore include:

Functionality	Impact

Real generation/storage performance parameters	Improves realism of simulation of frequency stability
Transmission network power transfer constraints	Allows simulation of energy system response to extreme events leading to overloading of asset capacity
Transmission network performance prediction	Allows prediction of real/reactive power losses to be made up and assessment of system’s mechanism for doing so.
RO business process simulation	Allows validation of architecture requirements regarding processes and communications of RO and provides a more realistic prediction of the degree to which control actions by other actors will be required.

10.3.12. DCC model

10.3.12.1. Purpose

The DCC model represents the Data Communication Company actor within EPO. The DCC is an existing GB smart metering business. The DCC receives the average half hourly data from the consumers’ in–house communication hub equipment, and provides the data to DCC service users, such as energy suppliers, electricity and gas network operators and authorised third parties (Data Communications Company, 2013).

10.3.12.2. Achievements and Next steps

Development to date has not required the DCC to be represented in the EPO simulation.

10.3.12.3. Design Overview (Input – Output)

No information is currently passed through the DCC model.

10.3.12.4. Data & IP

No data is used within the DCC model.

10.3.12.5. Impact

The DCC model does not currently contribute to the EPO simulation.

10.3.12.6. Validation

The DCC model has not been validated.

10.3.12.7. Future Development

Functionality	**Impact**
DCC business process simulation	Allows assessment of role and value of DCC, especially under information transfer constraints such as failure of local internet connectivity

10.4. Tool Features

10.4.1. Bulk configuration

10.4.1.1. Purpose

The bulk configuration subsystem provides configuration parameters to certain actor models, by reading in the output from the Allocation function and performing manipulations on it as defined in a mapping file for each actor model.

10.4.1.2. Achievements and Next steps

The bulk configuration function has been developed to load in the parameters required by the “full building model” variant of the Consumer model (see section 10.3.7). It allows large numbers of instances of the consumer model to be defined in the simulation, providing defaults for missing values and reshaping data as required. At present it has not been extended to provide data for the other actor models, but it is designed to be expansible to accommodate such ongoing needs.

10.4.1.3. Design Overview

The bulk configuration function is a Python program that reads data files output from the allocation function (in CSV format) and loads the content into the Simulink environment. The inputs and outputs are shown in Figure 50and outlined below.

Inputs:

1. **Allocation output data:** Produced by the Allocation function, they are CSV text files containing:
    a. Electrical network topology information
    b. Building properties, appliances and occupancy details
    c. Demand–time data sets
2. **Allocation function to model mapping details:** This dictates the mapping, aggregation and reshaping of data, and provides default values where required. There is one workbook for each actor model e.g. Consumer.

Outputs:

1. **Data for model execution:** Compiled data containing all the values for each actor model that are required to execute the simulation. This data is stored as MATLAB variable files, having the .mat file extension.

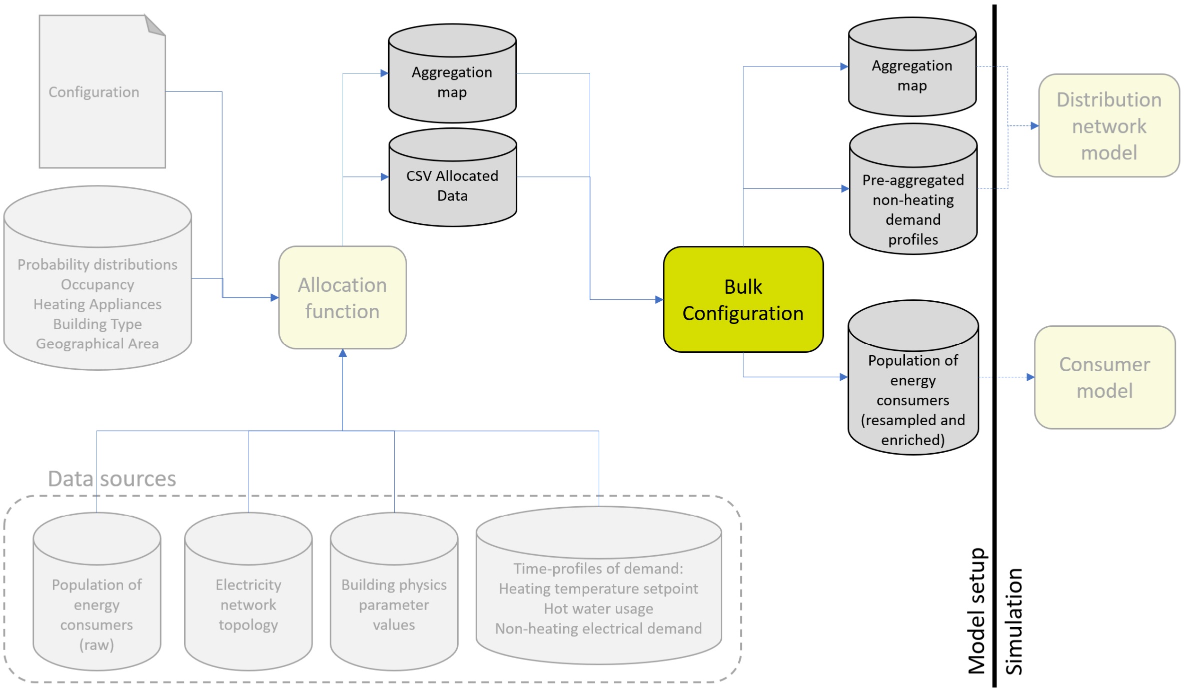

Figure 50 –Black–box diagram of bulk configuration function showing inputs and outputs, and upstream and downstream subsystems.

During the bulk configuration process, the data may be modified to allow for differences in the structure of the allocation output and the data required by the model. Supported modifications include:

- Providing default values in the event of missing data.
- Performing arithmetic operations on loaded data.
- Optionally loading different input data values depending on other data values
- Reshaping of data, for example time and demand data provided in a linear format is converted to a matrix containing consumer demand values distributed over the simulation period
- Directly loading in table–structured data

The relationships between data items in the allocation function output and the data items required by the model, including any modifications needed, are stored in mapping files, one for each actor model. The mapping file for each top–level subsystem is a standard Excel workbook.

To perform this process, the bulk configurator uses a slave MATLAB instance to convert the parameters into a compiled form. The resulting compiled data can be loaded immediately or at a later stage to perform the model analysis.

10.4.1.4. **Impact**

The bulk configuration function adds flexibility and efficiency to the data processing pipeline by its ability to carry out additional on–the–fly data manipulation steps. It also decouples development efforts between the allocation function and the components of the Simulink model. Additionally, it can be used to provide different ad–hoc reports from the same allocation data.

10.4.1.5. **Future Development**

Aside from the outstanding features in section 10.4.1 above, the Bulk Configuration function is expected to expand to include the following functions and capabilities:

Functionality	**Impact**
Computational optimisation	Improved capability to carry out large volumes of simulation runs

10.4.2. Model output logging

10.4.2.1. **Purpose**

The model output logging feature configures the logging of signals from the dynamic simulation based on user input and collates and exports the logged signals after simulation completion.

10.4.2.2. **Achievements and Next steps**

The model output logging enables the user to quickly select signals within the model to record. The rate at which the signals are logged is configurable (to minimise run–time and memory usage) and the logged signals can be instantly exported to an external spreadsheet for further analysis.

Both scalars and vectors can be logged (and viewed within the Simulink Data Inspector), however to date the function to export the logged data to a spreadsheet only supports scalar values.

10.4.2.3. **Design Overview**

The model is configured for logging as follows:

1. The user specifies which signals, of those available for logging in the model, should be logged and at what sampling time.
2. The user executes a function that takes the configuration and applies the logging status and rate to the signals in the model.
3. The user runs the simulation.

4. After the simulation is complete the user runs a second function to take the logged data and write it to a spreadsheet for further analysis.

The process is summarised graphically in Figure 51.

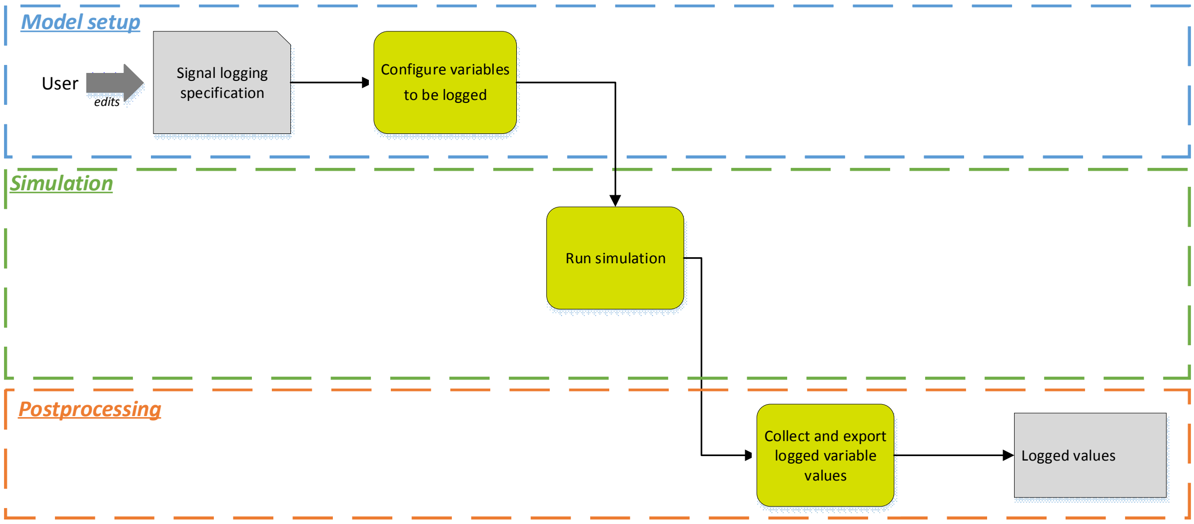

Figure 51 – Output Logging

10.4.2.4. Impact

The model output logging feature is a critical part of the overall EPO tool, as it enables the extraction of results from the model to analyse the behaviour of the system architecture. The feature enables the analysis team to execute a scenario, save the results, then perform a new analysis to compare the effects of the change.

10.4.2.5. Future Development

Aside from the outstanding features in 10.4.2, the model output logging feature is expected to expand to include the following functions and capabilities:

Functionality	**Impact**
Calculation of statistics on logged data	Improves efficiency of analysis process by providing immediate concise feedback on behaviour of simulation runs

10.4.3. Batch run execution

10.4.3.1. Purpose

The batch run execution subsystem runs sequential simulations using different configuration parameters as defined in a programme specified by the user. It configures each model component appropriately each time and records the data from each run separately.

10.4.3.2. **Achievements and Next steps**

With the current batch running capability, the user can specify the required parameter changes and then initiate a series of simulations that will automatically run sequentially. In each case the logged values from the simulation are stored in a csv file along with details of the run configuration, ready for further analysis.

To date the configuration of the batch running is a manual process, with the user configuring the value of each parameter for every run. This should be extended such that the user can specify a range of values, or a set of random samples from a distribution, with the values for each run then automatically populated.

The batch running is also a series activity which does not make maximum use of the multi–core processors available on modern computing hardware. Use of parallel processing will enable several batches to be run at the same time (depending on the number of processor cores available), thus improving computational efficiency.

10.4.3.3. **Design Overview**

The batch run execution feature operates as follows:

1. The signals to be logged are defined using the output logging capability (see section 10.4.2).
2. The data for the simulation is defined. This is a combination of base data, that remains constant throughout the various runs, and variable data, that changes between the various runs. This may involve the Allocation function (described in section 10.3.2) and the Bulk Configuration function (described in section 10.4.1).
3. The simulation is run.
4. The data is logged to a spreadsheet (again using the output logging capability).
5. If the batch has not completed, the process selects the next element in the parameter array and returns to step 3.
6. If the batch has completed, the user takes the results created during the runs and performs desired further analysis.

The process is summarised graphically in Figure 52.

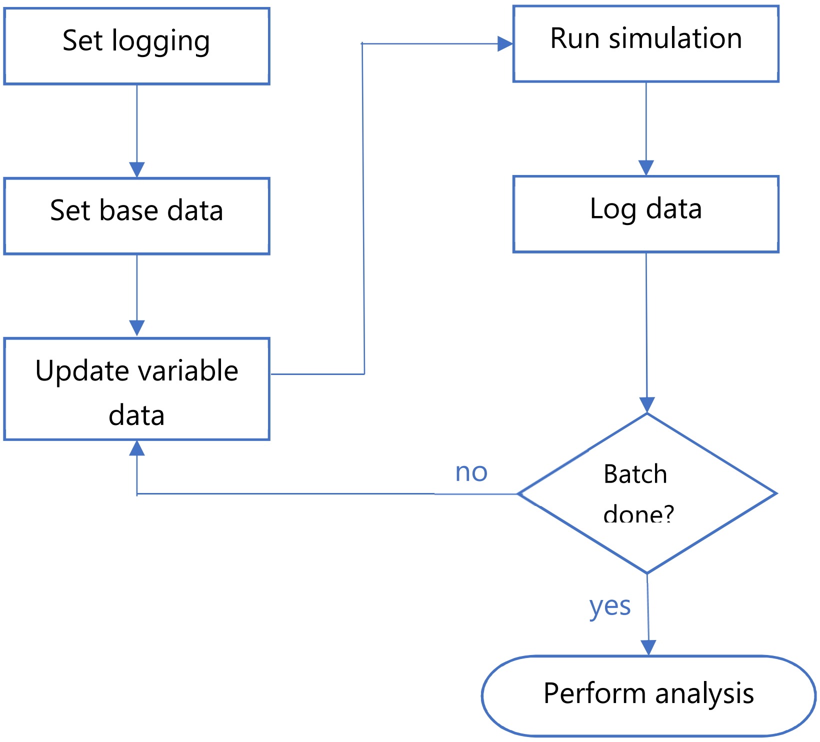

Figure 52 – Batch Running

10.4.3.4. **Impact**

The batch running facility is another important aspect of the EPO tool, as it enables the user to perform many simulations without the need to manually start each simulation and record the results. This minimises the time spent performing trivial simulation configurations, making best use of the user's time to perform meaningful analysis.

10.4.3.5. **Future Development**

Aside from the outstanding features in section 10.4.3.2, the batch run execution feature is expected to expand to include the following functions and capabilities:

Functionality	**Impact**
In–run parallel processing: different parts of a single simulation run in parallel streams rather than the same simulation (with different parameters) running on a different processor core. Only applicable where objects within the model are truly independent from each other.	Further reductions in computational effort, increasing Analysis throughput
Functions to support comparing and exploring results from a batch of runs	Improves ability of Analysis to explore architecture behaviour and generate insights

10.5. Processes

10.5.1. EPO requirements capture

10.5.1.1. Purpose

The process of compiling requirements for a subsystem within EPO draws together various sources of upstream information, including the definition of the Conceptual Architecture, and translates them into requirements for software subsystem that are sufficient to direct implementation. The EPO requirements are also used as the basis for defining test–cases for verification of the software subsystem (see section 10.5.2 below).

10.5.1.2. Process description

The method and steps taken to generate a software requirements specification in support of the delivery of the EPO tool models were primarily based on the ‘System V model’ System Development Life Cycle (SDLC). Figure 53 shows a diagram of the high–level process for generating an ERS, as well as its relationship with other documents.

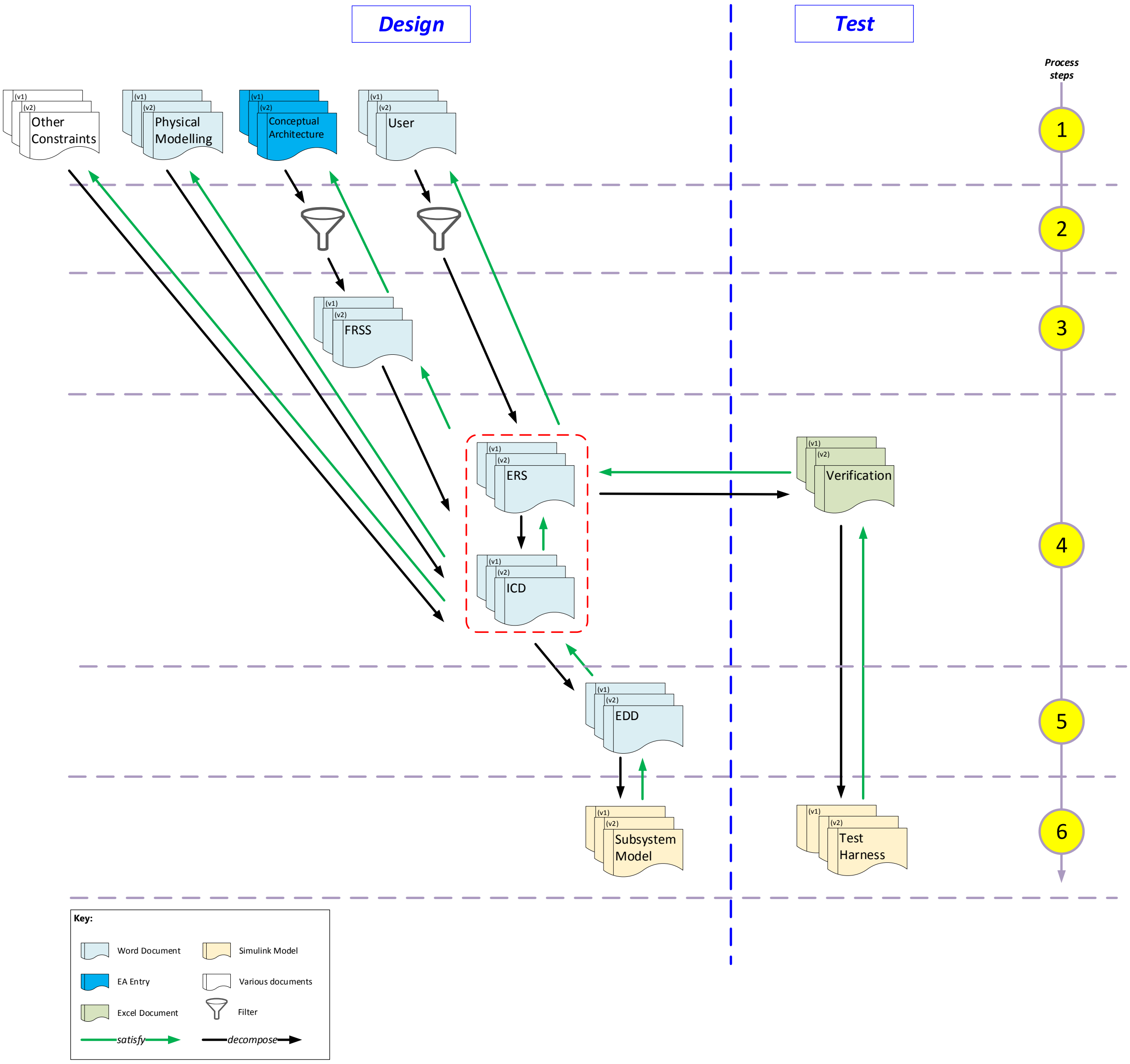

Figure 53 –ERS Generation process (high level)

The steps in the process are as follows:

1. The following information sources are analysed to identify the information that needed to be captured:
    a. Physical Modelling Requirements: the physical phenomena that should be represented in each component of the simulation.
    b. Conceptual Architecture Requirements: the definition of the future energy system architecture.
    c. User Feature Requirements: the features required by the software for the analysis team to be able to carry out the analysis workflow described in sections 3.1.
    d. Other constraints, including:

        i. requirement traceability mechanism (to parent requirements)
        ii. document audience
        iii. project timing
2. Short design reviews are conducted with stakeholders (team lead, analysis, architecture definition, verification and modelling teams) to define what features and functions should be implemented for each EPO subsystem model.
3. A Functional Requirements Specification sub–set (FRSS) document is created to capture the relevant Conceptual Architecture requirements and baselined, ready to be decomposed into low–level modelling requirements.
4. The low–level requirements to realise these features and functions are then defined and captured in two documents:
    - Per subsystem: EnergyPath® Operations Requirements Specification (ERS), based on a published template (Wiegers, 2011) (IEEE, 1998)
    - Global: Interface Control Document (ICD): A document that describes the interface(s) between all subsystems.

   The ERS and ICD are also used to develop verification test–cases for the subsystem as described in section 10.5.2.
5. The ERS and ICD are then used to develop a design for the subsystem, recorded in an EnergyPath® Operations Design Document (EDD). At this stage information is added to the ICD to define the implementation details of the subsystem's interfaces, for test development to proceed.
6. Finally, the subsystem is implemented in an appropriate development environment (Python, MATLAB, Simulink and/or Stateflow), and separately a test harness is developed to execute the verification test–cases to verify that the model satisfies that which is required of it.

All documents are stored electronically and version controlled. Further details on the configuration management process are given in section 10.5.3.

10.5.1.3. **Achievements and Next steps**

A process has been developed and brought into use for writing ERS and ICDs to capture and cascade requirements to the relevant stakeholders with a level of traceability and change control.

A satisfactory level of detail can now be captured and communicated to the stakeholders to then be able to:

- write verification tests
- write design documents
- implement subsystems
- test subsystems
- report on current state of development and testing

- trace requirements to their parent and child requirements
- trace test–cases to the requirements
- change and version control

10.5.1.4. **Impact**

The current process provides a robust framework for development activities. It provides requirements for every subsystem that define the intended operation, allowing both efficient implementation and independent testing of a subsystem with no need for the test developer to refer to the EDD or internal implementation of the subsystem. ERS may also be used by the analysis team to identify the relevant variant of a model to be used for a design run, and for change impact analysis.

10.5.1.5. **Future development**

The current process is limited in that the resulting information is stored in different repositories in different formats (e.g. Microsoft Word, Microsoft Excel, Git, Enterprise Architect etc.). Manual involvement is then needed to link together what was required, how it was implemented, and whether the output satisfied both the requirements and the underlying needs. Partially as a result, the process has not been applied uniformly across all subsystems. In future it would be desirable to source a tool to capture, host and manage requirements, traceability, test–cases, model implementation, change control and reporting, and ensure that the relevant skills are present within the development team.

10.5.2. Test and Release

10.5.2.1. **Purpose**

Testing of the EPO project is done to make objective assessments regarding the degree of conformance of the system to stated functional and non–functional requirements, as described in the previous section. Tests are developed based on the ERS and ICD and are applied at the subsystem level once an appropriate level of development and integration has been achieved.

Release management aggregates all the approved versions of the developed artefacts and publishes them in a form that can be used by the analysis team.

Further details may be found in the Verification and Validation Strategy[23].

10.5.2.2. **Process description**

The test process fits within the overall development process described in section 10.5.1.

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[23] "SSH WP3 Future GB Systems Architecture and EnergyPath® Operations Verification and Validation Strategy"

Test activities start early during the specification phase, reviewing EPO requirement specifications (ERS) for "testability". Test–cases are then developed against the requirements. Developed test–cases are aggregated into a general test repository using Jira Zephyr. During this phase, evolving requirements can be continuously fed into the test–case development process.

During the development phase, the requirements are implemented into subsystems using an Iterative Agile Sprint development concept. Once development is "feature complete" (where all the requirements are assumed to have been implemented), integration level testing is done to verify the subsystem against the requirements using the test–cases developed in the previous stage.

Test execution is managed using Jira test cycles where the test–cases to be executed are selected from the test–case repository into a time boxed cycle. Tests are then assigned to individual testers to perform. Test execution results and evidence are then aggregated, analysed and fed back into the development process.

To offset the increased testing and regression test effort, some test execution is automated. The automated test results and artefacts are stored in the central source code management system.

Test progress reporting, traceability and defect management processes are accomplished via Jira Zephyr. Jira Zephyr maintains the test–cases' linkage to the corresponding requirement specifications and defects.

Once all tests have passed, a release of the source code will be made. This takes the form of an archive file (in zip format) containing just the code relevant to the end user. Every change to the source code that passes testing will have an archive created. This archive is stored on a fileserver. The fileserver will have three distinct folders: Production, Testing and Development and read–only access to these folders is granted to only those persons who require it. All work in progress by developers will go into the Development folder, all potential release candidates that have been peer reviewed will go into Testing while code that is chosen as a release goes into Production. The archive name will be made up using a version number and timestamp to allow traceability back to the source code.

10.5.2.3. **Achievements and Next steps**

Currently the following has been achieved:

- Demonstration of requirements–based testing process: test–cases have been developed against a chosen EPO subsystem based on the requirements as expressed in the ERS (using both manual and automated testing). Tests have then been performed using the test–cases and the results of testing have been used to identify

defects to be addressed in development. This shows that the test process can verify EPO subsystems.
- A test results may be linked, through traceability information, to the test–case and the requirement that gave rise to the test–case. This demonstrates an end–to–end traceability link between the tests and the subsystem requirement specification.
- Development of a test automation framework to offset the anticipated increased testing effort and to provide incremental continuous testing with quick result feedback to uncover defects in the product.
- Setup of a Continuous Integration system within the development process, in which tests are automatically executed (using the test automation framework) at regular intervals, to verify product build reliability at greater frequency.
- Demonstration of workflow for development and management of test–cases.
- Demonstration of the release process.

Next steps:

- Increasing the use of automated testing against manual testing.
- Increase the coverage of regression tests.

10.5.2.4. **Impact**

- Testing helps in reducing the overall cost of EPO development as defects are eliminated at a very early stage in the development process where the cost of fixing is less than that at the later stages of development, thereby improving the overall quality of EPO deliveries.
- Every EPO project delivery is verified to meet the requirement specification.
- Verification helps establish confidence that the structure and practices chosen for the EPO project are working and able to deliver the goals.
- EPO release versions are packaged in a simple user–friendly format.

10.5.2.5. **Future Work**

Functionality	**Impact**
Automated test configuration and test data generation (via machine–readable ICD)	More efficient test generation allowing reduced time to detection of defects
Verification of multiple variants of subsystems	Provides confidence in implementation across many alternative models, to support scalability of simulation development
Automated generation of Traceability Matrix between requirements and test–cases	More efficient test reporting

Integration between test–case management tool (Jira Zephyr) and Continuous Build Verification System (Jenkins/test automation framework)	Improves testing efficiency through aggregating automated and manual tests into a single report and allowing more flexible triggering of test cycles
Tests of subsystem performance (execution time) against constraints	More computationally efficient code, leading to greater analysis throughput
Binary repository manager to store code releases, capturing metadata about released code such as test results, user who signed off on the release, links back to the details of the build, etc.	Improves confidence in code releases through access to underlying process details
Archive of virtual machine images containing source code and all dependencies needed to run it	Improves ability to return to previous versions of EPO and rerun analyses in the same environment as the original analysis

10.5.3. Configuration and change management

10.5.3.1. **Purpose**

As with the processes described in section 9.2 for the architecture development work, EPO configuration management records and tracks alignment between the artefacts produced during development activities. Change management meanwhile is used when defining the scope for a version of EPO, to assess the proposed tasks to include in that version based on an assessment of the effort required and accept, defer or reject them as appropriate.

10.5.3.2. **Process description**

To carry out configuration management, a *configuration baseline* must be defined for each version of EPO. This is achieved through a *configuration matrix* which records the versions of *configuration items* corresponding to that baseline. This is separate from the architecture configuration matrix detailed in section 3.1 but is complementary to it. For EPO, the configuration items are:

1. Functional requirement specifications – subset
2. ERS
3. ICD
4. EDDs
5. Source code (also including models and automated test scripts)
6. Test–cases

All artefacts are stored in a version control system, allowing for an accurate record of previous changes to be maintained as well as allowing a return to points in time of development. To define the baseline, versions of artefacts are stored and referenced as follows:

- Items 1 to 4 are stored in a SharePoint repository, and referenced by the SharePoint version ID.
- Item 5 is stored in one or more Git version–control repositories. Each iteration of the source code is uniquely identified by a 40–digit checksum hash while select commits will be chosen for release and tagged with a version number.
- Item 6 is stored in Jira Zephyr and referenced by assigning a label with the corresponding version ID to the relevant test–cases, against which a query can be run.

Although artefacts related to the future architecture development (and by extension the corresponding future architecture baseline) are included in the EPO baseline to provide a reference for model definition, in general EPO baselines will be independent of architecture baselines since development may proceed asynchronously in the two areas of definition.

For change management, proposed changes are collected on a change board as they arise along with their urgency (impact on ongoing and planned activities). Effort to implement each change is then assessed, in part using the traceability process described in section 10.5.4. Changes are then prioritised and allocated to current or future version development activities accordingly.

10.5.3.3. Achievements and Next steps

The configuration management process described in the previous section has been brought into use for EPO. Since only a small number of development cycles have been completed to date, the process has not been fully exercised regarding deferment of changes to future iterations.

10.5.3.4. Impact

Defining clear baselines for EPO and maintaining their integrity through configuration and change management ensures that the scope of a version of the software is known and documented, with changes managed and controlled. This allows focusing of development efforts towards a common well–defined goal. In addition, it also makes it possible, at the request from a stakeholder in future, to retrieve details of a previous version of EPO, rerun analyses carried out with that version and identify the likely results of including subsequent tool refinements in that analysis.

10.5.3.5. Future development

Functionality	Impact

Increased automation of process	Reduces effort for handling multiple simultaneous baselines. This is required to scale the WP3 capability to handle multiple strands of future architecture development and stakeholder requests.

10.5.4. Traceability

10.5.4.1. **Purpose**

Source code traceability is used to link together the artefacts produced during the development process described in section 10.5.1, within a configuration baseline as described in section 10.5.3: the requirements on EPO (in ERS), the detailed design (in EDDs) and the source code of the released software. It involves activities during the definition of these artefacts to add the relevant identifiers and linkage information.

10.5.4.2. **Process Description**

The traceability information is captured in the following locations:

- The configuration matrix described in section 10.5.3, linking FRSS document versions to ERS versions, EDD versions and source code revisions.
- A traceability matrix within each ERS, linking each ERS requirement ID to one of the sources listed in section 10.5.1: The Conceptual Architecture, the user requirements or other sources.
- A traceability matrix within each EDD document, linking the ERS requirement ID to a design statement reference ID (DR).
- Inclusion of DRs within the source code that is created or amended due to the original EPO requirement.

Figure 54 summarises this.

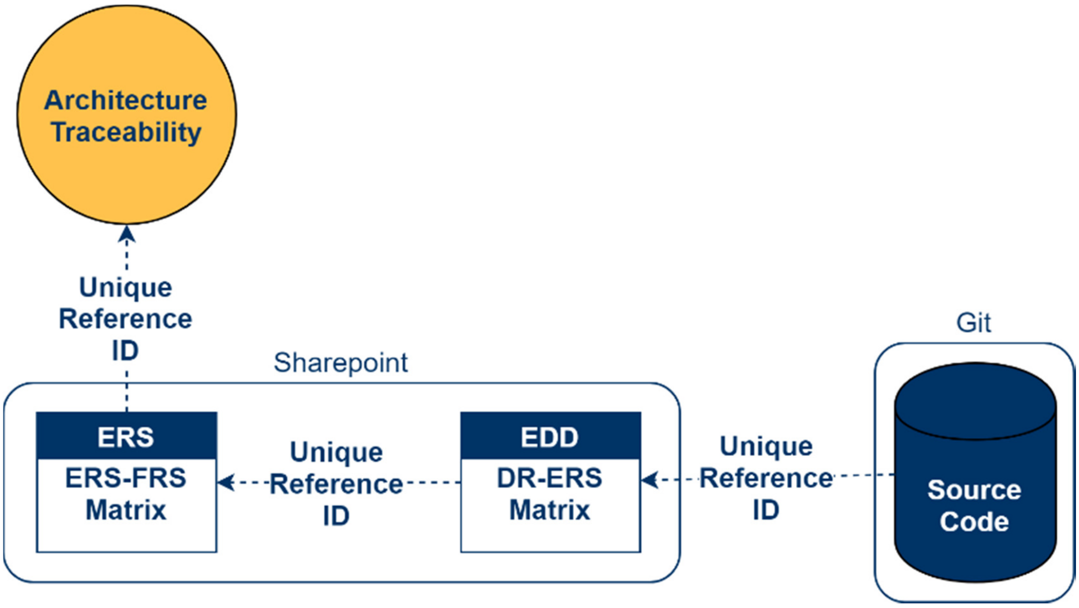

Figure 54 –Source code traceability.

A requirement may be traced from EA to source code by identifying the FRSS version to which the requirement was exported. The configuration matrix then identifies the ERS and EDD documents which satisfy the requirement. For fine–grained results the DRs within the EDD may be used to search within the source code at the appropriate revision in source control. If it is simply necessary to identify releases satisfying the requirement, a link to version control with the unique checksum hash from the matrix can be used.

A trace from source code to requirements would be performed by following the previous steps in reverse, starting by identifying the ERS and EDDs corresponding to that release version using the configuration matrix, or by identifying the EDD containing the DR.

10.5.4.3. **Achievements and Next steps**

This process is being used as intended, though not covering all EPO subsystems at present.

10.5.4.4. **Impact**

Source code traceability allows:

- Business analysts to confirm that requirements have been implemented and (combined with linked testing artefacts) that they have been met.
- Developers and modellers to guide their work when returning to bug fix requirements or implement new ones based upon existing ones.
- Project leadership to assess the effort required to implement a change, by aiding analysis of propagated changes in the source code when new requirements are created. This allows a more accurate time estimate of the time–to–deliver.

10.5.4.5. **Future Development**

Functionality	**Impact**
Automated linking of source code back to EDD via DRs.	Increases speed and accuracy of change impact analysis

10.6. Future work

In addition to the work described in the preceding sections to extend individual subsystems, there are several areas of broader–reaching development that are envisaged for the future of EPO:

Functionality	**Impact**
User–specified fault insertion capability (either ICT faults or power distribution faults)	Enables assessment of robustness of energy system to significant failures in/attacks on infrastructure
Industrial and commercial load models	Allows assessment of effect on energy system of demand represented by I&C loads
Integration of proprietary “trade secret” models supplied by external stakeholders	Allows assessment of effect of stakeholders’ business processes on energy system performance
Coordinated projection datasets for different future time horizons (5 years, 10 years, 20 years), covering allocation, weather, generation etc., based on best available research	Allows user to investigate variation in behaviour as the energy system evolves
Databases for storage of datasets	Improves traceability to data and robustness of data storage
Support for postprocessing and visualisation of simulation results	Improves efficiency of analysis by removing need to process data externally to EPO
Graphical user interface (GUI)	Increases efficiency of analysis activities

11. Appendix 6 – Detailed Analysis

Analysis using EnergyPath® Operations is performed to provide insights into how a potential energy system architecture would operate in a specific scenario. In this section, the roles and behaviours of the actors in the energy system are based on the exemplar architecture while the selected scenario defines the research question to be analysed and the boundary of operation (i.e. the level of functionality included and how it is configured). Figure 55 shows the actors implemented in this scenario and the connections between them. Those actors included are a sub–set of all the actors identified in the development activity required for the scenario under examination.

It is expected that one or more interested parties would help shape the analysis plan and would be presented with a detailed report describing the process of EnergyPath® Operations tool configuration as well as the results and insights. This process is often iterative, depending on the findings, and would support designers to rework their ideas or decision makers to conclude on the analysed proposals.

This section describes the analysis of an example scenario, framed within the chosen use–case:

> *How could an Energy Service Provider (ESP) balance their supply–demand position; having a relationship with both providers of energy and consumers of energy. It is assumed that a large proportion of the ESPs consumers own / operate hybrid heat pumps and live in a concentrated local area?*

The EPO tool was configured in accordance with the analysis plan described below which is summarised in Figure 56 to outline the analysis process undertaken. The complete analysis and results report is another of the project's deliverables. It provides further detail regarding the configuration of the model for this analysis; at each stage of the analysis, the key assumptions, decisions and methodology for performing the analysis are described. A summary of that report is provided in the sections below.

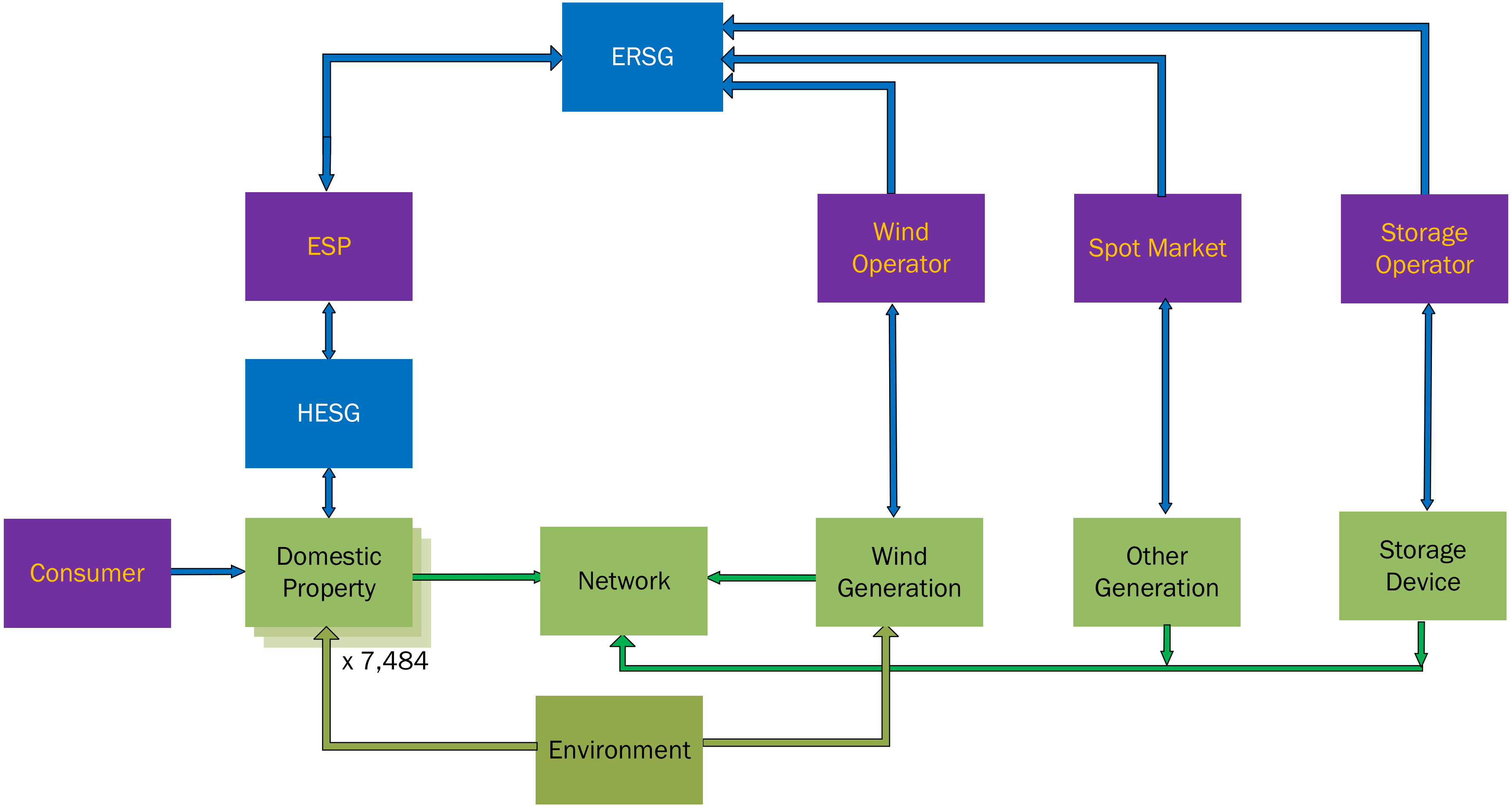

Figure 55 – Simplified View of Scope of EPO Model

11.1. Analysis Plan

11.1.1. Scenario

The scenario analyses the ability of an ESP to manage the difference between the demand for electricity and the available supply from a wind generator and through using battery storage.

A single ESP supplies a group of domestic properties with gas or electric heating according to the availability of cheap electricity (from the wind provider) and to maintain the customers' selected comfort level. The energy demand for each vector is dependent on the behaviour of occupants, the heating appliances installed and the weather conditions.

The ESP has a relationship with one wind generator, whose supply is dependent on the weather. Further to this, the ESP instructs a battery storage operator to charge when there is a surplus of generation, or to discharge when there is a deficit. The ESP can also purchase energy from a spot market (representing all the other generators) whenever additional supply is required.

Figure 55 provides an overview of the scenario and the connections between the different actors. EPO is configured to examine the problem of balancing energy supply and domestic demand from the perspective of the ESP. The distribution and transmission networks are considered to have infinite capacity (i.e. place no constraints on the system) in this analysis.

The actions of actors and the interactions between actors within this scenario, for both the physical and business representation, are outlined below (the numbering matches the numbers in square brackets in Figure 56).

10. Demand for electricity originates from a collection of domestic properties. A real geographical area is chosen as a basis, to capture the distribution of property types and to allow comparison to the national distribution. The heating appliances present in the properties are a mixture of combi–gas boilers (gas heating) and HHPs (electric heating), defined probabilistically. In this analysis no DSR capabilities are available.
11. The ESP delivers electricity and gas to the selected group of properties. Currently there is only one ESP modelled. If that ESP has failed to provision enough supply (compared to actual demand) then a physical imbalance will result.
12. The spot market, representing all other generators, supplies electricity instantaneously on request from the ESP.
13. The storage devices charge or discharge as requested by the ESP. There are limitations on the rate of charging and discharging. However, the storage's energy capacity is considered not constrained – rather this analysis seeks to understand the size of storage required to make this business model operate. Similarly, in this

example the storage's power ramp rates for charging and discharging have not been constrained.

14. The ESP receives a forecast of the aggregated demand profile of their consumers from the HESG every 15 minutes, covering the period from 15 to 30 minutes ahead of the forecast issue time at 60–second intervals. E.g. at 11am the ESP receives the consumer's demand forecast for each minute between 11:15 and 11:30.
15. The wind generator forecasts generation and sends this to the ESP every 15 minutes, covering the period from 15 to 30 minutes ahead of the forecast issue time at 60–second intervals. E.g. at 11am the ESP receives the forecasted wind output for each minute between 11:15 and 11:30.
16. When the forecasted wind generation is greater than demand, the ESP requests the storage operator to take the excess.
17. When the forecasted wind generation is less than demand, the ESP requests the storage operator to provide the deficit.
18. If the deficit is greater than the maximum power available from the storage, the ESP purchases additional energy from the spot market.

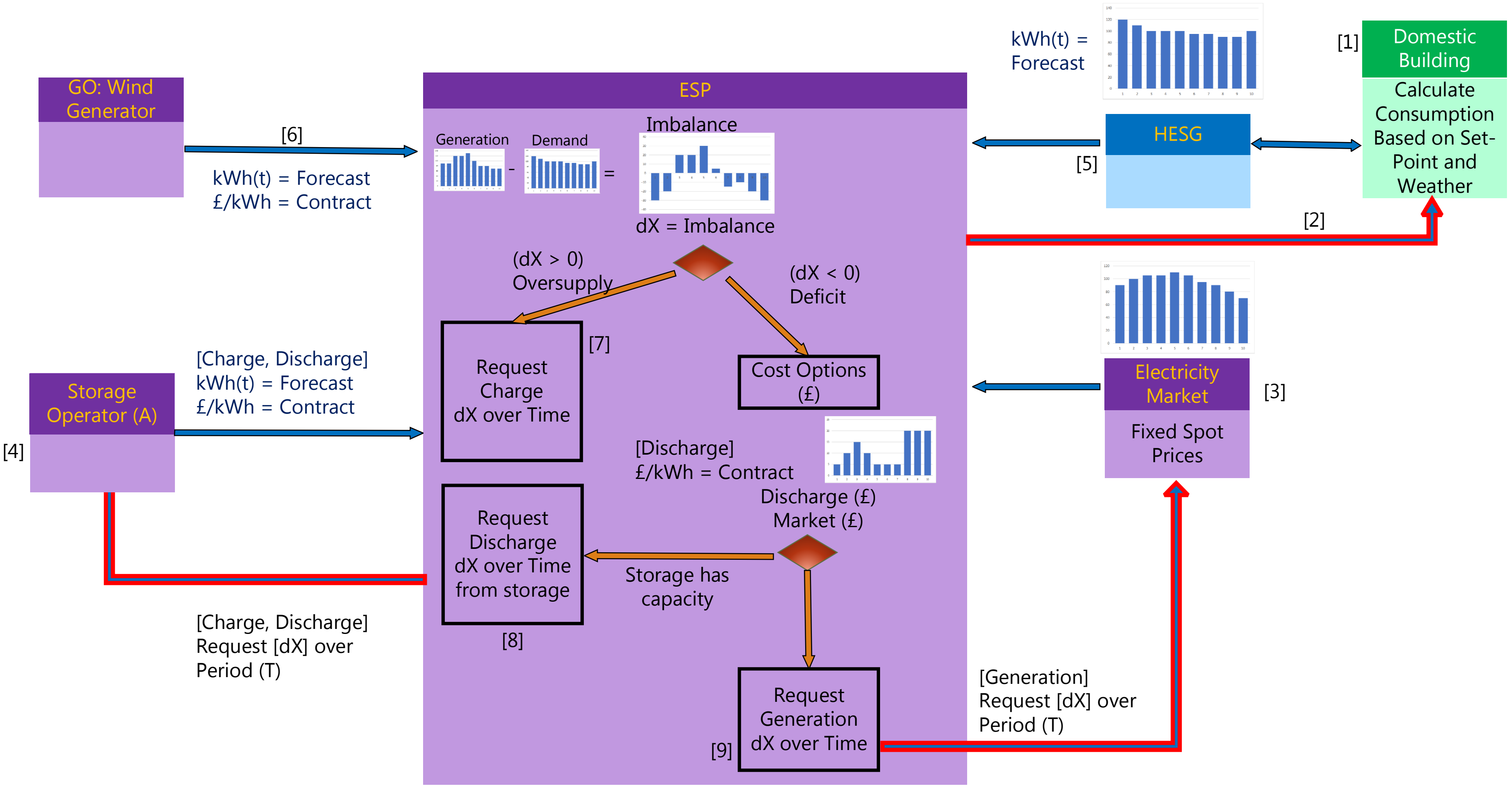

Figure 56 – Summary of key actors in EPO configuration for analysis

Analysis Questions

The analysis questions are framed to explore behaviour within the exemplar architecture from the selected scenario.

5. What is the cost to the ESP of supplying energy (electricity and gas)?
6. Within what limits can the difference between ESP supply (from generation and/or storage discharging) and demand (from consumers and/or storage charging) be maintained?
7. What storage capacity is required to handle the total difference between electricity demand and supply?
8. What proportion of the total energy supplied to the domestic properties comes from the wind generator, relative to spot market and gas? (This gives an indication of the decarbonisation that is achieved from this scenario.)

To provide insights into each of these questions, the corresponding key performance indicators (KPIs) in Table 4 will be extracted from the simulations performed.

Question	**KPI**	**Purpose**
1	ESP Cost	To understand whether this is an attractive financial proposition. The different prices for energy from wind generation, spot market and gas are constant (£ per kWh). The storage operator charges the ESP a fixed margin for charging / discharging energy (£ per kWh).
2	Demand Supply Imbalance	To determine whether the proposition will sufficiently balance to reduce the risk of voltage issues on the distribution network (within normal non–fault operation). This considers the imbalance in supply purchased and demand provided from the perspective of an ESP (kW).
3	Storage Capacity	This is represented as the cumulative discharge and charge (kWh) provided by the storage since the beginning of the simulation. The difference between maximum and minimum values indicates the storage energy capacity (energy) required to facilitate this proposition.
4	Energy from Wind Generation	To understand the decarbonisation of the energy system achieved. This is defined by the proportion of the total energy supplied to domestic properties that comes from wind generation (as a % of total energy consumed).

Table 4 - Summary of analysis questions and KPIs

11.1.2. Analysis Test–Case

The analysis considers a heating season running from the beginning of October to the beginning of the following April.

It was based on a region within Bridgend supplied from a single 33kV to 11kV substation, namely HV560024. This substation supplies 7,484 domestic properties. Compared to the national average the region has slightly larger houses with fewer solo occupants and fewer flats but can be considered a reasonably typical semi–urban area.

All houses were assumed to use either a combi–gas boiler or a hybrid heat pump (HHP) for heating. In properties with a combi–gas boiler, this provides all space and hot water heating. In properties with an HHP, the heat pump component provides all space heating, while the gas boiler component provides all water heating. The rated power of the appliances and other aspects of the heating system were set to be directly proportional to the size of the house. Appliances delivering space heating were switched on and off by a thermostat based on the simulated room temperature and its corresponding setpoint.

The proportion of HHPs in the scenario was chosen such that the electricity consumption from heat pumps is approximately equal to the overall non–heating demand (electricity for non–heating purposes) from all properties. Assuming that no flats have HHPs, this equated to 30% of all other property types. Since it is impossible to predict which houses will purchase HHPs, appliances were allocated to properties probabilistically where the probability distribution across appliance types depends on the property type (in this case the probability of a heat pump was set to 0% for a flat and 30% for e.g. a semi–detached house). Likewise, the number of occupants and their demands for each property were determined probabilistically, dictating the temperature set points, time of use and amount of hot water required.

Arbitrarily, the number of wind turbines was chosen to approximately match the average domestic property demand throughout the overall heating season. This decision was made to ensure a range of behaviour during the simulation, varying between wind generation exceeding demand and the reciprocal situation.

A charge/discharge rate limitation was selected so the storage operator can take all output from the wind generator, i.e. there is no need to curtail wind power, but peak demand can still exceed the peak storage output.

Table 5 summarises the different test–cases investigated in terms of the factors varied. Test–case 2b was taken as the base run. The main test–cases (2a and 2b) were run multiple times with different allocations of heating appliances and occupants to ensure that a range of results was obtained to account for the uncertainty around energy usage in each dwelling. To reduce simulation run–time the multiple runs of the offline consumer model were executed over a short time period. The configurations with the lowest, median and highest electricity consumption (denoted "LowC", "MedC" and "HighC") were identified and then re–run for the full–time period. Test–case 1, meanwhile, was only executed once since the only electricity consumption was background demand which would not be expected to vary significantly.

Table 6 summaries the prices used in the analysis. These are the constants in the KPIs defined in the analysis plan. The energy prices were selected as 'reasonable starting values' for this analysis. These are based on the day–ahead prices from the winter of 2016 and were altered to reflect the trend of wind energy becoming cheaper, with base load electricity and gas prices becoming more expensive; a 25% change the in the relevant directions was assumed for all prices relative to the 2016 values.

The storage margin price is an initial estimate and reflects the storage provider charging the ESP to store their excess purchased energy or to have it delivered back to them. This is unlike existing business models, but this formulation was chosen to explore value–chain hand–offs.

Test–case	Heating Appliance	Storage Power
1	All Gas Heating 100% Combi–Gas Boilers	Unrestricted charge/discharge rate
2a	Mixture of Combi–Gas and HHP 70% Combi–Gas Boilers 30% HHP	
2b		Restricted 10 MW max charge/discharge rate

Table 5 - Summary of cases for analysis runs

Aspect	Price	Rationale
Wind Generation	£46.5 MWh	25% less expensive than on–shore generation cost in 2016 (McKenna, Hofmann, Merkel, Fichtner, & Strachan, 2016)
Spot Market	£56.0 MWh	25% more expensive than UK day–ahead prices in winter months of 2016 (Nijhuis, Gibescu, & Cobben, 2016)
Gas	£13.6 MWh	25% more expensive than UK day–ahead prices in winter months of 2016 (Nijhuis, Gibescu, & Cobben, 2016)
Storage Margin	£10.0 MWh	Initial value chosen

Table 6 -Summary of costs used in analysis

11.1.3. Detailed Assumptions

To demonstrate the boundaries of the scenario, the most significant modelling assumptions are summarised below:

- Weather conditions are assumed uniform across the selected region. Variations in weather conditions are updated on an hourly basis from the data with values between the hours linearly interpolated. The weather, in the current model, affects both the wind generation and the domestic properties.
- For domestic properties, exchange of heat with the environment is only considered as conduction through the structure (i.e. no solar gain or convection through open windows). The thermal properties of the building fabric are based on property type, property age and floor area band classifications from the English Housing Survey. This provides a set of archetypes, which have unique combinations of these variables representing the performance of the buildings including, for example, the insulation performance.
- The energy storage device is represented as an energy flow with defined maximum rate constraints but infinite storage capacity.
- The precise number of occupants in each property is unknown. It is defined according to a probability based on floor area, derived from the English Housing Survey.
- The occupants' behaviour is defined by the CREST stochastic demand model (McKenna, Hofmann, Merkel, Fichtner, & Strachan, 2016). This assumes that the behaviours follow a repeated daily cycle that is different for weekdays and weekends and is a function of the number of occupants in a house. This does not consider change in use of heating between seasons, subtle changes in daily routine or special events, such as public holidays. In other words, the data assumes that heating systems are turned on at the start of winter and remain on with the same programme (time–profile of setpoint temperatures) until the end of spring. Although the heating programme is fixed, the energy use will change as the external temperature varies.

11.2. Results

To address the Use Case outlined in section 11.1, the model was configured to represent the scenario, the test–cases within the scenario (all combi–gas, 30% HHP with unrestricted storage power and 30% HHP with 10MW storage power limit) and the runs within those, described in section 11.2.1. The results are presented for each test–case and run separately.

11.2.1. Generation from Wind

Table 7 shows the overall energy consumed in the test–cases, split by vector; the overall gas and electricity consumption are the same in cases 2a and 2b, since it is only the means of satisfying the electrical demand which differs in these two cases. The deployment of heat pumps causes an 18 kWh/house/day reduction in gas usage (25% of the total).

			Electricity consumption (kWh/house/day)		
Test–case		**Run**	**Electricity**	**Gas**	**Total**
1	**All combi**	**Std**	**9.22**	**69.24**	**78.46**
2	**30% HHP**	**LowC**	21.93	51.17	73.10
		MedC	**22.56**	**51.11**	**73.67**
		HighC	23.32	48.96	72.28

Table 7 -Total Energy Consumption for Base Runs by Vector

Table 8 shows the amounts of electrical energy drawn from different sources (Storage, Wind Generation and Purchased from Spot Market), further broken down into lowest, median and highest–consumption runs for test–cases 2a and 2b.

			Electricity source production (net kWh/house, averaged over heating season)		
Test–case		**Run**	**Storage**	**Wind**	**Spot**
1	**All combi**	**Std**	**–1.91**	**11.12**	**0.00**
2a	**30% HHP Unrestricted Storage Power**	**LowC**	–0.33	**22.24**	0.00
		MedC	**0.28**		**0.00**
		HighC	1.04		0.00
2b	**30% HHP Storage 10MW Power Limit**	**LowC**	–0.48		0.15
		MedC	**0.07**		0.21
		HighC	0.77		0.27

Table 8 - Electricity Consumption for Base Runs by Source

The negative values for supply from storage for certain runs indicate where a surplus of wind generation leads to a net increase in energy held in the storage device over the simulation period. There is a significant surplus in test–case 1, but in test–cases 2a and 2b the energy provided and consumed match more closely (net energy produced/consumed from storage within 5% of the total energy consumed).

Comparison of test–cases 2a and 2b shows that restricting the maximum storage power output only causes the ESP to buy around 1% of the energy from the spot market, and nearly 99% of the electricity used by the consumers is supplied by the wind turbine. Energy bought from the spot market is transferred to additional energy accumulated in storage at the end of the simulation. The spot market is only used on rare occasions when there is low wind during hours of peak consumption, generally when the outside temperature is low.

11.2.2. ESP Cost

Table 9 shows the cost to the ESP to supply energy to the consumers, reported as the average cost per house over the heating season.

For the purposes of comparison two new test–cases are introduced here, which assume the same gas and electricity consumption as test–cases 1 and 2 but assume the ESP has no contract in place with a wind generator or a storage provider and so must purchase all energy at the relevant gas and electricity spot market prices (shown in Table 9). These are denoted Ref 1 and Ref 2 respectively, shown in the yellow rows. (see Figure 57)

			Energy cost to ESP by vector (£/house over heating season)		
Test–Case		**Run**	**Electricity**	**Gas**	**Total**
Ref 1	**All combi–gas**	**Std**	**101.16**	**184.56**	**285.73**
Ref 2	**30% HHP**	**LowC**	240.65	136.40	377.06
		MedC	**247.63**	**136.23**	**383.86**
		HighC	255.97	130.51	386.48
1	**All combi–gas**	**Std**	**93.09**	**184.56**	**277.66**
2a	**30% HHP Unrestricted Storage Power**	**LowC**	218.41	136.40	354.81
		MedC	**224.35**	**136.23**	**360.58**
		HighC	230.91	130.51	361.42
2b	**30% HHP Storage 10MW Power Limit**	**LowC**	217.22	136.40	353.62
		MedC	**223.12**	**136.23**	**359.35**
		HighC	229.68	130.51	360.18

Table 9 – Energy Cost to ESP by Vector across Test–Cases

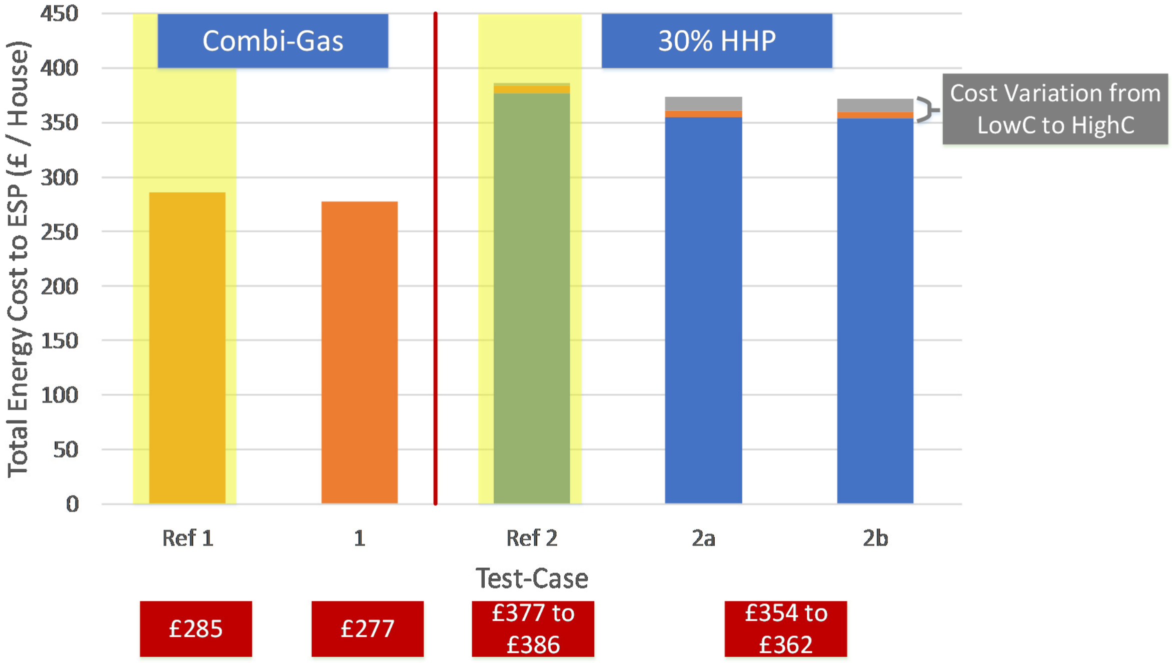

Figure 57 – Total Energy Cost for ESP across Test–Cases (£/house over heating season)

The results show that, as expected, the total cost of supplying energy in test–cases involving HHPs (test–cases Ref 2, 2a and 2b) is greater than where only combi–gas boilers are used (test–cases Ref 1 and 1). This suggests that for HHPs to achieve high adoption, some incentive needs to be provided for their use beyond the trend in relative prices of gas and electricity per kWh assumed in Table 9. The reduction in overall cost from Ref 1 to 1, and from Ref 2 to 2a and 2b, shows the advantage to an ESP in having longer–term contractual arrangements with energy resources rather than simply buying from the spot market, although this is contingent on the assumptions made in Table 9. There is minimal difference in cost between test–cases 2a and 2b (unrestricted storage power vs storage power output restricted to 10MW), since only a small fraction of the energy is purchased from the spot market.

11.2.3. Supply – Demand Imbalance

The instantaneous power drawn from the storage device, and the ESP's net supply–demand imbalance, necessarily vary over the course of the simulation. Descriptive statistics of these quantities are shown in Table 10 and Table 11 respectively. The values for imbalance are the difference between the total power supply and demand, averaged over 15–minute periods. In Table 10 negative values indicate charging of the storage devices when there is excess generation and positive values denote discharging when there is insufficient generation.

			Instantaneous storage power (kW)					
Test–case		Run	Mean	StdDev	Min	5%ile	95%ile	Max
1	All combi	Std	**–633**	**456**	**–3,994**	**–3,571**	**3,573**	**6,123**
2a	30% HHP Unrestricted Storage Power	LowC	–118	358	–8,505	–7,125	9,346	15,978
		MedC	**69**	**374**	**–8,458**	**–7,161**	**9,590**	**16,479**
		HighC	299	444	–8,473	–7,065	9,928	15,512
2b	30% HHP Storage 10MW Power Limit	LowC	–164	352	–8,505	–7,125	9,346	**10,000**
		MedC	**5**	**354**	**–8,458**	**–7,161**	**9,590**	
		HighC	223	406	–8,473	–7,065	9,872	

Table 10 -Storage Power (over heating season)

			Instantaneous supply–demand imbalance (kW)					
Test–case		Run	Mean	StdDev	Min	5%ile	95%ile	Max
1	All combi	Std	**0**	**139**	**–465**	**–216**	**234**	**651**
2a	30% HHP Unrestricted Storage Power	LowC	0	249	–1,272	–413	398	1,096
		MedC	**0**	**254**	**–1,130**	**–422**	**418**	**989**
		HighC	0	259	–1,353	–433	402	993
2b	30% HHP Storage 10MW Power Limit	LowC	0	264	–1,272	–413	398	1,093
		MedC	**0**	**272**	**–1,127**	**–422**	**418**	**989**
		HighC	0	273	–1,351	–433	402	993

Table 11 - Supply–Demand Imbalance (over heating season)

Comparing test–case 1 (all gas heating, i.e. electricity consumption represents non–heating loads) against test–cases 2a and 2b (30% HHP), while the mean imbalance remains zero the moment–to–moment variation in imbalance is significantly greater when electric heating is introduced; an increase would be expected, since overall consumption has doubled, but the minimum imbalance increases by a factor greater than two. This suggests that the characteristics of electric heating demand are more challenging for the system to satisfy than the non–heating demand.

Further analysis examining the probability distribution of the imbalance over the 'LowC', 'MedC' and 'HighC' runs for test–case 2b suggested that there are specific conditions where the balancing strategy is ineffective (results not shown); further investigation is required.

11.2.4. Storage Capacity

As described in section 11.2.1, the analysis performed does not constrain the energy capacity of the storage, and instead seeks to understand from the simulation what capacity would be required to support the assumed business models.

To this end, Table 12 shows a summary of the variation in state–of–charge (SoC) of the storage over the heating season. Data is presented as the total range (from minimum SoC recorded to maximum SoC recorded), and the range from the 5th to the 95th percentile SoC value. According to these results, in the worst–case run (test–case 1) the storage operator would need 1.5 GWh of energy capacity to satisfy the energy system's needs over the entire heating season. However, this assumes that the storage operator acts purely according to the instructions of the ESP. It is more realistic that they would have a mechanism to manage their own inventory, i.e. exporting energy to another part of the energy system when their SoC is high and importing it when their SoC is low. If this could reduce the range to the 5%ile–to–95%ile value, the required energy capacity would fall to around 0.5 GWh.

An alternative philosophy that could significantly reduce the storage energy capacity needed could be for the ESP to set up a contract with the wind generator on a day–by–day basis, each day matching the expected energy generated over that day with the expected consumption over that day; the arrangement simulated corresponds more closely to matching the consumption and generation over the entire heating season. Any deficit in energy available from the wind generator would be made up by spot market purchases. Storage would then be used within each day to time–shift generation to match demand but would not be required to absorb/supply energy over the entire heating season (Lawton, 2018).

			Variation in State–of–Charge (kWh)	
Test–case		Run	Total Range	5%ile to 95%ile
1	**All combi**	**Std**	**1,414,977**	**456,080**
2a	**30% HHP Unrestricted Storage Power**	**LowC**	1,098,569	358,138
		MedC	**1,149,736**	**374,092**
		HighC	1,294,015	443,727
2b	**30% HHP Storage 10 MW Power Limit**	**LowC**	1,090,409	351,734
		MedC	**1,100,381**	**353,896**
		HighC	1,207,129	405,899

Table 12 -Variation in State of Charge of the Storage Over the Heating Season

Factors Impacting KPI

Experientially it appears that the main factors affecting the analysis KPIs are the volatility in the consumer demand, the weather conditions, and the accuracy of the demand forecast. Short investigations into the volatility in consumer demand and the impact of the demand forecasting time constant are outlined below to provide further insight into the exemplar architecture's behaviour.

Volatility in Consumer Demand

In this scenario, the aim of the ESP is to arrange for electricity supply to track the aggregate consumer demand profile; any error in this tracking will lead to a supply–demand imbalance, which would require intervention by the System Operator to make up. Intuitively, increased volatility of the consumer demand will make this more challenging.

Figure 58 shows an example consumer demand profile, corresponding to a single weekday from the test–case 2b “MedC” run (30% HHP, 10MW storage power limit, median electricity demand). It also shows the corresponding calculated supply–demand imbalance for the system. From inspection of the graph, it may be seen that high imbalance values (e.g. just before 18:00) coincide with spikes or rapid changes in the aggregated consumer demand. This is hypothesised to be because the demand forecast received by the ESP, being a low–pass filtered version of the consumer profile, tends to reduce the amplitude of and increase the duration of such spikes in demand, and so the supply–side response as dispatched by the ESP lags the demand. –

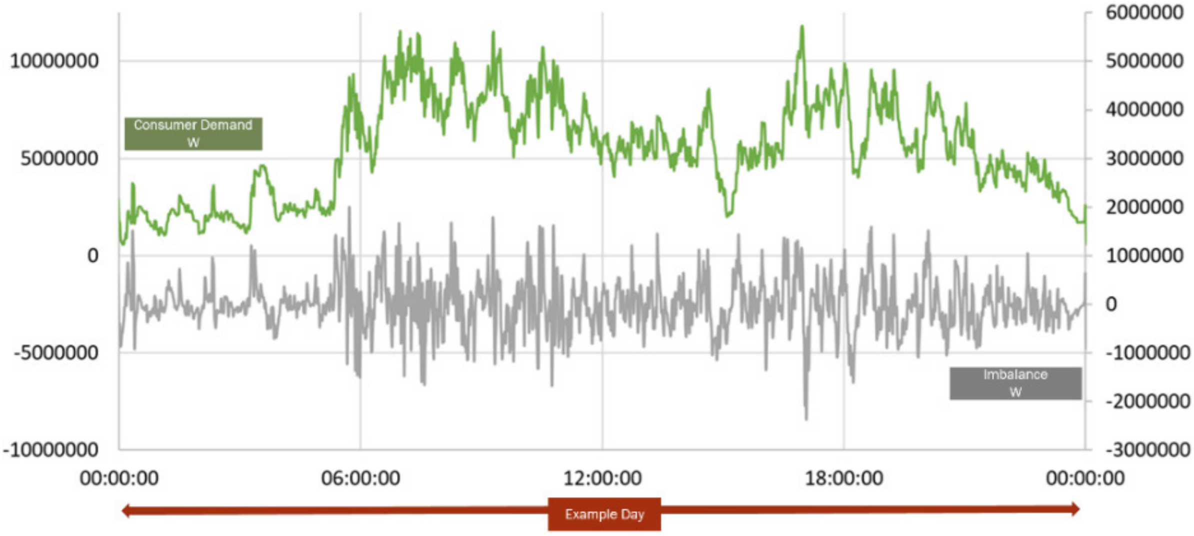

Figure 58 – Consumer Demand and Supply–Demand Imbalance over an Example Weekday (30% HHP)

Accuracy of Demand Forecast

The accuracy of the forecast of consumer demand is central to the scenario, as the demand forecast is one of the signals used by the ESP to calculate the amount of supply–side resources to dispatch. To test its effect, a set of runs were performed in which the forecast accuracy was varied but all other parameters were kept constant at the values used in test–case 2b (30% HHP and storage power limited to 10MW).

In the simulation the consumer demand profile is inherently perfectly forecastable, since it is computed in its entirety by the offline consumer model before the online scenario model is run. It is therefore possible to add a controllable amount of error to the consumer demand *forecast* relative to the *actual* consumer demand. In implementation terms, in this analysis the forecast was calculated by "smoothing" the actual consumer demand profile using a first–order linear low–pass filter. The amount of smoothing, and thus the error between the forecasted and the actual consumer demand, may be adjusted using the value of the *time constant* of the low–pass filter. This is a positive value measured in seconds, where a larger value corresponds to a smoother output and a smaller value causes the forecast to follow the short–term spikes in demand more closely; in all cases the forecast will match the long–term trend of the demand. The standard value used in all runs apart from those described in this section was 180 seconds.

Figure 59 shows the ESP's total energy cost (average £ per house over the heating season) as the forecast time constant increases from 15 seconds to 30 minutes (1,800 seconds). Likewise, Figure 60 shows the supply–demand imbalance corresponding to different values of the time constant (the standard deviation of the imbalance is plotted since the mean imbalance is very close to zero in all cases). The graphs show that as the time constant is increased (i.e. the forecast is made less accurate on a moment–to–moment basis), there is a small linear decrease in the energy cost to the ESP (dwarfed by the variation between the "LowC", "MedC" and "HighC" runs), but a significant increase in variability of the imbalance.

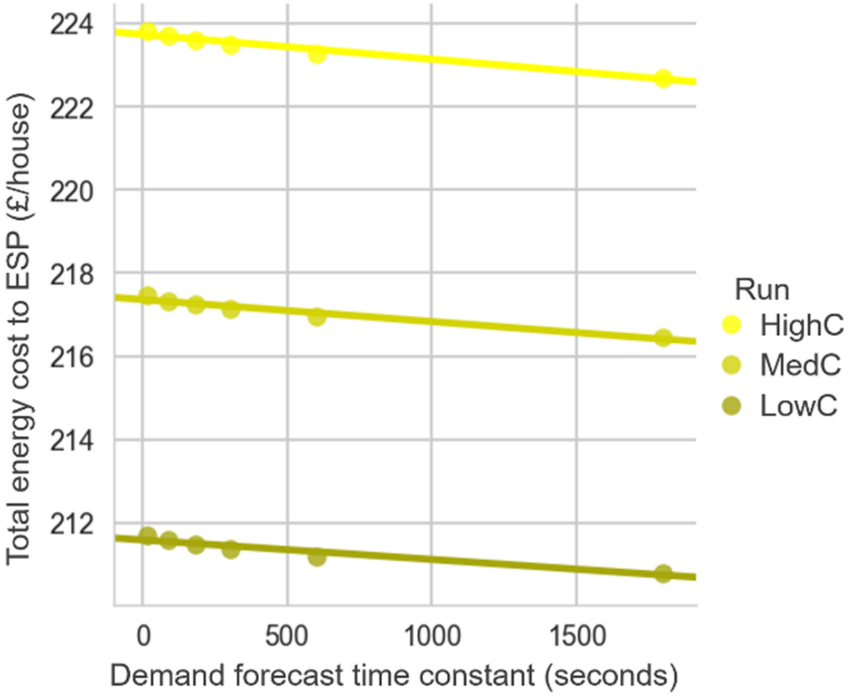

Figure 59 – ESP Running Cost Against Consumer Demand Forecast Time Constant

The slight reduction in the cost to the ESP with increasing time constant is potentially because fewer of the short–term spikes in demand survive the smoothing used to construct the forecast and so are visible to the ESP, meaning the ESP requests less short–term action by the storage provider to satisfy the spikes and thus incurs lower costs. As a result, since in this scenario there are no penalties to the ESP for failing to balance supply and demand, there is a perverse incentive for the ESP to be less responsive to variations in demand to reduce its costs (which worsens overall network balance). Regulation or market incentives will be required to prevent this from occurring.

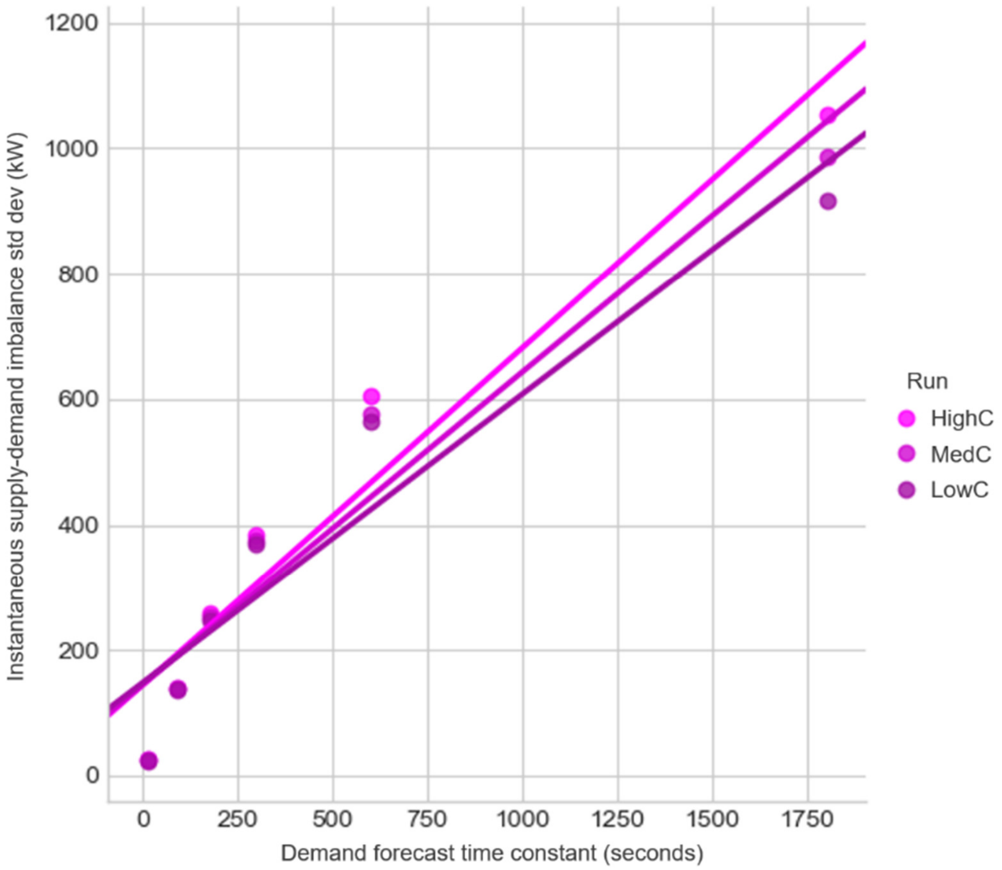

Figure 60 - Standard Deviation of Imbalance Against Consumer Demand Forecast Time Constant

Energy Systems Catapult
7th Floor, Cannon House
18 Priory Queensway
Birmingham
B4 6BS

es.catapult.org.uk
0121 203 3700