



Programme Area: Smart Systems and Heat

Project: WP3 Case Study Development Hybrid Heat Pumps

Title: Energy Systems Architecture Methodology: Enabling Multi-vector Market Design

Abstract:

This report has been prepared by the ESC from the third part of SSH, as a set of conceptual tools to develop and analyse system architectures. Whether there is ever a single “System Architect” or not, it is important that the design of complex and mission critical systems on which society depends are developed through a robust set of engineering processes that ensure they are fit for purpose. At the highest level this is about affordability, security and sustainability. Equitable access has dimensions that stretch well beyond technical and economic factors but the system should be designed so that equitable access is made easier and not harder; the system design should provide levers that public policy can use to deliver policy objectives.

Context:

The Case Study Development project was commissioned by the ETI in Nov 2015 as part of Work Package 3 (WP3) of the Smart Systems and Heat Phase 1 programme. The project was intended to develop Market, Business and ICT Integrated Solutions through system architectures to provide evidence and guidance for business strategy and policy to enable the UK low carbon heat transition. This was achieved through understanding the inter-relationships between market frameworks, business process, asset management and ICT solutions. Primary focus was on the implementation at the local level, but in the context of a national energy system transition.

Energy Systems Architecture Methodology: Enabling Multi-vector Market Design



November 2017

Foreword

Over the next thirty years our energy system will undergo a major transformation to deliver a modern, fit for purpose experience for people who use services that depend on energy. Examples of these are comfort, cleanliness, food preparation and preservation, security, communications and transport, amongst others. These services are used at home, at work and on the move. Manufacturing industry also needs energy, sometimes quite intensively.

This transformation will be driven by a number of factors, but in some form they are all a response to the challenge of climate change and/or the opportunity of new information technologies. For example, the most innovative companies in vehicle technologies are working on low carbon autonomous vehicles as their future business. There are a large number of technology innovations across the whole energy system which will contribute to this, for example offshore wind farms, better batteries and better ways of controlling heating systems.

In the last century, central heating and the switch from towns gas to natural gas created a major change in the provision of comfort and cleanliness, television transformed entertainment and more recently the internet has impacted most aspects of our daily lives. The coming energy transformation will bring together new technologies for supply, transport, storage and end-use appliances, together with new information technologies to deliver better services. These services need to be delivered affordably, securely, sustainably and equitably. Energy services are too important for them to be unreliable or for people not to be able to access them to a decent level. Social and economic barriers to access are especially important during a period of transition, which risks unintentionally leaving vulnerable people behind.

Previous major transformations in energy in the UK have been driven by state owned companies. At one point most of the electricity supply chain was in state hands, from mining coal to sending out the bills. The foundations of modern gas supply were also laid by visionary leaders of state organisations. Some people feel that the state should take a leading role at the very least in directing the main elements of the transition.

An alternative perspective would be that the Internet, despite its foundations being created by the US government, could only have been developed through millions of private decisions and innovations within a self-governing framework (underpinned by state rules and actions) based on principles that enabled innovation and good self-governance.

A third perspective would be that aggressive incrementalism and experimentation is the safest way forward, departing from present rules and approaches only where there is widespread agreement that they are not fit for purpose.

There is no obvious or easy answer to the best way to deliver this transition. Many people have come to the conclusion that different parts require different approaches, which are then integrated into an overall framework through policy and over-arching governance. The combination of different skills and the complexity of providing that governance have caused a number of energy industry players to propose some kind of "Systems Architect". The role of such an assembly of different talents would be very different between the three approaches above, but the content of the work would be about systems architecture.

What is an architecture in the energy system context?

The word architecture conjures up the design for a complex building, showing how it serves its occupants; the components and systems that hold it up, keep out the weather and keep it working. This idea of architecture has been extended to complex systems like aircraft, railway networks or information systems, including the whole internet.

A national energy system is far more complex than a single building, more like every aspect of a large city, including all the buildings, roads, fresh water, sewerage, etc. In such a complex system of systems with very large numbers of sub-systems, no single architect can determine all the details.

In a single building, the architect usually leaves the detailed design of the heating system or the choice of furniture to others; although critical details sometimes receive an architect's attention. In very complex systems the architect determines interfaces, who makes decisions about sub-systems and how issues about integration are resolved. In our city, we need to decide who is responsible for the traffic lights and whether that is the same as managing the railway and bus timetables. Organisational arrangements, rules for ownership and contracts and governance need to be set out.

Just like a city, an energy system has to keep operating while it evolves to meet changing needs and adopt new technologies. The architecture is therefore open and should determine how change is enabled, otherwise our city will stagnate and die.

The architect for our building needs to think about its whole lifecycle – how will it be operated and maintained, could it be extended or repurposed, what would happen if new technologies require it to be cabled differently or the heating system to be changed, how might fires be fought and people evacuated, does it need to withstand exceptional weather or earthquakes.

All of these concepts about complex systems design, lifecycle management and adaptation, governance, operation and change can be applied to energy systems. Indeed, our present

energy system did not evolve in a chaotic way but through a series of architecture processes that enabled a highly complex and functional system to emerge from millions of individual decisions within frameworks enabled and created ultimately by government but implemented through many skilled people in organisations with reasonably clear roles and spans of operation.

This report outlines how current work by the Energy Systems Catapult (ESC) for the Energy Technologies Institute (ETI) Smart Systems and Heat Programme is applying these systems engineering concepts to the energy sector, across three key dimensions:

- **Market Systems Architecture:** focused on policy, regulation and commercial interactions between actors; for example to internalise carbon cost, to protect consumers and to enable value exchange between actors with business drivers and actors with data and/or levers of control.
- **Physical Systems Architecture:** focused on how physical interactions, dependencies and constraints such as frequency, voltage, pressure, etc in gas, heat, electricity and liquid fuels are managed.
- **Information Systems Architecture:** focused on the information infrastructure arrangements that enable communication within and between actors, especially how cyber-security is maintained.

This report

The ETI Smart Systems & Heat (SSH) Programme is developing capability to address how energy services could be provided in domestic, commercial and institutional buildings through the transition discussed above. One part is focussed on changes within and to the buildings, a second part on investments in local gas, electricity and heat networks and a third part on the business and operating model of the whole system.

The SSH Programme is being delivered by the new Energy Systems Catapult (ESC), who will be taking it onwards with new sources of funding and a wider circle of stakeholders beyond the end of the ETI. The ETI has funded the first phase of the Programme to enable the ESC to develop tools and expertise, and gather experience and data from smaller scale trials.

This report has been prepared by the ESC from the third part of SSH, as a set of conceptual tools to develop and analyse system architectures. Whether there is ever a single “System Architect” or not, it is important that the design of complex and mission critical systems on which society depends are developed through a robust set of engineering processes that ensure they are fit for purpose. At the highest level this is about affordability, security and sustainability. Equitable access has dimensions that stretch well beyond technical and economic factors but the system should be designed so that equitable access is made easier and not harder; the system design should provide levers that public policy can use to deliver policy objectives.

The report presents a series of conceptual tools and analyses developed from systems engineering tools applied to the future UK energy system. These are technical tools to structure discussions about system architectures and how to develop and assess them.

During 2017, the ETI is publishing the majority of the detailed outputs of its projects over the Ten Years of Innovation since its launch in 2008. Work on energy system architectures is not yet complete; however, the ETI has decided to publish this key deliverable from the work area that is addressing end-to-end system operation and control before a rounded set of outputs is available. This deliverable is moderately technical and designed for use by people participating actively in two key questions:

- What kind of governance would best enable innovative, competitive and consumer focussed delivery of energy services that ensure no one is left behind?
- What kinds of architecture might this energy eco-system have and how might we make choices that enable the kinds of changes that are required, while managing risks?

Our purpose in publishing it is to encourage and inform debate. Engaging with the Energy Systems Catapult will provide valuable feedback about how the UK energy system can develop to meet future needs.

Andrew Haslett FREng
Chief Engineer
Energy Technologies Institute



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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.
Enabling Platforms	An actor whose role is to enable interactions between many:many Individual Actors. This may be for collective decision making amongst a group of Individual Actors (Planning Dialogues) or it may be for enabling market competition and/or cooperation between Individual Actors (Gateways).
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.
Firewall	The boundary drawn around a Test Bed. It must be demonstrated that both the Shared Ecosystem and the Individual Actors' operations within it are scalable and resilient to all reasonable failure modes. This is a prerequisite for seeking regulatory permission to scale the Test Bed for the purposes of enabling Individual Actors to commercialise business models, processes and systems designed for a Shared Ecosystem that differs from business as usual.
Gateways	One of the two types of Enabling Platform, specifically for the purposes of enabling market competition and/or cooperation between Individual Actors. They are codified throughout this report using red blocks.
Governance	The means by which 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 as a whole. It encompasses how the rules, standards and market actions are structured, sustained, regulated and held accountable.
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.
Performance Level	A definition of the levels of performance a particular Service Attribute may be set at. Levels may be discrete (e.g. unlimited, interruptible or time of use priced network access), or they may be continuous (e.g. contract duration).
Planning Dialogues	One of the two types of Enabling Platform, specifically for the purposes of enabling a group of Individual Actors to make collective decisions openly.
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.
Shared Ecosystem	The environment within which Individual Actors cooperate and/or compete. It is based on a set of fundamental principles and an open architecture; which manifest themselves tangibly in the form of Enabling Platforms with open governance. The Shared Ecosystem sets context for Individual Actors, and it adapts quickly in response to emergent innovation opportunities.
SSH	Smart Systems and Heat. A programme designed to tackle the holistic set of market failures inhibiting the UK from decarbonising heat.
Test Bed	Refers to a real-world instance of the Shared Ecosystem (including governance, rules, Enabling Platforms, etc) where multiple Individual Actors can trial new business models, processes and technologies. Other names may include: 'living labs', 'Energy Innovation Zones', 'New Energy Areas', etc.
User Stories	A systems engineering technical term which describes what a particular Actor would want, or need, to achieve within the system of systems with regard to their role in each Whole System Objective.
V Model	A key systems engineering concept, involving decomposition of a system of interest into individual blocks, with defined interfaces between them (including commercial, information and physical interfaces), from a high-level of conceptual abstraction through to levels of detail to implement.
Whole System Objective	Describes things that need to be achieved within the system of systems which require interaction between multiple Actors individual User Stories.

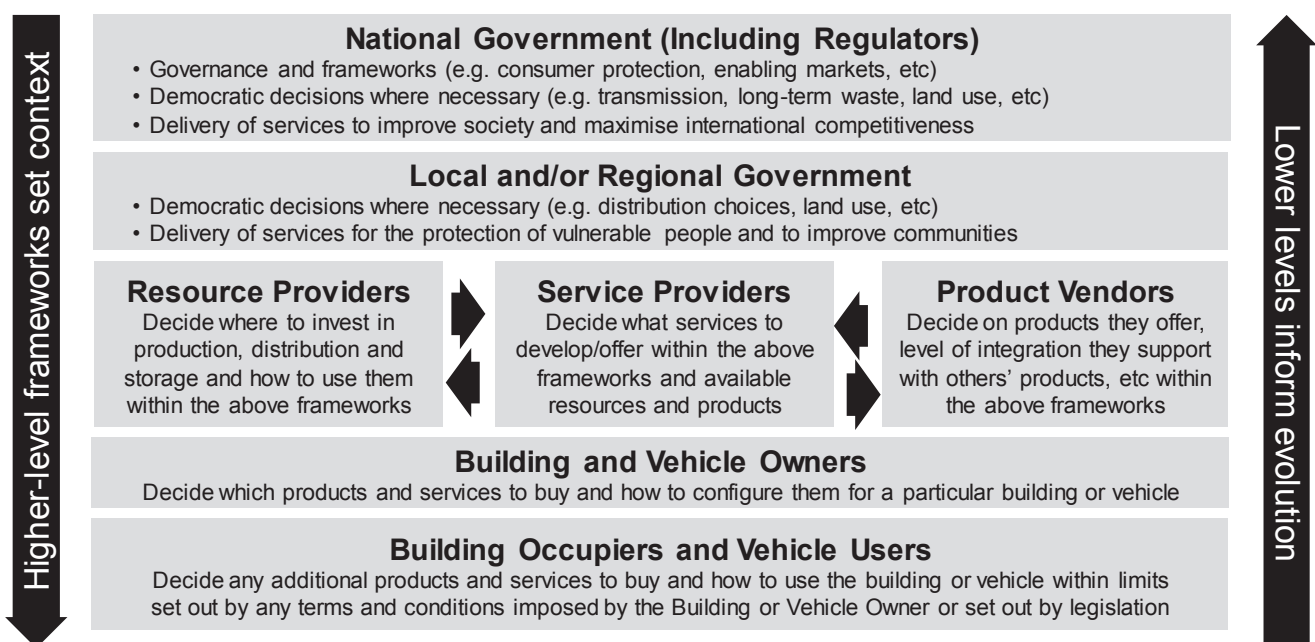
1. Introduction

Decarbonisation of the energy system requires that the world in 2050 will look radically different from today: from the places we source our energy; to the pipes and wires in the ground; and on to the way in which we power our industry, commerce, agriculture, home life and transport. The three decades until then sounds a long time, until we consider two things: first, the scale of the change and the pace we have achieved since the UK signed the Kyoto Protocol over twenty years ago; and second, the inter-dependence between the vast number of Individual Actors that need to be involved in the transition process as outlined below in Figure 1. As an example, we need to almost eliminate carbon from every single home at a pace of a million homes a year; but we are currently only achieving a pace of less than twenty thousand homes year.

There is a growing consensus on the types of component that will be required: wind turbines, combined heat and power, heat networks, upgraded electricity networks, repurposed gas

grids to carry hydrogen, heat storage, heat pumps, plug-in vehicles and so on. But there is no consensus on the combination of components, propositions or business models that might form the optimal energy system in 2050. Given how immature many of these are, it is inevitable a consensus won't be achieved in advance. Indeed, in other sectors that have seen radical transformations such as computing, the consensus often turns out to be wrong when we discover performance, costs and use cases vastly different to what was imagined. It is also very context specific, so will vary by customer, geography and time. In reality, it is far less an issue of 'picking the winners' and far more of an integration issue of ensuring the right package of things is brought together in the right place at the right time. To achieve this requires a much greater focus on customer service experience and supply chain optimisation, so Information and Computing Technology (ICT) is increasingly critical to enabling this as it has been in other sectors such as transport and healthcare.

Figure 1 Multiple actors with different motivations, relationships, data and levers of control will need to play different but interdependent roles



In the last quarter of the twentieth century, the UK's energy sector evolved to focus on driving cost out of business as usual operations. While this privatisation and unbundling has undoubtedly had many benefits, it has also created major systems integration gaps; key responsibilities that effectively fall between the Individual Actors. These gaps essentially leave Individual Actors across the energy system operating in silos. The transition to a low carbon energy system is increasingly stressing these traditional silos, as more distributed and renewable generation is adopted, heat and transport are electrified, hybrid products connect energy vectors together (liquid fuels, electricity, heat and gases) and advanced information systems enable entirely new types of business model.

Individual Actors across the energy system need to operate with an unprecedented agility to work constructively across these silos to achieve the radical overhaul of the energy system required by 2050. The environment within which the vast number of Individual Actors cooperate and/or compete across silos could be thought of as the Shared Ecosystem. System of Systems Architecture is a disciplined process that enables the full range of options to be created and evaluated for how this Shared Ecosystem could work in the future; without being constrained by thinking in terms of incremental adjustments to the status quo or needing to know in advance all the propositions, business models or technologies. The methods have their pedigree in enabling development of the world's most complex systems with highly emergent properties; properties that no one could anticipate in advance and yet turned out to be hugely beneficial. For example, the Global Positioning System has enabled a revolution in navigation, the Internet has enabled a revolution in global trade and social exchange, etc.

The purpose of Work Package 3 of the SSH Phase 1 programme is: to explore options for a future Shared Ecosystem; to create and test a workflow for gradually defining 'slices'¹ of it; and to build a first of a kind holistic simulation (EnergyPath Operations) to enable interactions of a diverse range of Individual Actors within different options for the Shared Ecosystem to be understood. It is explicitly not the objective of the work to promote one particular view of the future energy system architecture over another, but rather to provide a methodology by which stakeholders can engage in considering the options. There are two reasons why the work may be misinterpreted in this respect. First, to test the methodology from high level concept down to low level detail, it is necessary to choose an exemplar system architecture. Second, to develop a real-world test bed in which Individual Actors can explore value that could be unlocked through new ways of interacting with one another in a future Shared Ecosystem, it is necessary to choose a suitable architecture for that test bed; section 4.3 discusses how to minimise inherent inflexibility in this choice.

This paper presents the methodology and experience of its application in the work to date within the SSH Phase 1 programme to help share learning with stakeholders across the energy sector and beyond.

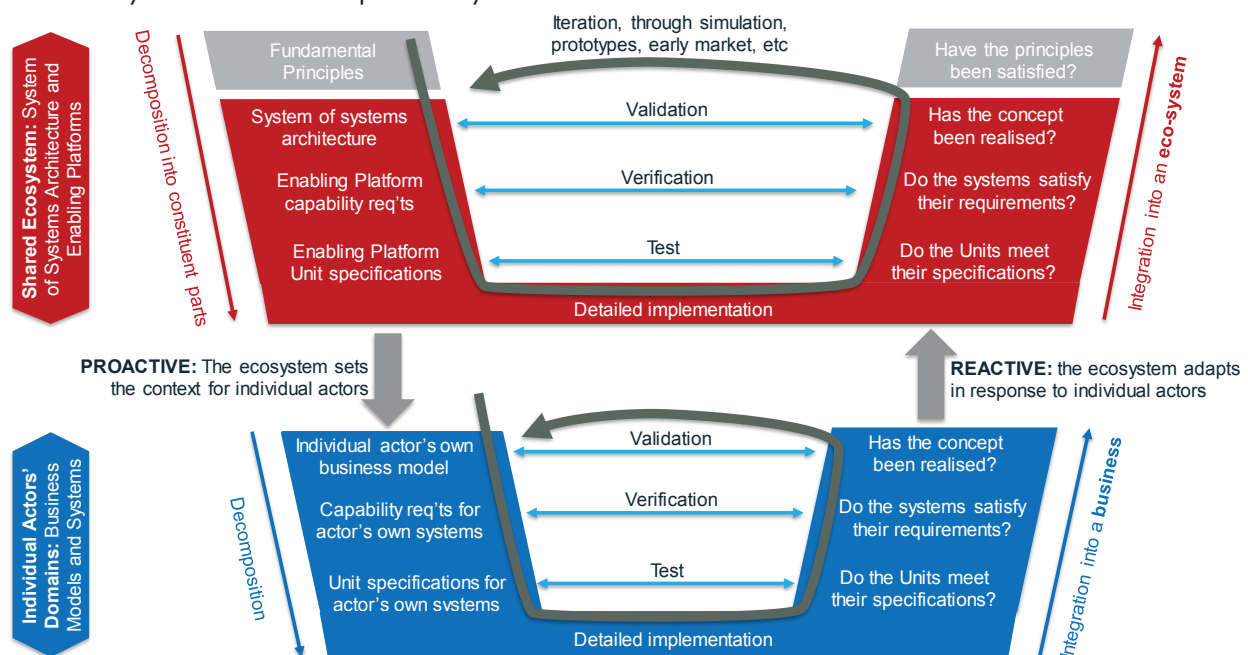
2. High-level Methodology

Standard systems engineering methods are being adapted from other sectors as required for this work. A key reference concept is the systems engineering 'V Model', as summarised in the diagram below in Figure 2. For this work specifically, the standard 'V Model' concept has been modified to separate the Shared Ecosystem (codified as red blocks throughout this paper), of which there is only one, from the Individual Actors' domains (codified as light blue blocks throughout this paper), of which there are many. The Shared Ecosystem is defined by fundamental principles and a system of systems architecture which describes how different actors are able to interact with one another. The Shared Ecosystem is made up of Enabling Platforms that enable the many-to-many interactions required between Individual Actors.

The Shared Ecosystem is proactive, in that it sets the context for Individual Actors' innovation domains; but it is also reactive in that it adapts and evolves in response to Individual Actors' innovations. One could think of it in some respects like the internet; it has an architecture which is defined at any given point in time but continues to evolve, and that architecture manifests itself through Enabling Platforms that are also defined at a specific point in time but continue to evolve. A system of systems architecture is never static; it is a continually evolving definition of how all the pieces interact with one another.

Abstraction is a critical concept in the systems engineering process, in order to manage the otherwise overwhelming complexity. Abstraction involves decomposing systems into blocks with

Figure 2 A key reference concept - the systems "V model"

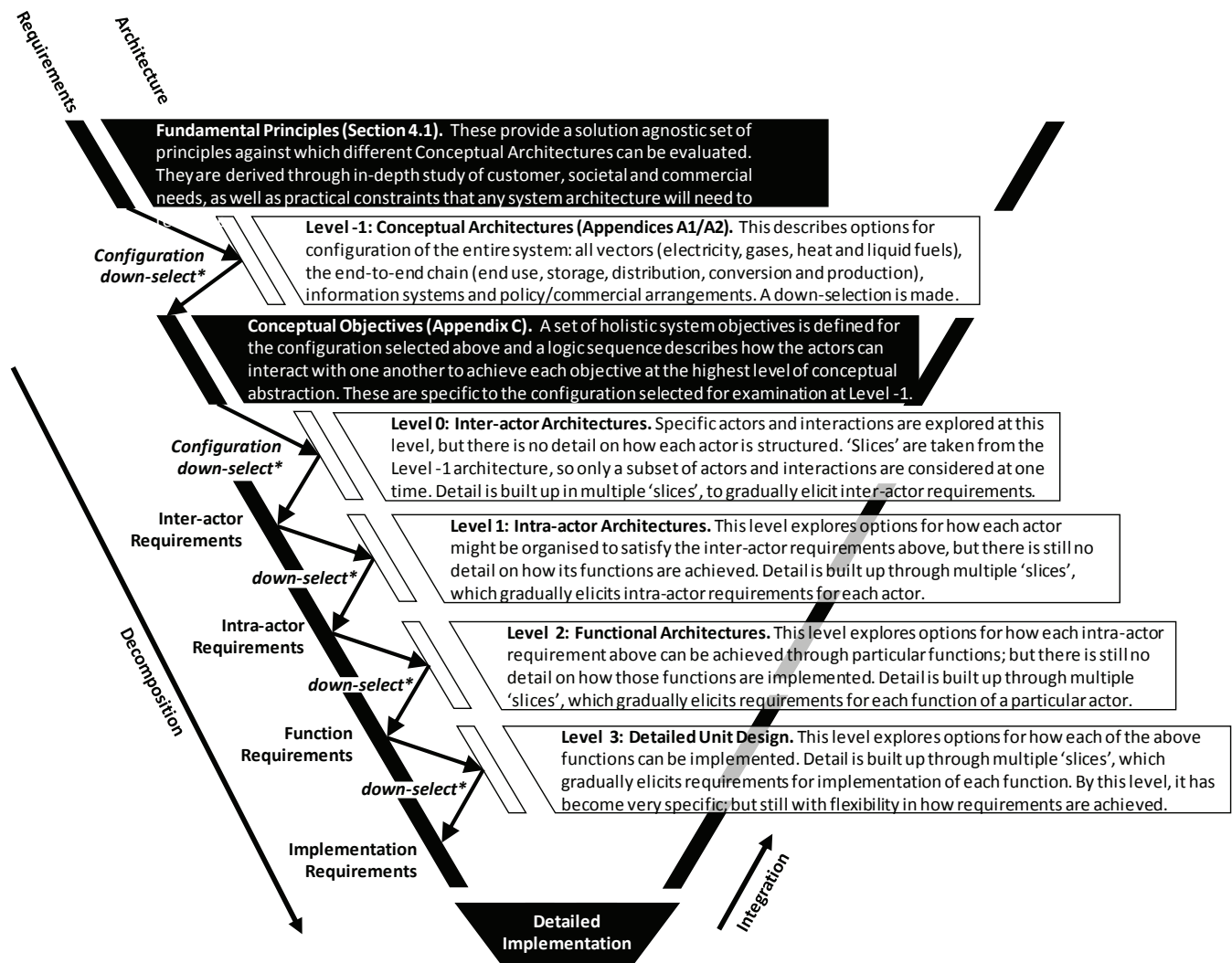


¹ Within the timeframe of SSH Phase 1, these 'slices' are those interactions relevant to gas/electric hybrid heat pumps. The workflow and the EnergyPath Operations tool are intended to be applied to other 'slices' in future ESC work.

defined interfaces between them at varying levels of conceptualisation. The interfaces describe the physical, information and commercial interactions. A key objective in the way in which a system is decomposed into blocks is to enable each block to be isolated with a clearly defined boundary so that block can be decomposed into the next level of detail independently of the other blocks; it is only at the very highest level of conceptual abstraction that the whole system is described. This is especially powerful for the definition of a Shared Ecosystem where it is impossible to know in advance all the things that Individual Actors might do within it. The specific levels of abstraction that have been adopted are summarised below in Figure 3.

A key objective in the way in which a system is structured into levels of conceptualisation is to enable options to be evaluated and down-selects to be made at each level and for each block; overall, thousands of options could be considered and it would be impossible to detail all of them. Traceability from the highest level of conceptualisation to the lowest level of specific implementation ensures that implications of decisions and changes can be worked through a whole system design. This approach enables a highly iterative design and development process, where risks in each down-select can be effectively managed.

Figure 3 Specific levels of abstraction adopted for energy systems architecture



* Down-selects are required at all levels given the vast number of options, so time can be focused on detailing only the most credible options. There are risks inherent in all down-selects, since they need to be made at a given level prior to details being created for the levels below. If these risks can't be closed-out, a return to an alternative option may be required. An example of the types of risks in the down-select at Level -1 is given in Appendix C. Traceability is critical to being able to revisit earlier levels and modify the architecture as required.

The blocks a system is decomposed into and the levels of conceptualisation also enable structured and focused stakeholder engagement: from strategic policy makers needing to take a whole system view at Level -1 and Level 0 but supported by insights from Level 1; to individual business strategists needing to develop plans for their domain(s) at Level 1 but supported by insights from the context at Level 0 and their business specific issues at Level 2; and on to designers of individual elements at Level 2 downward.

At Level -1 (Conceptual Architectures) and Level 0 (Inter-actor Architectures), a shared sector-wide view on a target architecture needs to be established; there can only be one target architecture at a given point in time, as it sets the context in which all the stakeholders create their own solutions. Of course, the more flexible the target architecture is at Level -1 and Level 0 – or, in other words, the more open it is to as yet unforeseen innovations – the easier it will be to achieve this through consensus. Nonetheless, it is quite plausible that any change to the existing architecture will be seen as potentially detrimental to the interests of one or more incumbent stakeholder; so a consensus might not be achievable. Hence, central government is likely to need to play an important leadership role in realising a shared sector-wide view; engaging all the stakeholders, but ultimately making decisions to provide clarity on the target architecture.

At Level 1 (Intra-actor Architectures), the distinction between the Shared Ecosystem and the Individual Actors becomes important as different approaches to their detailing at subsequent Levels is necessary. For the Enabling Platforms that make up the Shared Ecosystem, it is necessary that an open, transparent and engaging process is adopted. For the Individual Actors, they are free to innovate to the extent enabled by the Shared Ecosystem; and, of course, the different architectures explored at Level -1 and Level 0 have varying degrees of openness to enabling innovation. It can't be expected that Individual Actors, many of whom will be competitors in some way, will be willing to share the details of their future business model thinking in an open, transparent or engaging process. The structure above enables Individual Actors to develop the subsequent Levels independently of the process by which the Shared Ecosystem is developed.

However, since Individual Actors' business model innovations are inevitably interdependent with one another and with the Shared Ecosystem, it is necessary that they can test these interdependencies; first through a holistic system simulation, then through a real-world test bed and ultimately commercialisation.

3. Understanding Interdependencies

Section 1 set out the need for exploring radically different Shared Ecosystems to enable Individual Actors to work constructively across the silos. Section 2 set out the methodology by which radically different options relative to business as usual can be explored from the very highest level downwards. However, the implication of a different Shared Ecosystem is that Individual Actors can't simply extrapolate from business as usual data to understand how their new business models, processes and technologies might interact with one another in practice. For example, electricity networks are largely operated on a 'fit and forget' basis today; but if the network is actively managed it changes the interaction between network operator and retailer. In most investment contexts, any given Individual Actor can look at the world around them and make reasonable extrapolations from past trends to indicate how it might change in order to make their own choices with regard to future business models, processes and systems. That is simply not possible when the world around them is changing as much as it is. Holistic simulation is a very economical and low risk way to explore a large range of options.

EnergyPath Operations is a simulation capability being developed by the Energy Systems Catapult as part of the Smart Systems and Heat programme. It will enable different Shared Ecosystems to be codified into a simulation environment where a wide range of Individual

Actors can input a representation of their own business model, processes and systems in order to obtain insight on interaction with others. Of course, it is necessary that 'black box' models (compiled code that can't be reverse engineered) of the detail of Individual Actors' representations can be accepted into the process, to navigate the inevitable commercial complexities between competitors³. Matlab Simulink has been chosen as the core simulation engine for EnergyPath Operations, which is a standard tool used in other industry sectors for whole system simulation.

Test labs are also important to evaluating new technologies, control techniques and so on in a controlled environment that would present too much of a risk in a live system environment. Simulation, test labs and real-world test beds (as described in the next paragraph) can be combined to create a powerful means to evaluate overall integrated system performance at different scales. For example, data from real homes and consumers generated in a test bed could be combined with test lab data on the behaviour of a set of physical assets under particularly stressful design conditions; all integrated via whole system simulation.

However, simulation can only go so far; especially when factors such as human behaviour come into play, which is notoriously difficult to model with any degree of confidence. There is hence a need to establish a test bed² environment in

² 'Test Bed' refers to a real-world instance of the Shared Ecosystem (including governance, rules, Enabling Platforms, etc) where multiple Individual Actors can trial new business models, processes and technologies. Alternative names for the same principle include 'living lab', 'Energy Innovation Zones', 'New Energy Areas', 'Energy Zones', etc.

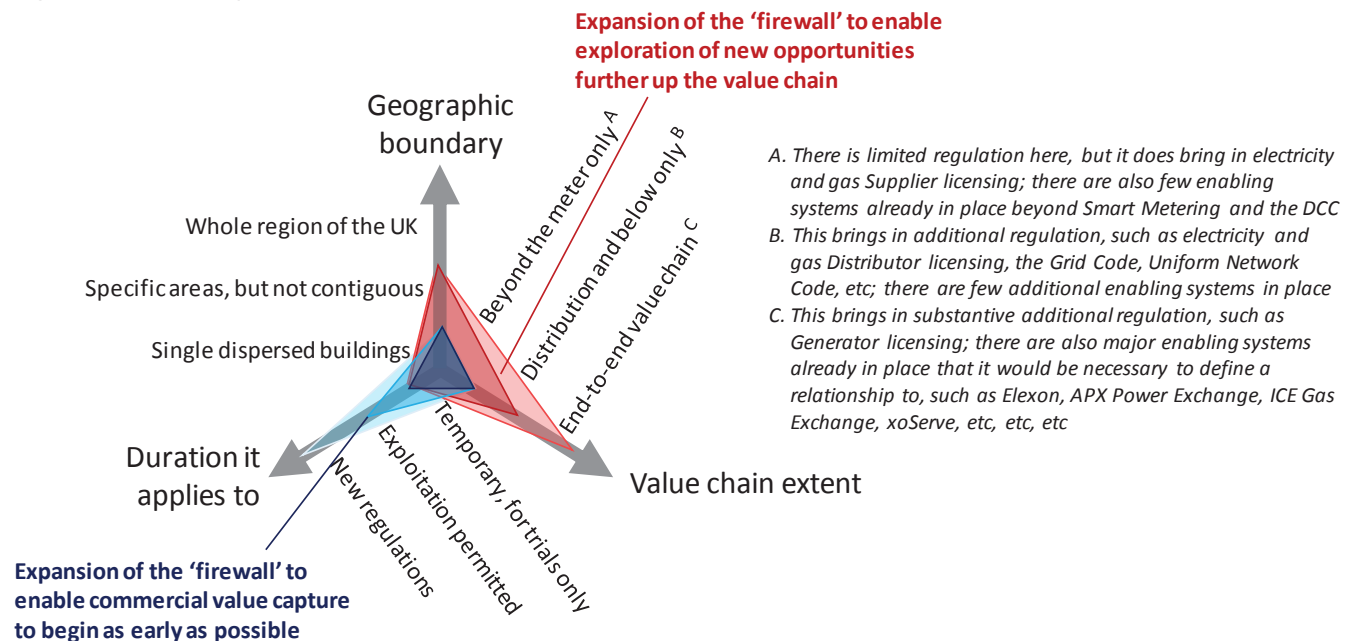
³ This technique is adopted in other industries, for example in aerospace where a systems integrator may be assembling a system from components supplied by multiple competitors; indeed, for systems integrators such as BAe Systems, the integrator is often a competing provider of components as well as the overall systems integrator.

which Individual Actors can try out new business models, processes and systems in a Shared Ecosystem that supports them. Major changes to the business as usual policies, regulations and rules are inherent in establishing the Shared Ecosystem in the real-world. Given this, the concept of a test bed with a 'firewall' around it is important. Essentially, the 'firewall' is drawing a specific boundary around the geography, value chain extent and duration a test bed applies to as outlined in Figure 4; and obtaining permissions from Government to establish a different set of policies, regulations and rules within that 'firewall'. The 'firewall' needs enforcing to ensure activities within are operated in a robust and scalable way; for example ensuring supply and demand are balanced, ensuring resilience to systemic failure modes such as cyber-security, etc. This enables a test bed⁴ to be created where many organisations can explore new value with one another.

The boundary of the 'firewall' can expand over time, and it does not necessarily need to be geographically contiguous or cover all elements

of the value chain at one time. This could mean that, initially, a 'firewall' is established around a geographically dispersed set of volunteering Homes and only covers the part of the value chain beyond the meter where there is currently limited energy specific policy and regulation that would require derogations. In this case, since individual Householders have volunteered, they are also free to leave at any time and return to the business as usual policy, regulation and rules arrangements. Depending on the attitude of policy makers, this could also mean that commercial innovators are able to gradually expand their opportunity space geographically and along the value chain over time at different speeds as opposed to needing to secure a top-down wholesale change of the policy, regulation and rule arrangements. This could enable virtually interconnected micro-grids to gradually emerge and expand in different non-contiguous locations over time, joined-up through use of the same Shared Ecosystem; hence enabling a phased approach to transforming the UK's energy system architecture.

Figure 4 Bounding a test bed with an expandable firewall



⁴ OfGEM initiated its sandbox in February 2017. It creates the opportunity to trial business propositions that will benefit consumers without incurring all the usual regulatory requirements. A test bed builds on this concept by creating an instance of a Shared Ecosystem that enables multiple Individual Actors to innovate within their own domain while also unlocking whole system value by interacting with one another through the Enabling Platforms.

4. Experience in Implementing the Methodology

4.1. Defining the Fundamental Principles

Early work was focused on building a deep internal knowledge base to adequately understand the problem space as a critical foundation. This included study of the physical dynamics of electricity, gas and heat systems; infrastructure planning policy and processes; carbon policy and investment dynamics; consumer service needs; information systems capabilities; etc.

A set of Fundamental Principles for the Future GB Energy System was created as a result of having built this deep internal knowledge base. The Future Power System Architecture (FPSA) project also identified 35 new 'functions' the Power sector needs to provide for in future, which were also accounted for during work on the SSH programme. The Fundamental Principles are solution agnostic and are used to evaluate different candidates at Level -1. Although they can be summarised, in reality they are a set of core concepts an architecture team needs to understand in considerable detail; and internalisation only really arises from practical experience, such as through hands-on development effort. In summary:

- **Commercially Aligned:** Ensuring actors optimise the whole value chain across all energy vectors
 - **Security and Resilience:** Ensuring the system is resilient to systemic failure modes
- Consumer-centric:** A future energy system must address the consumer's needs of energy, therefore have an insight into why they use the commodity and what is important to them, such as comfort and convenience. It must also provide freedom of supplier choice. This principle recognises that consumers have different needs from each other and that segmentation is therefore important. The current regulated system struggles with defining consumer needs, except in terms of cost and vulnerability; most consumers purchase on value, not cost. Aesthetics, responsiveness, hassle and personalisation are example factors.
- Societal Objective:** The system must have the capability to allow the energy system to evolve to meet the wider objectives of providing long term energy accessibility, energy security, energy equity and environmental sustainability. There are risks to vulnerable people in a transition, whether the barriers are economic, social or skills and confidence based. Energy availability to industry is also important.
- Physically Constrained:** It must account for the constraints on the system in terms of production, distribution and storage across all energy vectors. This includes accounting for not only current but emerging and potential future technologies, including increased distributed generation, intermittent generation from renewables, and the decarbonisation of transport and heat.
- **Consumer-centric:** Ensuring the whole energy system is focused on meeting consumer needs
 - **Societal Objectives:** Ensuring the system evolves affordably, equitably, securely and sustainably
 - **Physically Constrained:** Ensuring constraints are reconciled in strategic and operational timeframes

Excitement around individual technologies often drives early support and adoption, but there are physical (and therefore economic) realities about energy technologies. When they are combined in a system their impact is very often not what was expected during the period of early enthusiasm. Whole system analysis is an important tool in architecture design without which expensive mistakes are inevitable.

Commercially Aligned: It must seek to enable an actor with a particular business motive to acquire the required relationships, data and levers of control held by other actors; recognising that it is inevitable different actors will have different motivations and access to relationships, data and levers of control. This includes the life cycle cost and impact of any new potential technologies. Unless rewards, costs, risks and responsibilities can be aligned through value flow across the business system, then the actors will not behave individually or collectively in a way that delivers high performance at low cost. Also, there are likely to be hidden costs and risks which will end up being borne by some combination of taxpayers and consumers. Systemic failure is a real risk for an energy system as much as for a banking system. This is especially true during a major transition, such as the energy system now faces.

Security and Resilience: It must ensure the system is resilient to systemic failure modes. The system should provide 'stable control', such that the occurrence and impact of any major outages (to all actors) are minimised. Good architecture provides security at three levels – operational, investment environment and strategic direction. Although a good architecture is required, it is only the foundation from which security can be delivered.

4.2. Exploring Options and making a Down-selection at Level -1: Conceptual Architectures

To explore a diverse range of options at the highest level of conceptual abstraction, four dimensions of difference were defined with a specific set of levels for each dimension. Combining these dimensions and their various levels enables a multitude of different options to be identified at the highest level of conceptual abstraction: the Level -1 Conceptual Architectures. Twelve different options⁵ are set out in Appendix A1, together with a discussion that explores the advantages and disadvantages of each of them; and an initial evaluation is set out in Appendix A2 that enables a preliminary down-select to a specific candidate for further detailing. The four dimensions and the key issues are summarised below.

The exploration of fundamentally different architectures introduces a wide range of new concepts, actors, roles and responsibilities. Many of these are not easy to describe and reference analogies only extend so far before they become unhelpful. Furthermore, each actor needs to build their understanding of issues in adjacent domains; issues they have historically had little need to investigate, such as electric vehicle impacts on electricity retailers. Building a shared language for new concepts, actors, roles and responsibilities is critical to an effective dialogue. In some cases the challenge is confounded by similar existing concepts or terminology that leads to confusion, such as the term Distribution System Operator.

Dimension 1) Level of value chain bundling:

Articulates how much of the value chain is incorporated into single entities, ranging from a state licensed monopoly to full unbundling of production through to retail.

There are considerable benefits in ensuring optimal decision making by devolving decisions to the Individual Actor closest to the relevant details,

⁵ There are significantly fewer options described in Appendix B1 than the potential permutations of the dimensions of difference and their levels because of interrelationships between the dimensions. For example, the level of sophistication in dimensions (2) and (3) directly affects the level of sophistication achievable in dimension (4).

to ensure the right package of things is brought together in the right place at the right time; navigating uncertainty, innovation and supply chain investment.

There are further value optimisation benefits in unbundling the whole end-to-end value chain: production, conversion, distribution, storage and retail. The benefits arise from the competitive driver to increase profitability, since unbundling enables increased specialisation and proximity to the important details to identify complex performance improvement and cost reduction opportunities; alongside more sharply focused business objectives for each part of the value chain. However, system benefits are easily lost through unbundling if transaction costs between many-to-many Individual Actors are too high and/or there is not traceability to the acts or omissions of specific actors. 'Gateways' are a specific type of Enabling Platform within the Shared Ecosystem to enable these many-to-many commercial value chains to form; they are intermediary business models that enable Service Level Agreements to be agreed and delivered between two parties with confidence even though they may never actually meet one another.

The choice on whether retail is bundled with networks is critical, since system metrics such as frequency, pressure, voltage, etc are emergent properties of the overall system and not the acts or omissions of any specific actor; in other words, these metrics can't achieve traceability to a specific retailer. In this case, metering at individual building level becomes critical to the value chain functioning; and meter data must be aggregated independently of any Individual Actor to verify compliance with Service Level Agreements.

If the competitive driver can't be unlocked for all or part of the value chain, effective democratic process becomes essential as the primary driver of value optimisation. In all options, there are certain elements of the value chain where this is almost inevitable; for example, due to the natural monopoly inherent in distribution networks. 'Planning Dialogues' are another specific type of Enabling Platform within the Shared Ecosystem to enable open, transparent and engaging processes of democratic decision making.

Dimension 2) How interfaces between upstream and downstream actors are formed: Articulates how downstream actors procure upstream resources; and correspondingly how upstream constraints transfer to downstream actors. It ranges from simple regulator mandates, through commodity trading and central buyer arrangements to sophisticated Service Level Agreements.

In all configurations with some degree of value chain unbundling, the price, and forecast expectations of price, for a defined product or service provides the critical information on which Individual Actors can make choices in both strategic and operational timeframes. Products and services can be defined in different ways, which affects the value of the associated price information. For example, electricity may be conceptualised as a commodity product, defined as a unit of energy at a particular point in time and space entirely independent of its means of production. While this works well for most commodity products, electricity has the unique property that it can't be stored in a sufficient volume for a sufficient length of time to decouple the unit of energy from the physical characteristics of its means of production; whereas a litre of diesel, for example, needs no information about the wells, tankers, refineries or pipes involved in its production and distribution. Alternatively, one could conceptualise electricity as a resource service, defined by a Service Level Agreement that articulates key performance attributes of the service (ramp-up/-down rate, lead time to standby, etc) and fee structure (standing payment for the right to capacity, payments for putting the resource into standby, payments for producing output, etc).

If the product or service is defined incorrectly, price signals can easily become ineffective requiring state intervention to mitigate the issues. Continuing the electricity example, it is currently conceptualised as a commodity product. However, as electricity production requires a surplus of capacity for the purposes of system resilience, the price for a unit of commodity trends toward the marginal cost of production. This inhibits capital cost recovery and necessitates the regulatory interventions we see in electricity

markets around the world today. The mitigating actions can become especially challenging to implement where there are a combination of low marginal cost and high marginal cost resources, which can lead to highly volatile spot markets as we see in Germany today, for example, where prices can oscillate between strongly positive to strongly negative every thirty minutes through a day as market responses over- or under-shoot.

Service Level Agreements are a key concept to support value chain unbundling. Standard service attributes and performance levels for each attribute provide consistent commercial terminology to reduce transaction costs between many-to-many Individual Actors. Furthermore, standard classes of Service Level Agreement with particular configurations of performance levels for each relevant service attribute further reduce transaction cost by creating standard definitions that can be more easily valued and traded. For example, an SLA for an electricity production service would include service attributes such as ramp-up rate and the buyer and seller would agree the service levels for each of the attributes; with higher service levels attracting higher prices, which reveals the value of particular attributes to drive decision making in asset investment time horizons. Different resource providers will adopt different strategies for meeting an SLA, such as combining wind turbines, batteries and gas generation; in other words, the SLA is abstracted from the specific details of a particular physical asset. The service can then be used within the terms of the Service Level Agreement, embedding constraints such as capacity, to drive decision making in operational time horizons.

It is essential that all Individual Actors in a value chain generate enough of a financial return to have the incentive to act. For example, an electricity distributor may have a strong incentive to avoid capital investment in upgrading a network through active demand management but, assuming retail is unbundled from distribution, does not have any direct consumer relationships; and the retailer does not own all the devices from different vendors within the consumers' premises either, where warranty liabilities and other issues may be incurred. Consequently, for all the required actors to have

an incentive to act, the distributor, retailer and device vendors must all make their own financial returns.

Dimension 3) Level of sophistication in the retail proposition: Articulates how consumer service terms are defined between consumers and supply chain, from simple commodity retail to complex services.

Consumers' needs and preferences vary enormously, as do the conditions and constraints of their homes and businesses. Decarbonisation requires the ability to ensure the right package of things is brought together in the right place at the right time. In configurations limited to commodity retail, it is very difficult to see how consumers' preferences are revealed or how anyone helps them navigate the conditions and constraints of their home or business. By way of analogy, in broadband telecoms multiple service levels have been offered to consumers at different prices and, to a first approximation, it has been discovered that the majority of people are willing and able to pay to ensure the network works 'on-demand' at their convenience.

Further, in order to create flexibility in the way in which energy delivery is managed to meet consumer service expectations, it is essential that an envelope of operation can be articulated between consumer and retailer. Simple on-/off-peak tariff arrangements in future systems with high electrification of heat and high proportions of renewable generation are not suitable since the time windows where supply vs. demand is constrained do not occur on any regular cycle; and complex dynamic tariffs don't give consumers clarity.

Moreover, vulnerable consumers are a special segment where the social safety net provided by the state is important to ensure people are treated in an equitable manner. For this segment, there are options for the state to procure services on their behalf; for example using data to target, tailor and improve solutions for tackling inequity. However, to unlock such opportunities requires that both policies and business models transition in parallel; businesses won't introduce services reliant on different government policy arrangements, and policy makers won't introduce

policies predicated on unproven service solutions.

Dimension 4) Means of internalising carbon cost: Articulates how carbon cost is internalised, ranging from simple carbon subsidy or taxation through to technology-agnostic outcome based carbon constraints.

One approach to internalising carbon cost is to do so in as technology agnostic a way as possible, to enable Individual Actors to make their own choices to navigate uncertainty, innovation and supply chain investment. This has the advantage that Individual Actors can use their proximity to the important details to invest in long-term innovation and supply chain investment to navigate the uncertainties. It has the disadvantage that there is no central authority that can provide certainty – even if it is false certainty – exactly what technologies are going to be deployed where and when over the period to 2050.

The options within this dimension are dependent on the level of sophistication in the other dimensions. For example, in the electricity and gas market today, the retail proposition is limited to commodity metering; hence, there is no party providing overall integration services to assemble the supply chain to ensure consumer service outcomes are delivered and so policy makers are left with little option but to implement technology specific component subsidies or taxes. In configurations with an integrator role, be that a Regional Energy Services Company where distribution and retail are bundled or competing Energy Services Providers, policy makers have options for outcome based carbon policies that devolve navigation of uncertainty, innovation and supply chain investment.

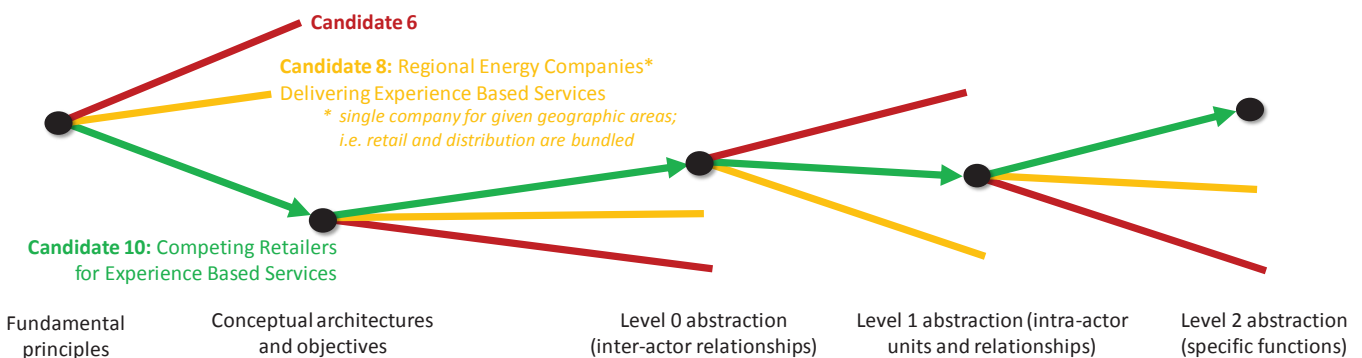
4.3. Evaluating the Risks in the Down-select at Level -1 and Planning Risk Reduction

As illustrated in Figure 5 below, there are many different architectures that could be adopted. However, it would be impractical to detail all of them. Hence, it is necessary that down-selections are made at each level of abstraction based on the available information. Inevitably, this means there are risks inherent in these necessary down-selections that need managing carefully. A structured architecture process enables earlier decisions to be revisited later and the implications of change worked through.

The four dimensions described in the preceding section are ordered in terms of level of sophistication and, to a first approximation, it would generally be possible for a more sophisticated architecture to be capable of supporting a lower level with limited adaptation, but a higher level would require major overhaul.

For early innovation, it is prudent to create a test bed with a sophisticated architecture for the Shared Ecosystem implemented through prototypes of the Enabling Platforms. The sophistication can be reduced over time as and where appropriate, but it will enable Individual Actors to discover through developments and demonstrations where the real value, issues, etc are. A test bed with a less sophisticated architecture is inevitably less amenable to facilitating very open innovation. At the initial stage of establishing a test bed there is high flexibility, but as organisations begin to develop their own business models, processes and

Figure 5 There are many down-selects to be made at each level of abstraction



systems within that test bed a less sophisticated architecture inevitably becomes increasingly inflexible. For example, an architecture based on services retail being unbundled from distribution (Candidate 10) would be amenable to being re-bundled (the next best option from initial evaluation, Candidate 8); but not architecting for unbundling would create inflexibility due to the consequent choices of Individual Actors.

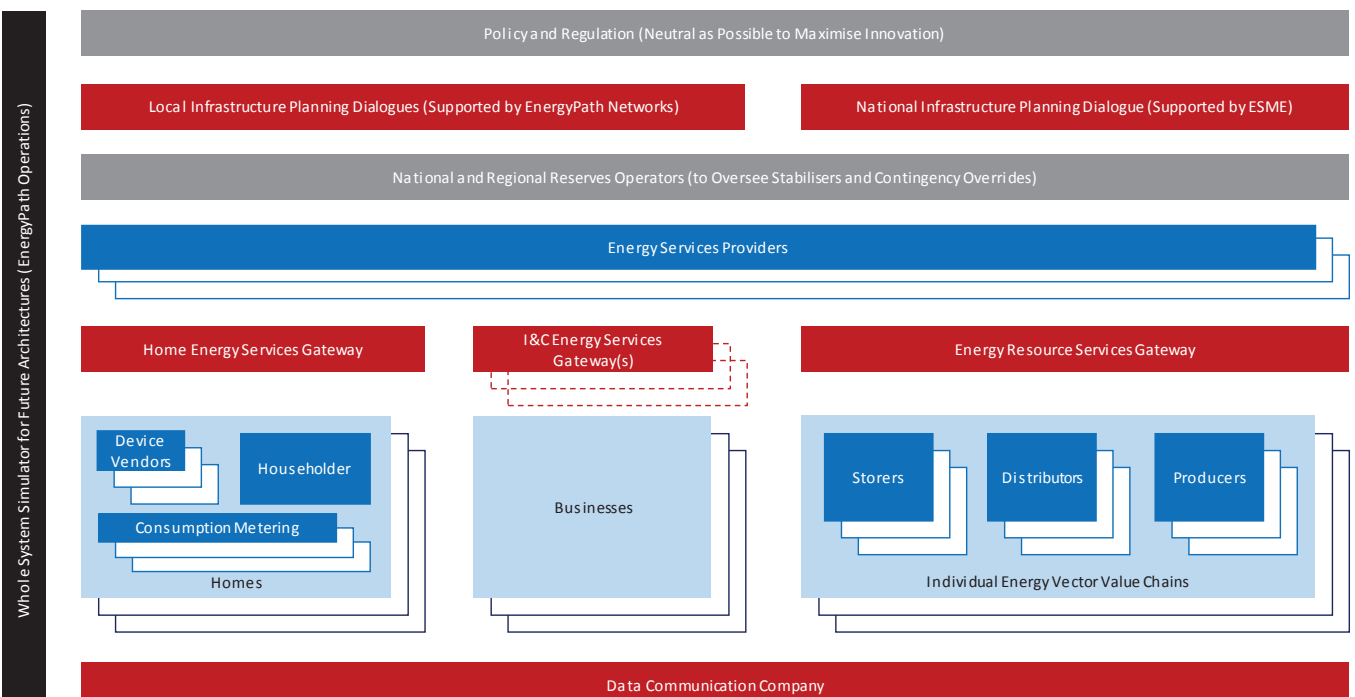
There are risks at each down-select at each level of abstraction and these risks need to be systematically identified and risk reduction actions undertaken. By way of example, as illustrated in Appendix C, the ability of competing Energy Services Providers to price in risks related to the cost to serve a particular customer is a significant risk inherent in Candidate 10 with two key elements: (1) the ability to understand, shape and bound customer service expectations; and (2) the resources required to meet those expectations. This requires real-world trials to understand the risk, and preparedness of fall-backs in the event the risk cannot be closed out successfully; in this case, the fall-back is to bundle distribution and retail such that risk can be spread across all consumers in a given geography and hence avoid self-selection of particular retailers by more or less risky consumer segments (Candidate 8). It is a legitimate choice, however,

to nonetheless maximise future optionality and flexibility by still adopting and scaling-up the more sophisticated architecture; the potential downside being aspects that may add costs without direct benefits if those aspects are not actually exploited at that point in time.

4.4. Describing the Down-selected Candidate at Level -1: Conceptual Objectives

Appendix D provides a more detailed description of all the actors within Candidate 10 at Level -1, which is summarised in Figure 6. A worked example is at the end of this section on how they interact with one another in support of one actor's very specific business objective: reducing or delaying capital investment in electricity distribution networks. In summary, the Shared Ecosystem is comprised of two different types of Enabling Platform. The first, Planning Dialogues, enable collective decision making for decisions where competitive market forces are unlikely to play out to any form of effective decision due to natural monopolies; for example, local area network planning. It is critical that these are sponsored by an entity with a democratic mandate to make collective decisions on behalf of end consumers; which means local, regional or national government. It is also critical that

Figure 6 Level -1 overview of candidate 10 architecture



the whole process is engaging, transparent and objective to build and maintain trust. The second, Gateways, enable multiple Individual Actors to form commercial value chains where competitive market forces can play out to reach effective decisions that government can hence be largely agnostic about; for example, multiple electricity network operators trading network capacity with multiple Energy Services Providers trading demand flexibility. A Data Communications Company is required to aggregate data from Consumption Meters in order for the Gateways to verify Service Level Agreement usage and compliance. National and Regional Reserves Providers ensure stabiliser mechanisms (for example avoiding sharp control changes in aggregate supply or demand) and special contingency overrides (for example in the event of cyber-security attacks that exploit supply and/or demand controls in hostile ways to destabilise the system) are implemented to ensure supply vs demand is continuously matched. Policy & Regulation ensures consumers are protected, carbon is internalised, etc.

Appendix B provides a set of logic sequences that describe how these actors interact with one another at the highest level of conceptual abstraction to meet holistic system objectives. It also provides a set of Architectural User Stories, which breaks down each holistic system objective into the specific roles of specific actors. The holistic system objectives at the highest level of conceptual abstraction are:

1. **Householders finding energy services.**

In Candidate 10, retail is unbundled from distribution. Any Householder or Business will want to be able to find an energy service from any Energy Services Provider. This will require a shared language of service outcomes between buyers and sellers (analogous to how AirBnB has formed a sophisticated language to align expectations) and open data structures so consumers are free to decide who to share their data with so they can price risk.

2. **Executing domestic energy services.**

Any Household or Business will want to be able to buy energy services from any Provider, so it will be necessary that any Provider can acquire data and request control for any device from

any Device Vendor within premises. This implies a need to enable value flow between Services Providers and Device Vendors who may never meet, to create a commercial driver for integration. Standard device class Service Level Agreements defining device performance, how it may be used and the fees payable can enable such value flow at low transaction cost. Governance to modify, add or retire device classes is important to ensuring the system can evolve.

3. Householders raising service complaints. In the first instance, a Services Provider should have chance to remedy any issues. However, to build trust, the Enabling Platforms need to provide arbitration and, ultimately, underwrite losses between two parties that may never meet. Transparent feedback creates the incentive for all parties to behave, provided that there is a shared language (as per Objective 1); without which, buyers risk poor performance and sellers risk bad reviews. This is analogous to internet based retail platforms such as AirBnB, eBay, Alibaba, etc.

4. **Building up the energy resources supply chain.**

In order that the Services Providers can genuinely differentiate their services, they need free choice over how to assemble their supply chain. Standard service attributes and performance levels for each attribute can reduce transaction costs. Further, standard resource class Service Level Agreements, with particular combinations of performance levels for each service attribute, could maximise tradability. Governance to modify, add or retire resource classes is important to ensure the system can evolve

5. Closing out supply-demand. Objective 1 involves Services Providers agreeing a service envelope with Householders and Businesses. Objective 4 involves Services Providers acquiring the right to use a certain amount of a Resource Providers' capacity under defined conditions/constraints. In combination, these define the flexibility and constraints within which a Services Provider can operate. It is then necessary that the Services Provider can gather data, issue control requests and receive confirmations to ensure their supply vs. demand position is continually balanced.

6. Stabiliser mechanisms and special contingency overrides. Given the number of different parties actively involved in managing supply and/or demand, systemic stabilising mechanisms and special contingency measures for major systemic threats need to be built-in. Failure Mode Effects Analysis is required to plan for the range of issues that may occur through misaligned commercial motives (such as a Services Provider using demand controls to fix imbalance positions at short notice, causing sharp changes in demand), accident (such as failure of a computing system) or malicious act (such as hacking of demand control systems to cause sharp changes in supply or demand).

7. Internalisation of carbon costs. The way in which carbon costs are internalised into Individual Actors' businesses has a profound effect on their incentive to invest for the long-term in innovation and supply chain development for decarbonisation. The existence of Energy Services Providers as a point of integration between consumer service expectations and supply chain challenges creates the option for technology agnostic policies that focus on the desired outcomes rather than how those outcomes are achieved. However, there is no perfect policy as real-

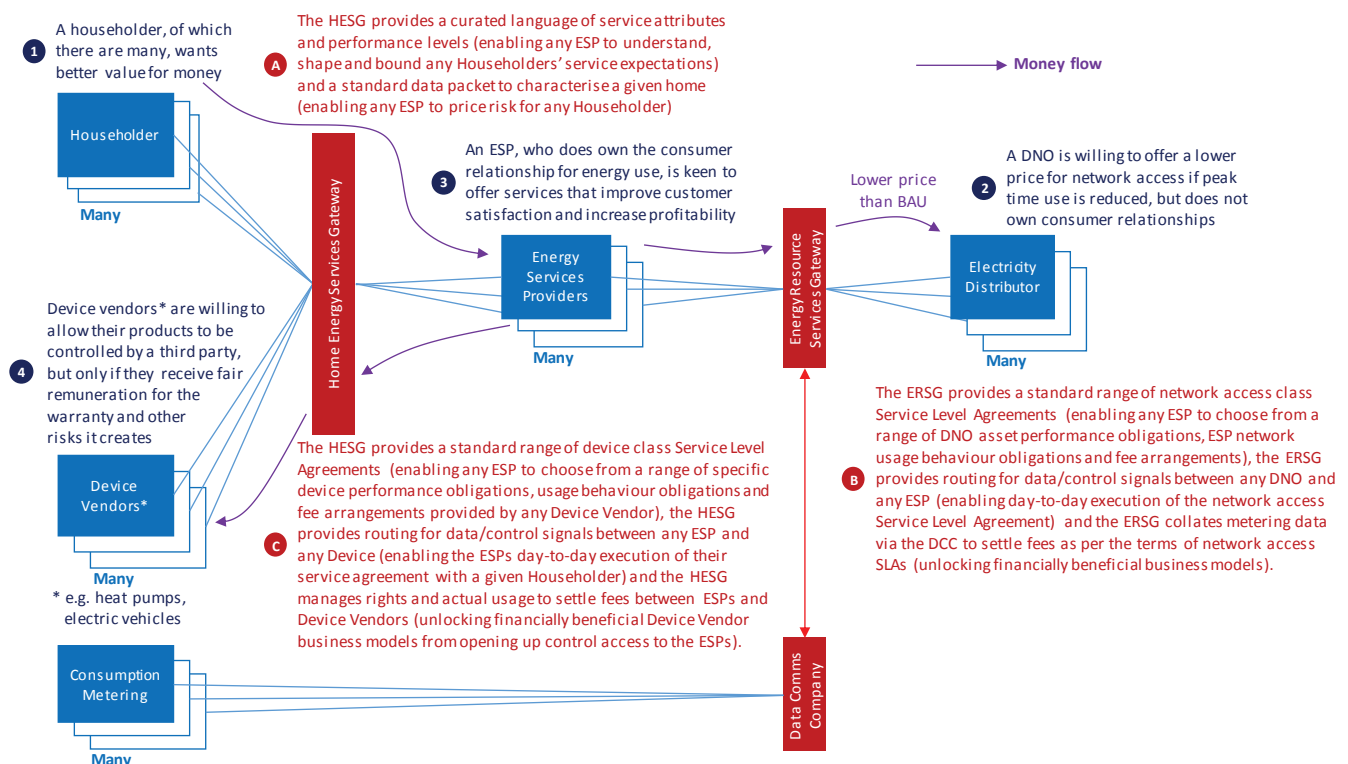
world measurement issues, split incentives between actors, etc create inevitable real-world compromises.

8. Regulatory oversight of market effectiveness. In a world where buyers and sellers provide open feedback on one another to create the incentive for Individual Actors to behave and intermediary Enabling Platforms provide arbitration and risk underwriting, new regulatory approaches are required. Learning can be brought from other domains, such as eBay, Alibaba, Uber, AirBnB, etc.

4.5. End-to-end Worked Example: Avoiding or delaying network reinforcement costs

Multiple electricity distribution network operators are already doing demonstrations of the potential for avoiding or delaying network reinforcement costs through active demand management. However, they don't currently have direct customer relationships (unless UK policy makers choose to bundle retail back together with distribution, which is considered in the candidate architectures defined and evaluated in Appendices A1 and A2). This unbundling of distribution and retail is an inherent feature of

Figure 7 Worked example - avoiding or delaying network reinforcement costs



Candidate 10. Given this, in order to bring it to market, they would need to play into a value chain comprised of many Householders => many Energy Services Providers => many Device Vendors + many electricity Distributors, as outlined in Figure 7.

As this fairly simple example shows, there are multiple new economic opportunities created by enabling value flow between an actor with a particular objective and the actors with the required relationships, data and levers of control to achieve it. Householders benefit from an increased focus on their service expectations and reduced service costs. Energy Service Providers benefit from greater competitiveness and increased margin per customer. Distribution Network Operators benefit from avoided capital investment to meet regulatory obligations. Device Vendors benefit from a new revenue stream by enabling demand management. The UK economy, and hence political process, benefits from greater productivity.

This fairly simple example also starts to illustrate how the Enabling Platforms can be set up not only to adapt and evolve as new economic opportunities emerge but also to stimulate innovation. By providing consistent terminology understood by both buyers and sellers, sophisticated service propositions can be constructed and valued. For example, a shared language to articulate domestic heat service outcomes enables Energy Services Providers to construct propositions using a set of service attributes, such as 'time to warm on demand', and performance levels for each attribute. Householders will decide which proposition they value most, which over time will reveal market preferences and willingness to pay. This building block of consistent terminology establishes a significant degree of inherent extensibility.

Going beyond the building block of consistent terminology, formulating standard classes of Service Level Agreement further reduces transaction costs and increases tradability. This is especially important where a high volume of low value transactions is required; such as control of individual electric vehicle recharging. Governance is of course required to enable adding, modifying or retiring of the standard classes. If, for example,

a Device Vendor believes that it can provide a better way of managing part of energy service delivery then it has two options to bring this into play via the Home Energy Services Gateway. The first to instigate a change management process for an existing device class Service Level Agreement, which is appropriate if enough of the other actors see a sufficiently similar opportunity; the second to instigate a process to create a new class definition, which is appropriate if other actors wish to retain the old class definition, perhaps to help manage transition periods. The judges of whether this is a good or bad evolution are then the Energy Service Providers, who choose whether to use that device class, and the Householders, who choose whether they value the 'improved' service enabled by that device class. Over time, a device class may cease to be used, so a process is required to review and retire classes.

For higher value, lower volume transactions, such as those associated with the Energy Resource Services Gateway, the transaction cost is of less concern and so there are two options for bringing a better offering into play: using the individual service attributes and performance levels to construct a bespoke Service Level Agreement; or initiating a similar governance process to add or modify a standard class. The advantage of the latter approach being increased tradability of the SLA, but this might not be appropriate at the initial introduction of a new offering.

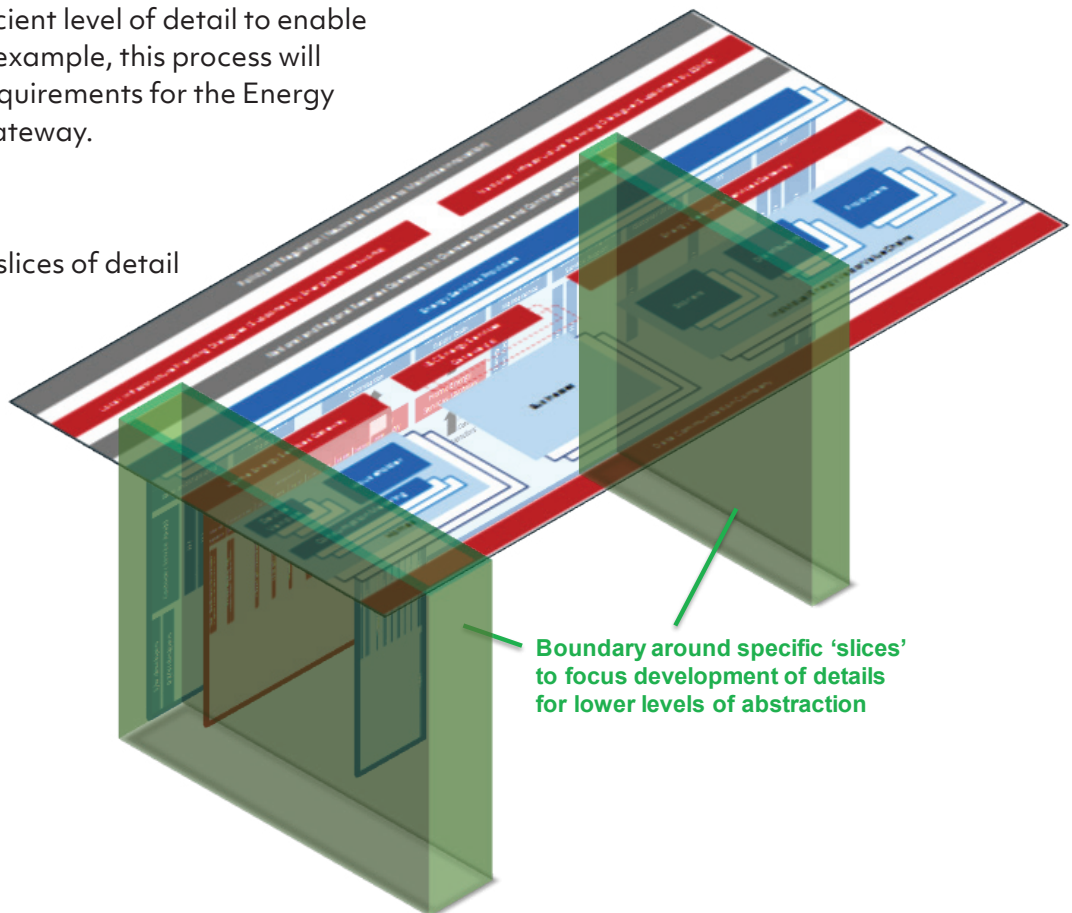
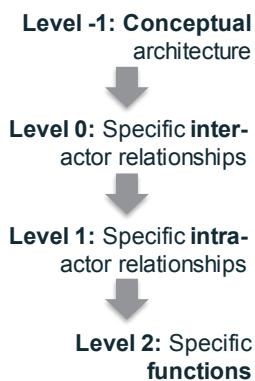
While the example presented only shows electricity distribution, the same concept of standard resource class Service Level Agreements applies to production and storage as well; and across all energy vectors. For example, a standard electricity production resource SLA would reflect ramp-up rate, forecast horizon, etc; the Resource Provider would supply availability forecast data (such as due to wind conditions) to the Energy Services Provider(s); and the Energy Services Provider(s) would optimise their demand (via the HESG) and alternative resource provision (via the ERSG).

4.6. Developing Further 'slices' of Detail

Before proceeding into the more specific levels of abstraction, it is necessary to draw a boundary around the particular 'slices' that are to be explored. The boundary enables the architecture to be built-up gradually over time. Ongoing work is developing further details for 'slices' relating to the mass scale introduction of hybrid heat pumps; subsequent work could focus on 'slices' relating to electric vehicles, for example. As these 'slices' are built up, they elicit requirements for each entity at a sufficient level of detail to enable implementation; for example, this process will gradually build up requirements for the Energy Resource Services Gateway.

As illustrated in the systems V Model on page 2, once sufficient definition is achieved it would be expected that the first design iterations are achieved through simulation of the end-to-end value chains using EnergyPath Operations; and, once sufficient confidence is built through simulation, prototypes and a test bed.

Figure 8 Developing slices of detail



5. Conclusion

The structured system of systems architecture methods that have unlocked significant value in other sectors can be applied equally within the energy sector.

However, the nature of the energy sector requires architectural thinking in terms of commercial market structures, information infrastructures and physical interfaces to be combined in a way that is not necessary in other sectors. Crucially, there is no single authority for the energy system and so it is important to use the methods to help the sector define interfaces and establish value flow mechanisms that enable an actor with a business motive to acquire the required relationships, data and levers of control held by other actors; rather than to use the methods in the way a central planner might.

Applied thoughtfully, a system of systems architecture methodology can:

- Stimulate innovation and long-term supply chain investment, enabling highly emergent benefits to be discovered over time that, as has happened elsewhere, often cannot be foreseen;
- Combine the power of market based decision making where appropriate by reducing transaction costs between actors, and the necessity of democratic decision making focused where needed; and
- Enable responsibilities for societal objectives, such as decarbonisation, to be devolved to the actors best placed to use their proximity to the important details to navigate the complexities and risks.

Furthermore, both digitisation and decarbonisation are leading to:

- Fundamental changes in the way energy is produced and used as heat and mobility are decarbonised, making customer-side and resource-side decisions increasingly interdependent;

- Significantly greater interconnectedness between energy vectors, due to hybrid products such as hybrid heating systems and plug-in hybrid electric vehicles connecting energy vectors together;
- New business models bringing the customer experience and distributed energy resources behind the meter into much sharper focus, enabled by the emergence of the Internet of Things; and
- An increasingly closed-loop between the dynamics of the resource-side, which is becoming increasingly variable due to renewable energy production, and the customer-side, which is becoming increasingly open to active management due to the emergence of advanced ICT.

A system of systems architecture methodology enables consideration and evaluation of entirely new organisational arrangements relative to one another; as opposed to being limited to thinking in terms of incremental adjustments to business as usual arrangements. In so doing, it becomes apparent that both digitisation and decarbonisation are highly likely to cause significant friction within the current arrangements; which were primarily designed to drive cost efficiency within individual silos rather than to enable multiple actors to work across silos to achieve a radical overhaul of the entire energy system. Alternatives may well bring sufficiently substantive benefits to warrant tackling the challenges of realising a new set of arrangements.

But it is not sufficient to be able to consider and evaluate alternative arrangements. The implication of both digitisation and decarbonisation is that a vast array of Individual Actors will develop new business models, processes, systems, products and services; and increased clarity on the Shared Ecosystem

within which they may be operating in future will significantly reduce their risk exposure. Whole system simulation and a real-world test bed are critical to enabling organisations to rapidly develop and evolve their solutions.

This first report has only set out the work at the highest level of conceptual abstraction. Ongoing work is firstly developing the details for the subsequent levels of abstraction for a set of 'slices' of one of the candidate architectures; and secondly working to establish a whole system simulation capability, EnergyPath Operations. In addition, the Catapult is working to establish a test bed to support innovators.

Appendix A1: Candidate System of Systems Architectures

This section sets out twelve candidate system of systems architectures for the Future GB energy system. The major differences between concepts are summarised into four dimensions to aid comparison. These are not dimensions of evaluation (which are the five principles set out in section 4.1). The four dimensions are ordered in terms of level of sophistication and, to a first approximation, it would generally be possible for a more sophisticated architecture to be capable of supporting a lower level with limited adaptation, but a higher level would require major overhaul (as indicated by shading in the diagrams below). Consequently, for the Catapult, it is prudent to consider a sophisticated architecture for the purposes of enabling sector-wide innovation through developments and demonstrations that can help the sector to reveal the value (or otherwise) prior to scaling anything up; it can always be reduced later in the areas of low value or high risk.

A. Level of value chain bundling.

This dimension articulates how much of the value chain is incorporated into single entities. The scale is from:

- A single organisation with full responsibility for production through to retail (similar to the current arrangements for electricity in France); to
- Regional downstream monopolies with upstream competition (similar to the current arrangements for electricity in Germany); and on to
- A fully unbundled value chain where production, transmission, distribution, storage and retail are explicitly separated (similar to the current UK arrangements).

B. How interfaces between upstream and downstream actors are formed.

This dimension articulates how downstream actors procure upstream resources; and correspondingly how upstream constraints

transfer to downstream actors to operate within. The scale is from:

- Regulator mandates specifying what individual actors must do and how much they should pay/ be paid; to
- Commodity trading of energy produced in given settlement periods, but with a central buyer to procure capacity (to some extent similar to the UK's old Central Electricity Generating Board approach); to
- Commodity trading, but without a central buyer such that asset capital cost recovery must be achieved through usage fees (essentially the UK's model today); to
- A 'peer-to-peer' arrangement, where consumers buy directly from producers so are effectively responsible for balancing their own supply-demand position; and on to
- A 'Service Level Agreements' arrangement, where integrators form SLAs with resource providers that define the key attributes of how the integrator can use the resource (e.g. wind generation constrained by weather, energy storage constrained by loss rate, etc.) and also define the operational data required (e.g. wind forecasts) and control requests permissible (e.g. prepare to release energy from store).

C. Level of sophistication in the retail proposition.

This dimension articulates how consumer service terms are defined between consumers and supply chain. The scale is from:

- Diversity only on price, with everything else effectively set by regulator mandates; to
- Complex commodity pricing, reflecting varying resource costs and utilisation factors, which for industrial or large commercial consumers may extend as far as direct exposure to the volatility of spot market pricing but that would be too high a risk for the rest of the consumer base (this is similar to the current UK position); and on to

- A 'Service Level Agreements' arrangement, where integrators form SLAs with consumers that articulates level of service (e.g. how quickly a building will heat up on demand), flexibility (e.g. temperature band and schedule that must be achieved, leaving the integrator to choose how and when to deliver energy to achieve it), etc.

D.Means of internalising carbon cost.

This dimension articulates how carbon cost is internalised. The achievability of increasing sophistication in this dimension is inherently dependent on the level of sophistication in the other dimensions; for example, a carbon threshold on retailers requires a deep understanding of the experience energy affords for their customers in order for the retailer to stand a chance at actually reducing carbon. The scale is from:

- A simple carbon tax on consumers, which has been achieved in other countries (e.g. Denmark has a considerable tax on gas usage that has driven heat network development) and is achieved in some parts of the UK today (e.g. liquid fuel taxes), but is generally considered to be politically toxic in the UK for particular energy uses that remain very difficult to decarbonise (e.g. heat); to
- A more complex carbon tax on producers, which to some extent already exists in the UK but with a high degree of variability between parts of the system (e.g. very high tax on crude oil extraction, but little tax on electricity generation) that leads to sub-optimal outcomes from a total cost to society perspective; to
- A 'cap and trade' carbon credits arrangement placed on producers, similar to the EU's Emissions Trading Scheme, but which does not really incentivise exploitation of demand side levers; and on to
- A 'carbon threshold' arrangement on energy retailers, which is similar to the way in which the automotive industry is regulated to drive down carbon via a technology agnostic portfolio threshold on the integrator that essentially makes the ability to balance customer needs with avoidance of carbon penalties a primary driver of competitive advantage.

It should be noted these dimensions of difference are specific to the conceptual architecture level

of a candidate's definition, which is focused around the organisation of actors, roles and responsibilities into a market. At the next levels, factors such as the level of integration between energy vectors, the approach to grid stabilisation, etc will emerge as key dimensions of difference between candidates.

Candidate 1 – National Multi-vector Energy Company Retailing Energy as a Commodity

The closest analogy to this arrangement is the electricity sector in France today, but with enhanced integration between key energy vectors, especially electricity, gas and heat, that is not currently the arrangement in France. This architecture has a single National Multi-vector Energy Company that sells energy to customers as a commodity. The key actors, roles and responsibilities in this concept are:

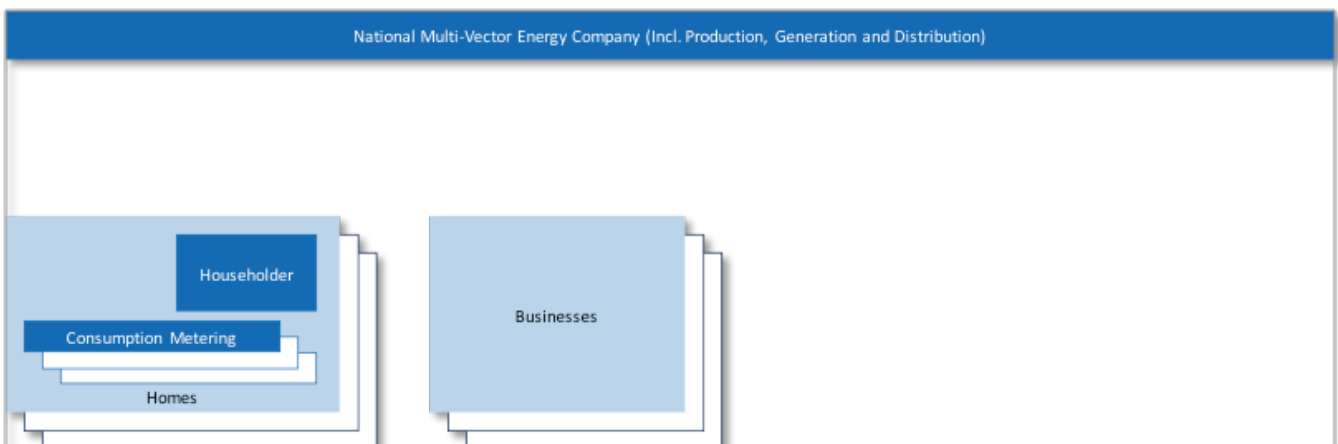
- The National Multi-vector Energy Company is the sole party with responsibility for building up the required portfolio of production, distribution and storage assets required to satisfy customer demand. They don't necessarily design, build, operate or finance that portfolio, however; they may build up the required portfolio via long-term contracts with third parties.
- Homes and businesses are effectively passive consumers of energy, where the Energy Company has little insight on the service value the consumed energy affords; although the Energy Company may well implement time of use pricing to encourage homes and business to use energy in a way that best meets the needs of the system. Demand side flexibility is hence limited to the ability to influence behaviour through tariffs, which is unlikely to provide much flexibility for events that cannot be catered for through simple pricing (e.g. periods of high demand due to cold weather coinciding with low supply due to low wind, which does not occur in a regular time window).
- The Energy Company may be split into multiple divisions, or subsidiaries, to deal with particular energy vectors or particular parts of the system,

but nonetheless works to optimise utilisation of different energy vectors to the extent possible given the limited demand side flexibility inherent in a concept limited to time of use retail pricing.

- Consumption meters in individual homes and businesses may well be read remotely using a smart metering arrangement, but the required telecommunications infrastructure would be owned or commissioned directly by the Energy Company. This infrastructure may extend to remote time switching for electric heating, like the current Radio Tele-Switch system in the UK or equivalent system in France today.

- There is no requirement for intermediaries (e.g. Data Communications Company, Home Energy Services Gateway, Energy Trading Platform, etc.), as market arrangements are simple.
- Device Vendors (such as electric vehicle manufacturers, boiler makers, heating control vendors, etc.) are largely left to develop products with limited energy system integration; the possible exception being the historic integration of electric heating remote time switches.

The architecture has the following sophistication based on the four dimensions, and the following parties:



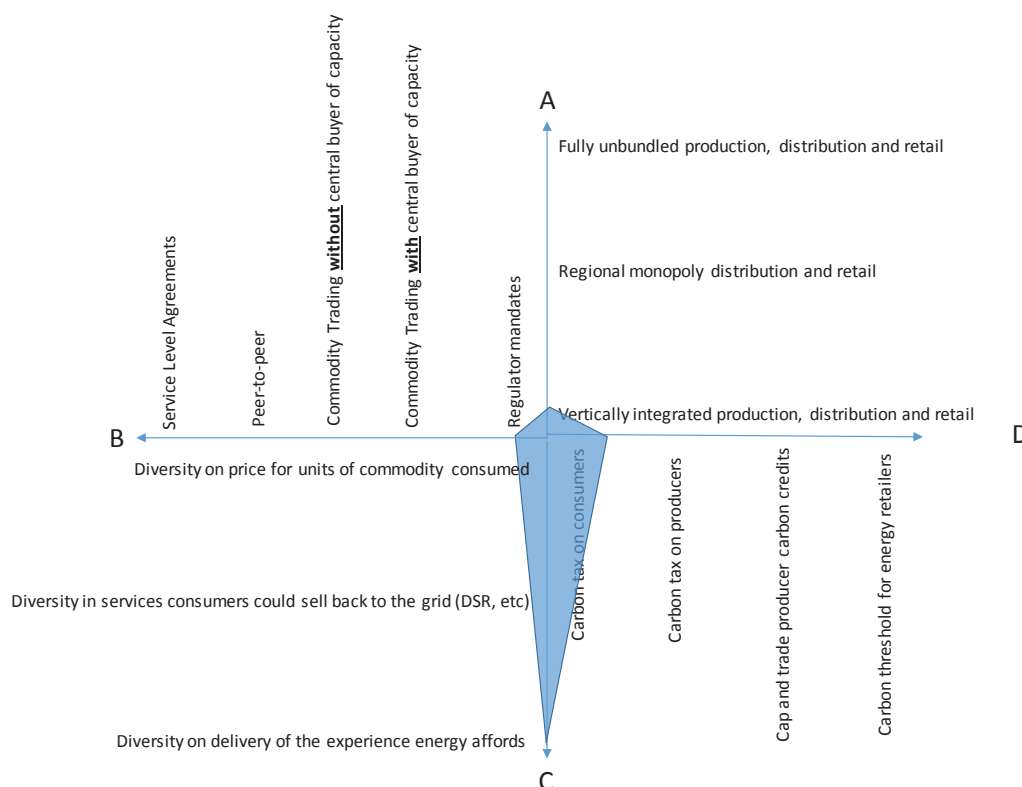
Candidate 2 – National Multi-vector Energy Company Retailing Experience Based Services

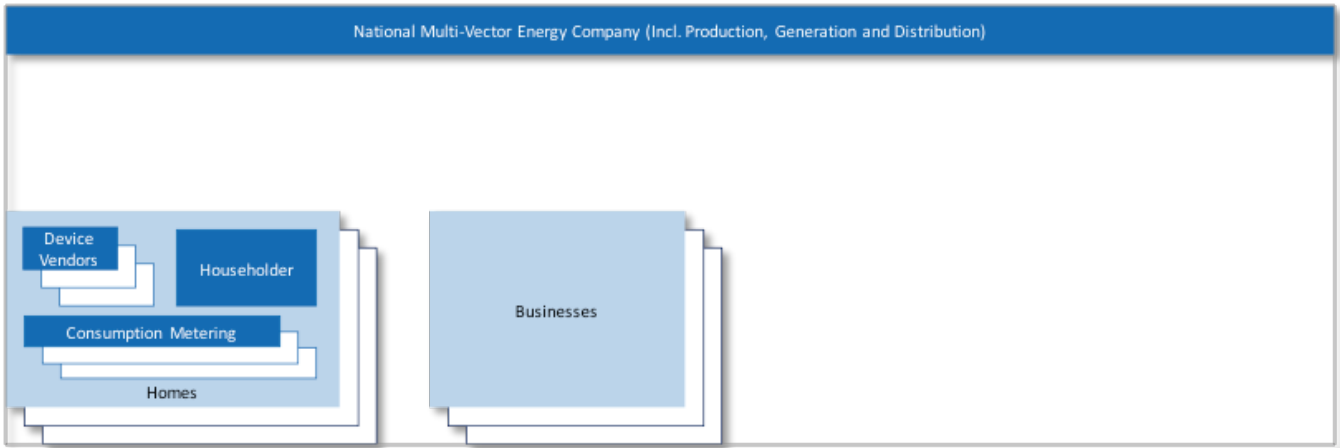
This is an extension to the first concept, changing the retail proposition from simple commodity consumption to experience based services; such as a fixed price for times when the home will be heated to a specified level of warmth, a fixed price and duration to heat the home on demand, etc. The key variations to the actors, roles and responsibilities relative to the first concept are:

- In order to generate the required data and control capabilities required to design and deliver customer focused services, it must be possible for the National Multi-vector Energy Company to access the data and control capabilities of devices. Given the simple market arrangement, the Energy Company would develop and maintain a set of standards for the key devices, which device vendors would be obligated to abide by.
- The householder is a much more active participant, and would be able to choose from a range of different levels of service at varying

prices (e.g. highly responsive on demand use vs low responsive on demand use); i.e. revealing consumer preferences. The shift to paying for levels of service as opposed to units of commodity consumed enables the Energy Company to manage the way in which it delivers energy to achieve the service outcome; i.e. establishing demand side flexibility.

- Given the lack of competition for experience based services, and hence a lack of any competitive driver to work harder in the interests of customers, effective democratic process is critical to ensuring evolution of a range of services that meet peoples' real needs.
- Given there is a single party responsible for balancing supply and demand, and for satisfying customers' needs, a relatively simple control arrangement could be implemented in which system frequency is used at the individual building level (or device level) to stabilise the system negating the need for a complex supervisory control arrangement. To avoid passing risk / uncertainty onto consumers as a consequence of this control arrangement, it is essential that pricing is based on achieving outcomes as opposed to units of commodity consumed.





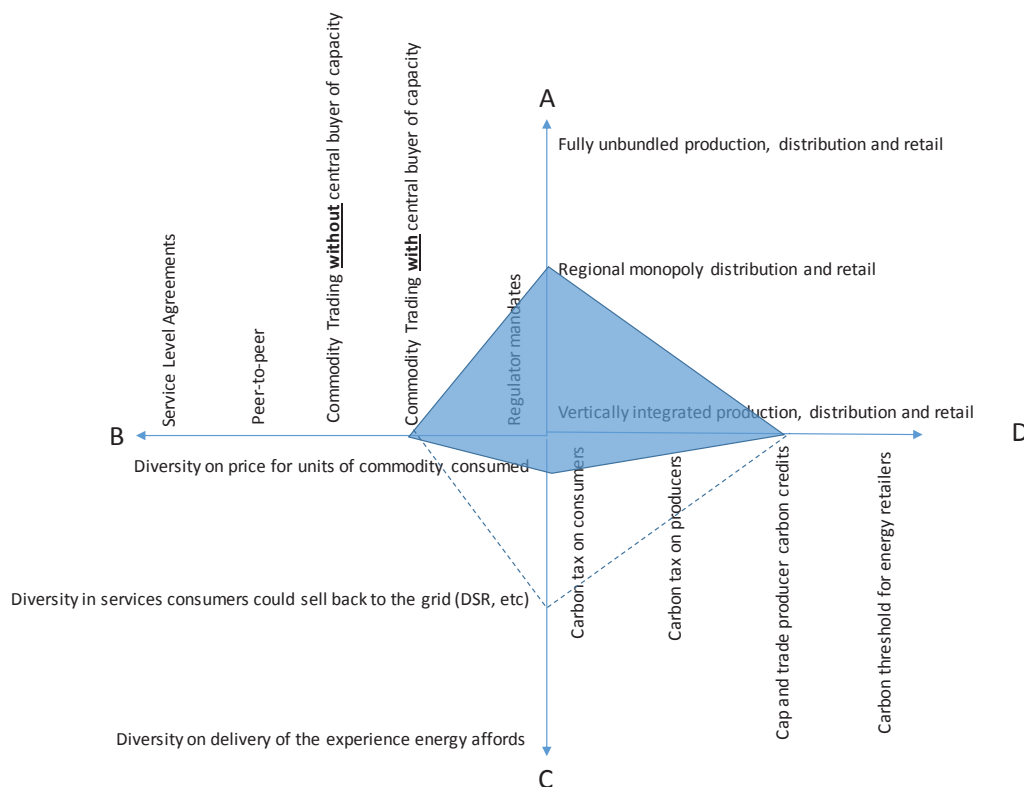
Candidate 3 – Regional Multi-Vector Energy Companies Retailing a Commodity, Supported by a Central Buyer

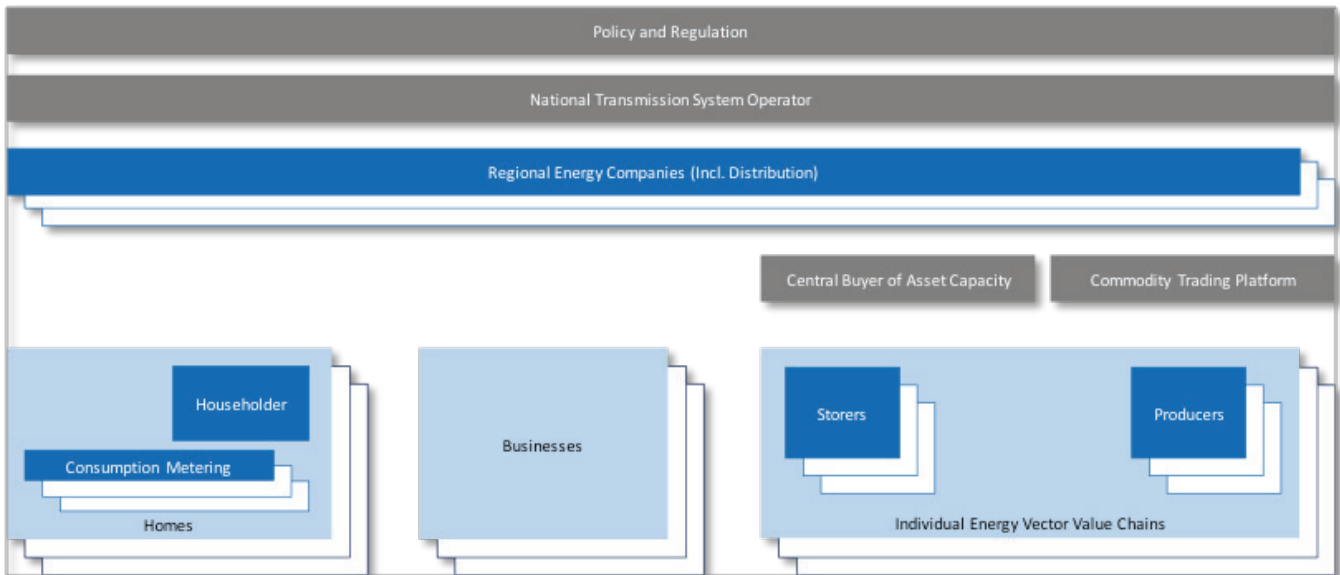
This arrangement takes concept (1) and unbundles energy production and transmission from regional monopolies for distribution and retail. The key variations to the actors, roles and responsibilities relative to concept (1) are:

- The Regional Multi-Vector Energy Company is the sole party responsible for ensuring supply and demand are constantly matched in a given

geographic area, with high resolution metering at the connection points to the national transmission infrastructures ensuring this.

- The Central Buyer is responsible for procuring upstream assets with sufficient capacity to meet the aggregate peak demand of all Regional Energy Companies. This is similar to having a nationalised generation board where the capital cost to build new assets are socialised, by a counterparty signing a long-term deal for capacity of upstream assets. The Regional Energy Companies then buy energy for given Settlement Periods at the marginal cost of production via a Commodity Trading Platform.



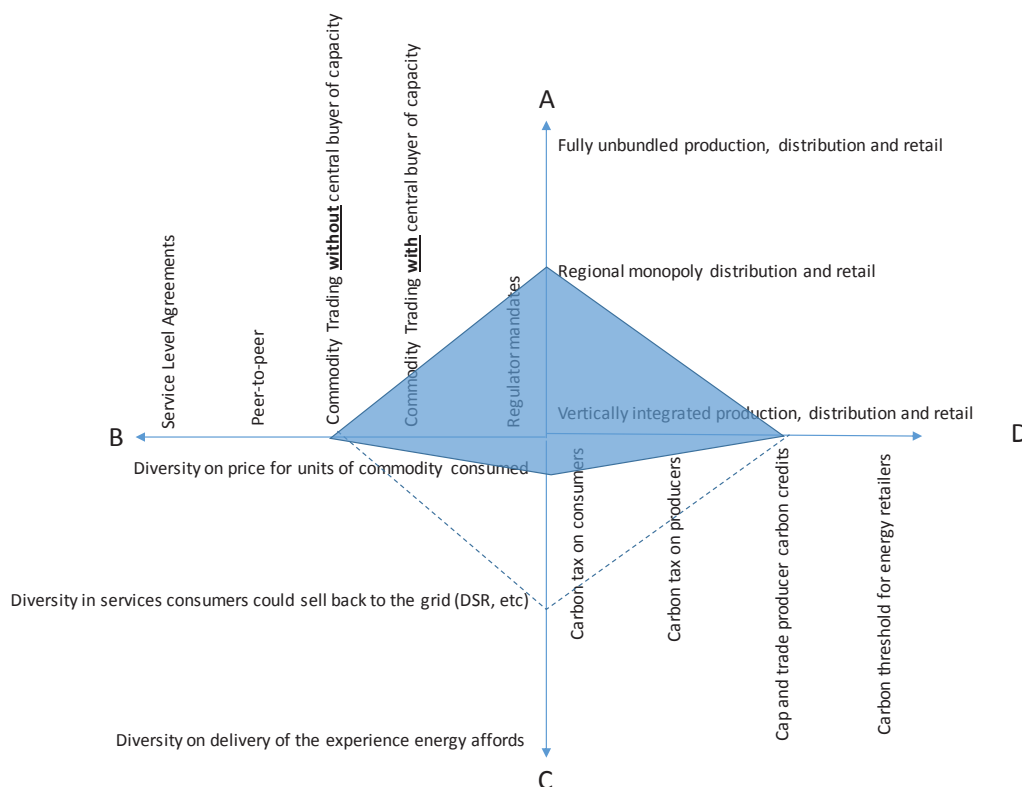


Candidate 4 – Regional Multi-Vector Energy Companies Retailing a Commodity, W/o Central Buyer

This concept removes the Central Buyer role from concept (3), requiring that investors in production and storage assets recover their costs through commodity consumption payments; i.e. there is generally no counterparty signing a

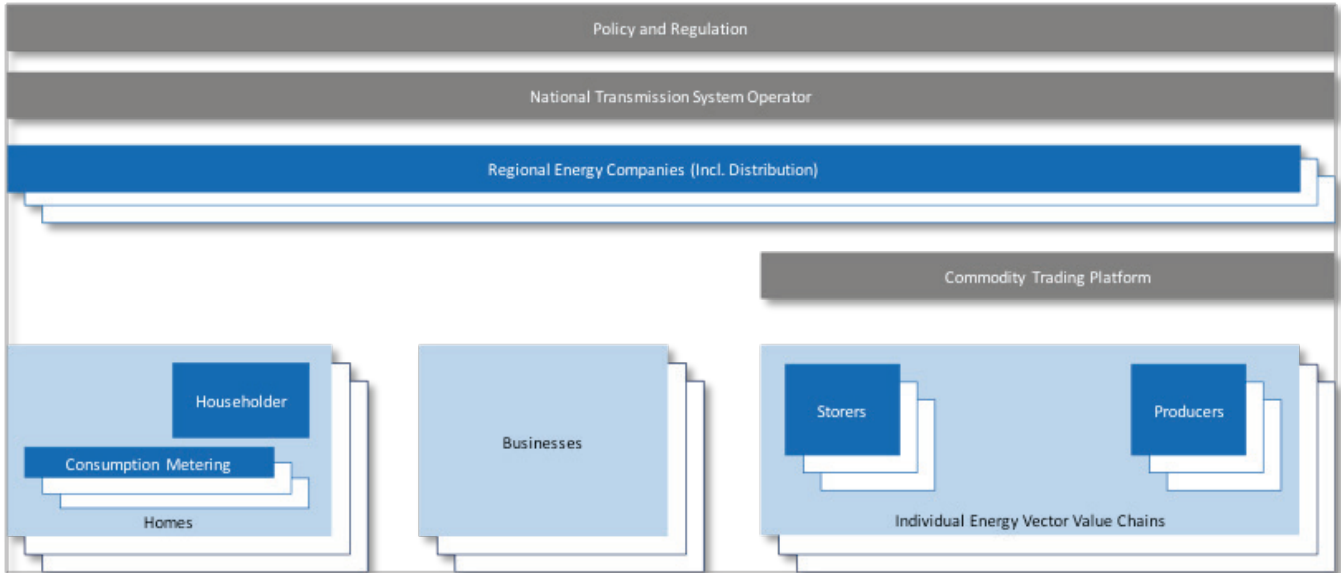
long-term deal for capacity of upstream assets. The closest analogy to this arrangement is the current electricity system in Germany. The high capital costs, but low operating costs, of low carbon energy assets such as wind power require long-term policy stability to enable investors to price risk since there is no Central Buyer to act as counter-party.

Given that there must always be enough production resource to satisfy demand at any instant, which also cannot be actively managed in



this concept, there is inevitably always a surplus of available supply which pushes pricing toward the marginal cost of production. The consequence of this is that production and storage asset investors can't recover their capital costs via commodity

consumption payments alone. This leads to a need for either Regional Energy Companies buying their own assets or large state asset subsidies.

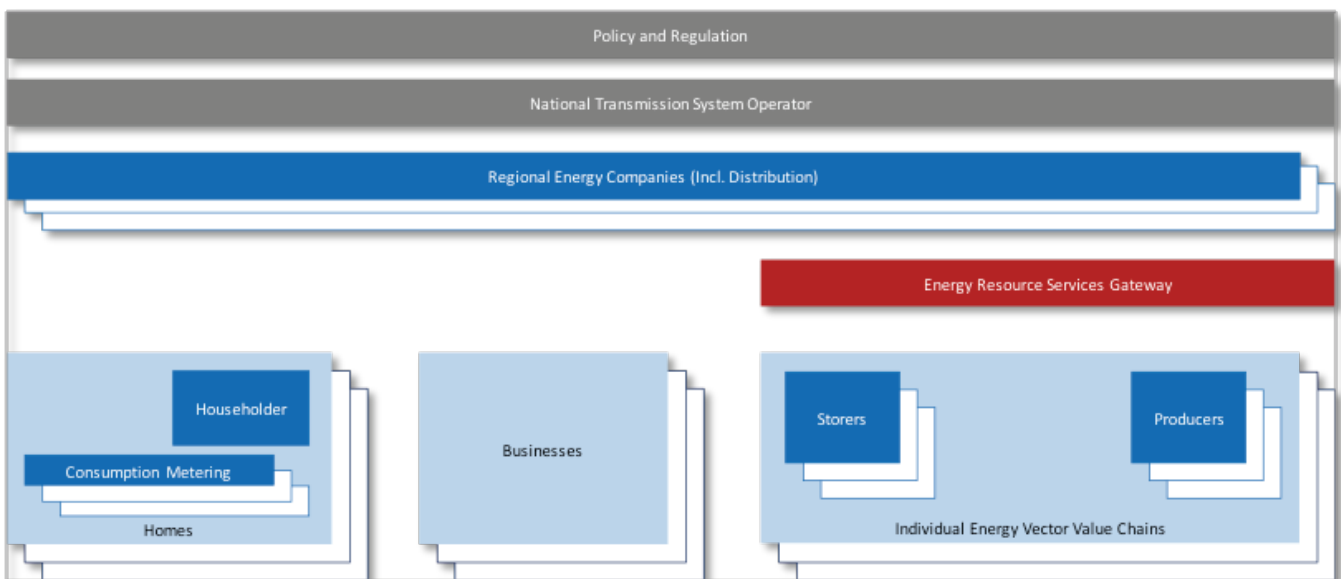
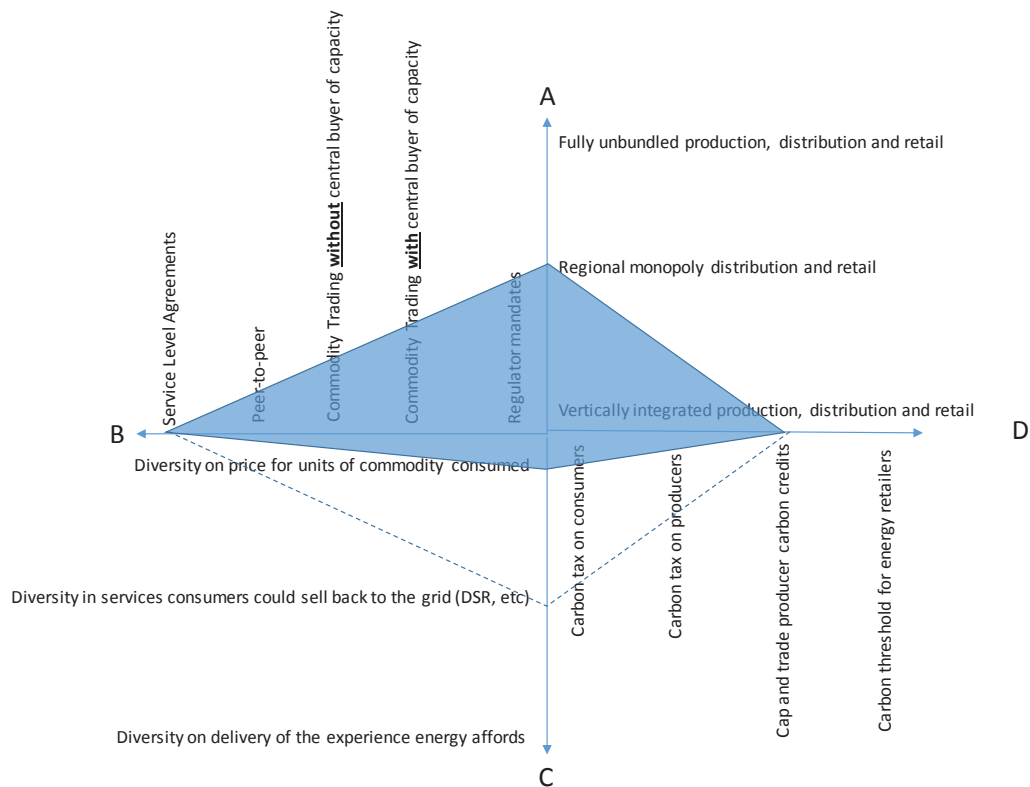


Candidate 5 – Regional Multi-Vector Energy Companies Retailing a Commodity, with Resource SLAs

This concept significantly enhances the integration between Regional Energy Companies and their upstream resource providers via an Energy Resource Services Gateway enabling forming and execution of resource Service Level Agreements (SLAs). The Regional Energy Companies are effectively the counterparty for investment in upstream asset capacity via signing these SLAs that define, amongst other things, the right of that Regional Energy Company to a certain amount of a Resource Provider's capacity under certain terms (ramp-up/-down rate, etc). The Energy Resource Services Gateway enables individual competing resource providers to make competing offers for resource provision to Regional Energy Companies, where the offer is defined as a Service Level Agreement that incorporates attributes such as:

- For storage, standard service attributes include entry rate, exit rate, loss rate, lead time to start charging/discharging, store capacity, minimum contract period, etc.
- For production, standard service attributes include ramp-up rate, ramp-down rate, lead time to standby, carbon content, minimum contract period, etc.

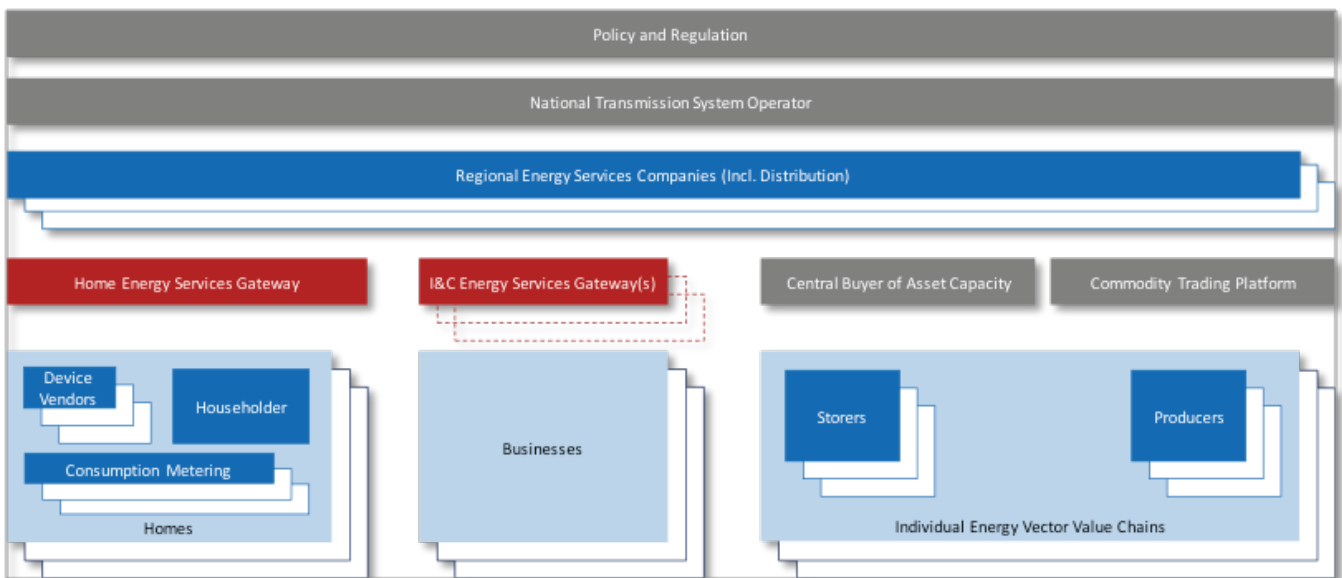
The Energy Resource Services Gateway provides a constant stream of data on the status of resource assets, such as wind forecasts, to enable a Regional Energy Company to plan its operations in the pursuit of minimising cost for its customers. It also provides a route for control requests to be sent to resource assets, such as to ready a gas plant for generating electricity.



Candidate 6 – Regional Multi-Vector Energy Companies Retailing Services, Supported by a Central Buyer

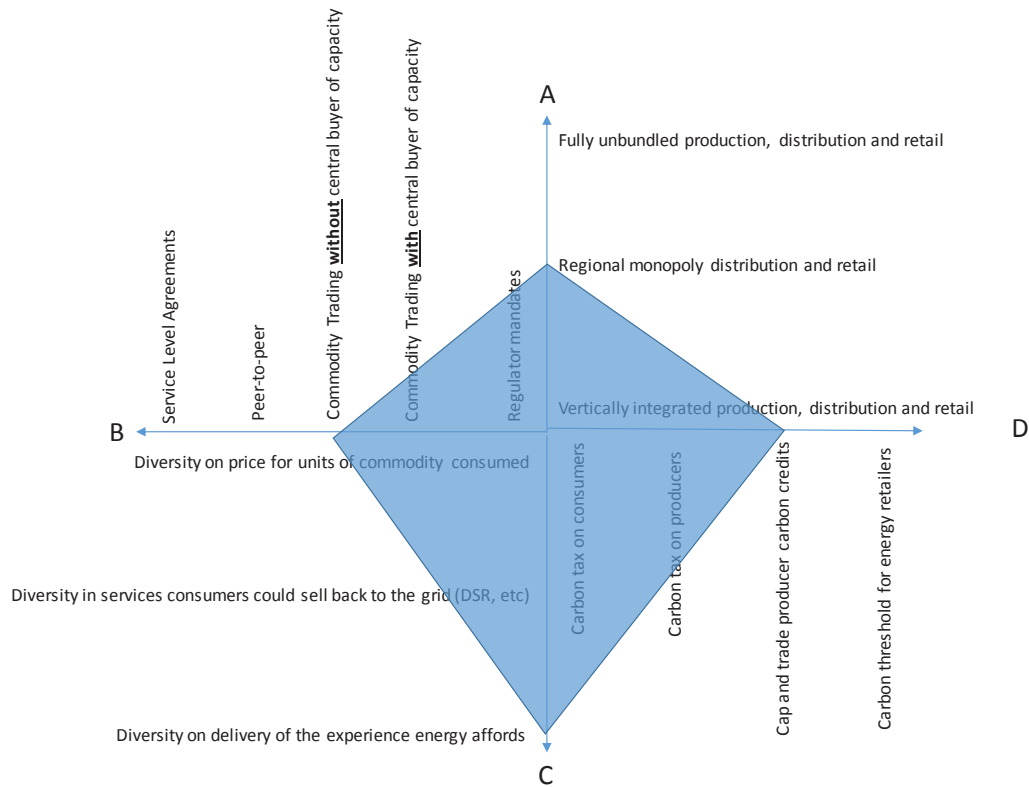
This arrangement begins with concept (3) and significantly enhances the customer offer to an experience based service, where a customer service agreement defines the required envelope of operation (e.g. when/where the home should

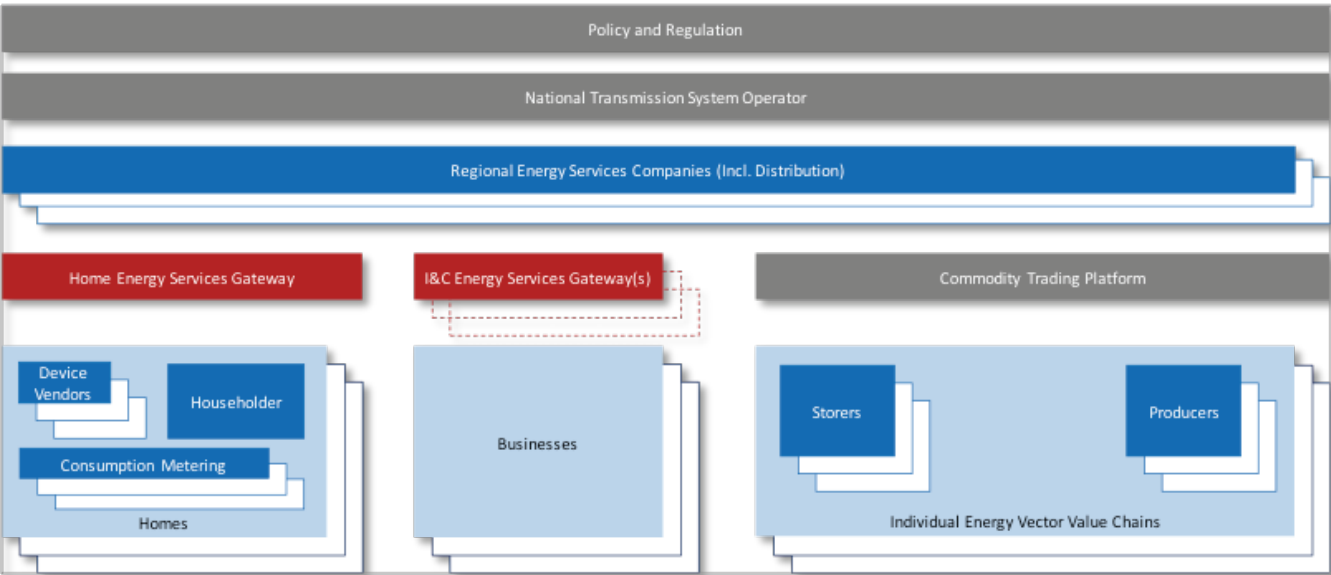
be warm, how warm, how long it will take to reach the required level of warmth on demand, etc.). The Home Energy Services Gateway enables the multiple Regional Energy Companies to gather data on which to be able to design services from a multitude of devices around homes in their geographic area from various Vendors; and to enable them to access the control capabilities of devices to execute those services. Unlike concept (2), there is no state mandating of Device Vendors to make their devices available to the Regional



Candidate 7 – Regional Multi-Vector Energy Companies Retailing Services, Without a Central Buyer

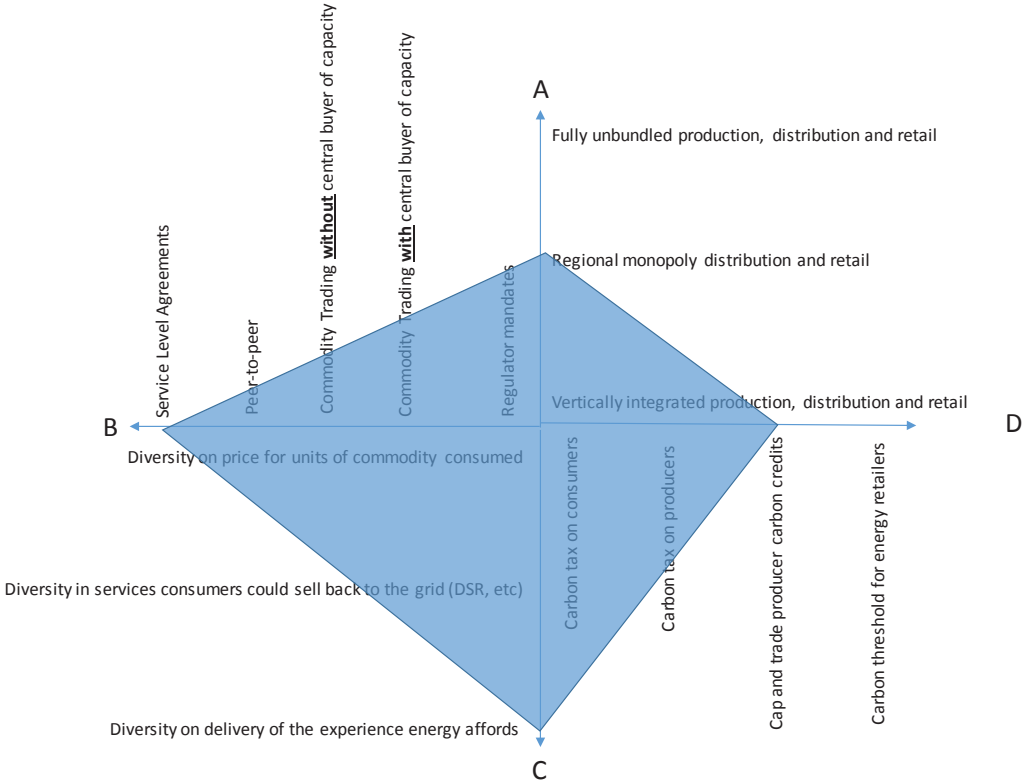
This arrangement takes concept (4) and significantly enhances the customer offer to an experience based service in the same way as described for concept (6).

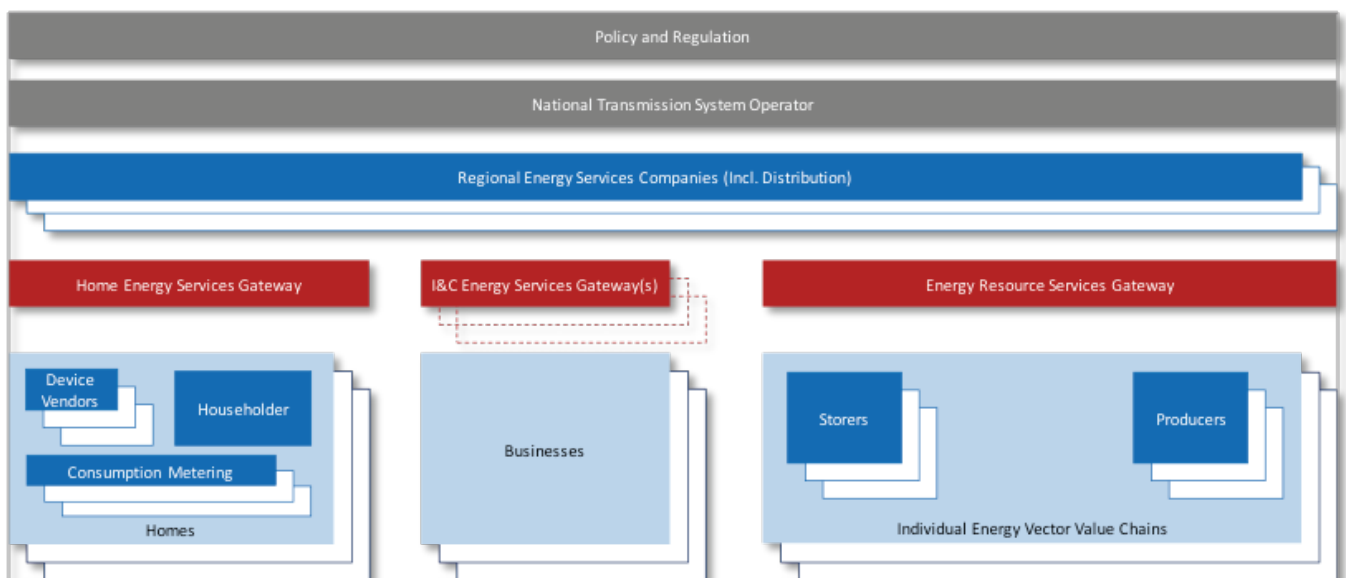




Candidate 8 – Regional Multi-Vector Energy Companies Retailing Services, with resource SLAs

This arrangement takes concept (5) and significantly enhances the customer offer to an experience based service in the same way as described for concept (6).





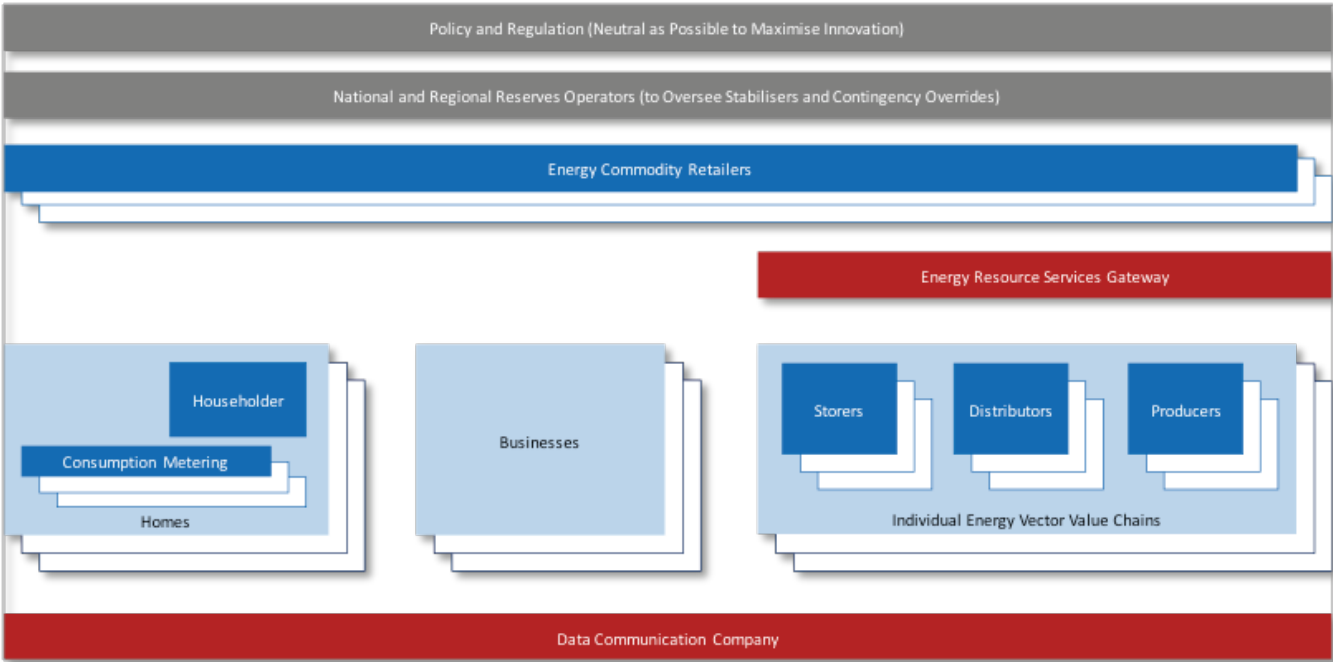
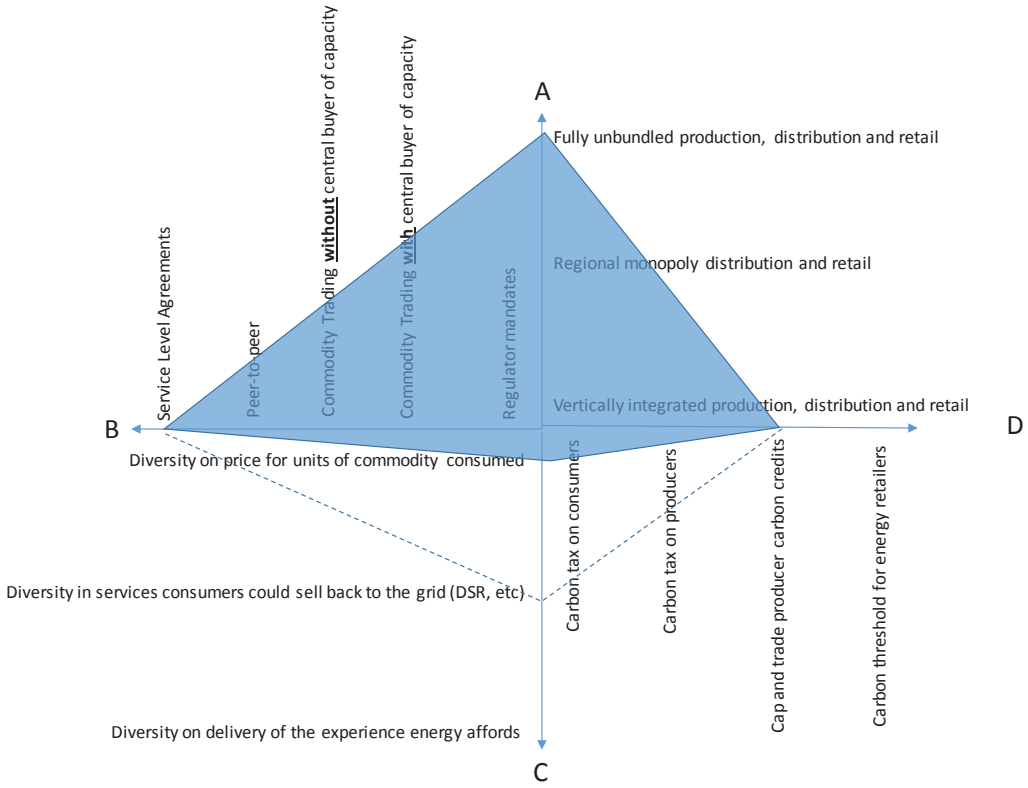
Candidate 9 – Fully Unbundled Retail of Commodity consumption, with Resource SLAs

This takes concept (5) and unbundles the retail element of the value chain. Since retail is now unbundled from distribution, four fundamental additions are required:

- The high resolution metering at connection points between national transmission infrastructure and regional distribution infrastructure is no longer sufficient to achieve traceability to the actions of the key actor responsible for bulk balancing of supply vs. demand (the competing Energy Commodity Retailers), since there are now many of them operating in a given area. Hence, high fidelity Consumption Metering is required at building level capable of measuring not only total number of units of commodity consumed in a given Settlement Period but also a 'signature' for the load profile within that Settlement Period. This is required to: (a) minimise socialisation of balancing costs by minimising the residual imbalance; and (b) avoid scope for load management by an Energy Commodity Retailer that deliberately destabilises the system for commercial gain.
- The technical metrics against which Energy Commodity Retailers balance their supply vs. demand position is entirely based on metering data; which is unlike the Regional Energy Companies arrangement since technical metrics such as frequency, voltage, pressure, etc cannot be used because they are properties of the whole system and not properties of the actions of a specific actor. This is especially challenging for system frequency, which requires near-perfect matching of supply vs. demand at every instant. It is hence somewhat inevitable there will be a residual imbalance and it is part of the role of the Reserves Operator(s) to resolve this residual imbalance.
- A Data Communications Company, and associated business processes for handover when consumers switch Energy Commodity Retailer, are required in order to enable any Energy Commodity Retailer to take responsibility for any consumption meter, since there is no longer a simple regional monopoly arrangement.
- Since retail is now unbundled from distribution, the Energy Resource Services Gateway must also provide the capability for multiple competing Energy Services Providers to form Service Level Agreements with Distributors for different levels of services (e.g. time of use pricing, interruptible contract, unlimited, etc.) in

addition to doing so for production and storage. However, it is unlikely there would be much use of SLAs outside of institutional and commercial (I&C) consumers other than the unlimited option

(effectively as today), given the lack of services based retail propositions that create demand side flexibility.



Candidate 10 – Fully Unbundled Retail of Experience Based Services, with Resource SLAs

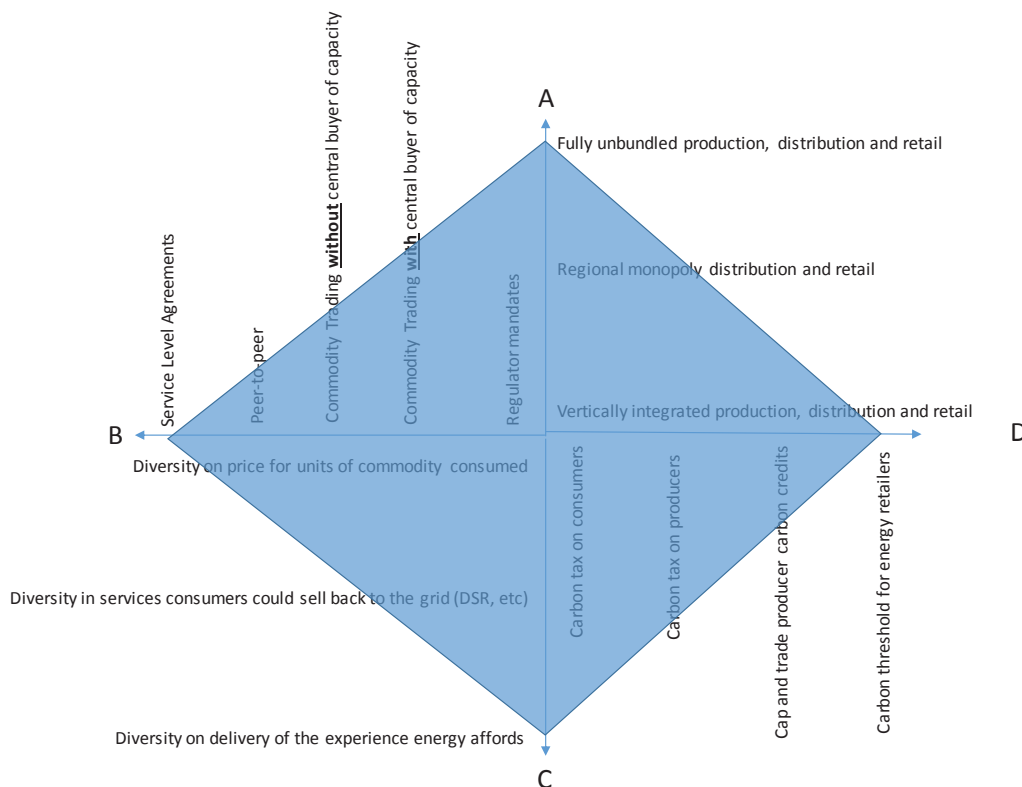
This arrangement builds upon concept (9) to add in elements that enable the retail proposition to be changed to a services arrangement similar to that described for concept (6); but with the key additions that the Home Energy Services Gateway must now also provide consumers with the means to navigate a market of competing offers from multiple Energy Services Providers and to handle dispute resolution in the event of their chosen provider not performing.

The Home Energy Services Gateway and a move to outcome focused services builds flexibility on the demand side; and similarly, the Energy Resource Services Gateway and a move to Service Level Agreements builds flexibility on the supply side. This effectively positions the Energy Services Providers as the centre-point in a complex multi-actor closed-loop control system. The need for a consumption metering arrangement that provides traceability to the actions of the Energy Services

Providers, as described for concept (9), is now not only important but absolutely critical to ensuring behaviours of individual actors are maintained in the interests of overall system operability. This is because each actor now has substantial volumes of supply and/or demand under their control; volumes that far exceed the limited balancing levers the GB System Operator has at its disposal to resolve supply-demand imbalances in the system today.

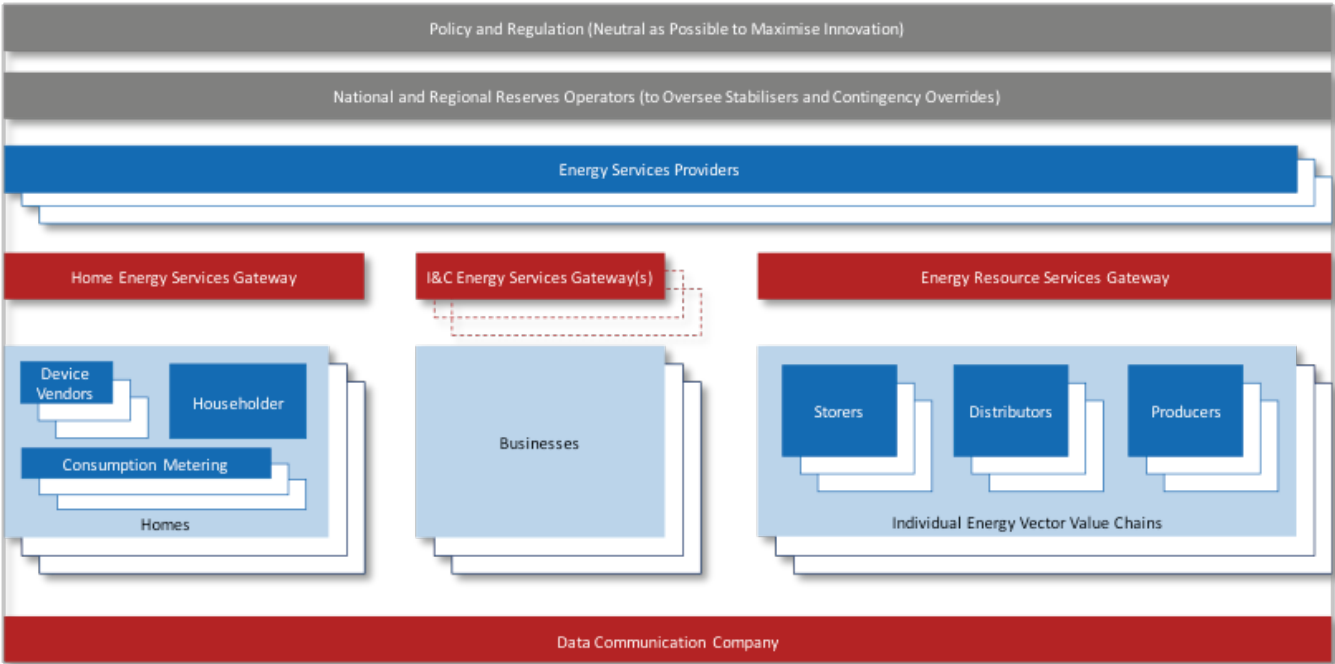
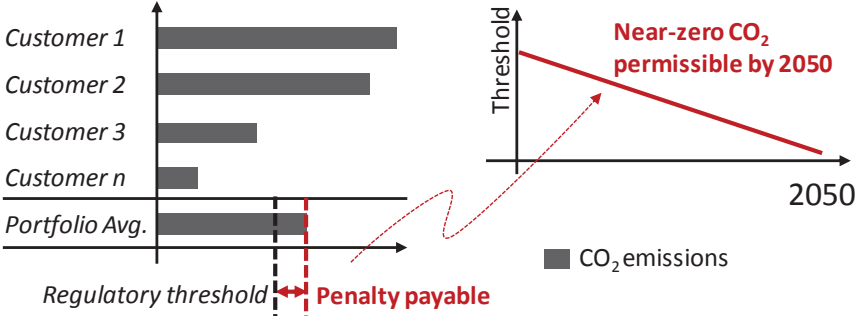
Since retail is now fully unbundled, technical metrics such as frequency, voltage, pressure, etc can no longer be used as a primary control input since it is a factor over which the individual Energy Services Provider has no control and therefore could not reasonably be expected to take responsibility for any resulting imbalances in their supply-demand position. Frequency responsive appliances could still be used for providing overrides for special contingencies (i.e. once in a few year emergency events), for which appropriate compensation arrangements would need to be defined as part of the market rules.

This arrangement opens a new option for carbon policy, in which a technology agnostic portfolio



level carbon threshold is placed on the Energy Services Provider as illustrated below. If the Energy Services Provider exceeds their portfolio carbon threshold in a given year (e.g. based on an average gCO₂/home, adjusted for house type/size/age), then a penalty is payable; if below, there is no penalty. This is very similar to the carbon policy driving very substantive private investment in long-term innovation and supply

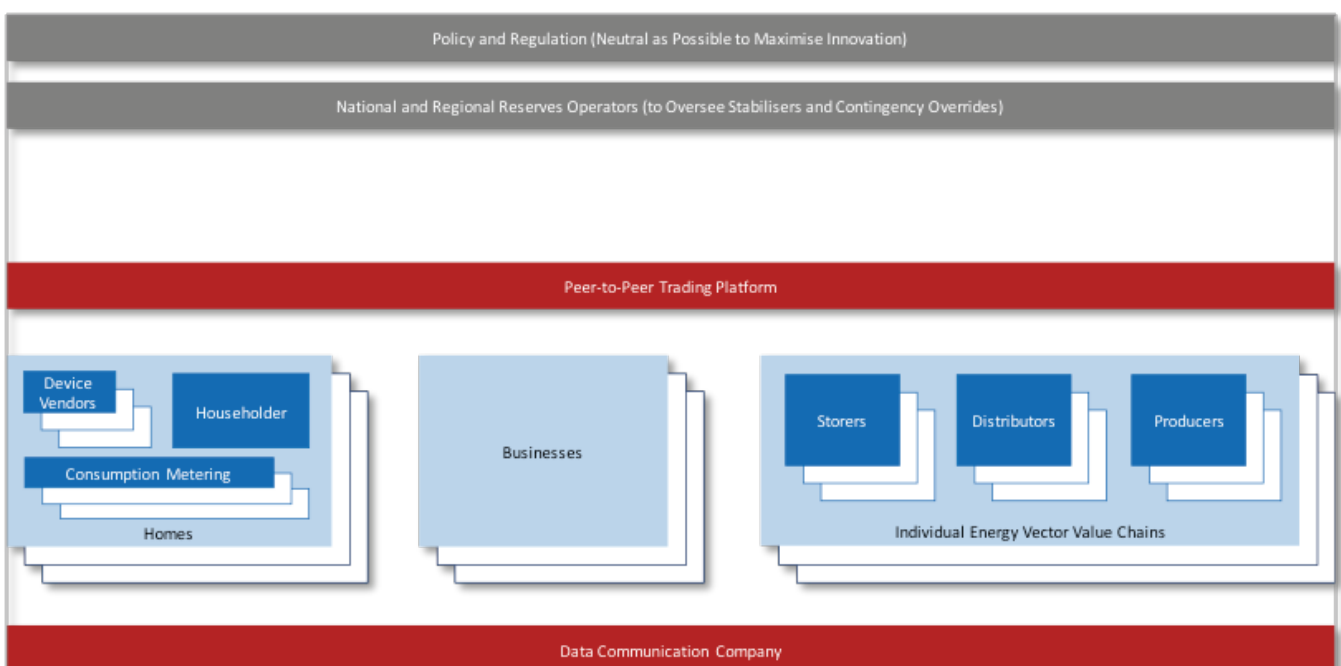
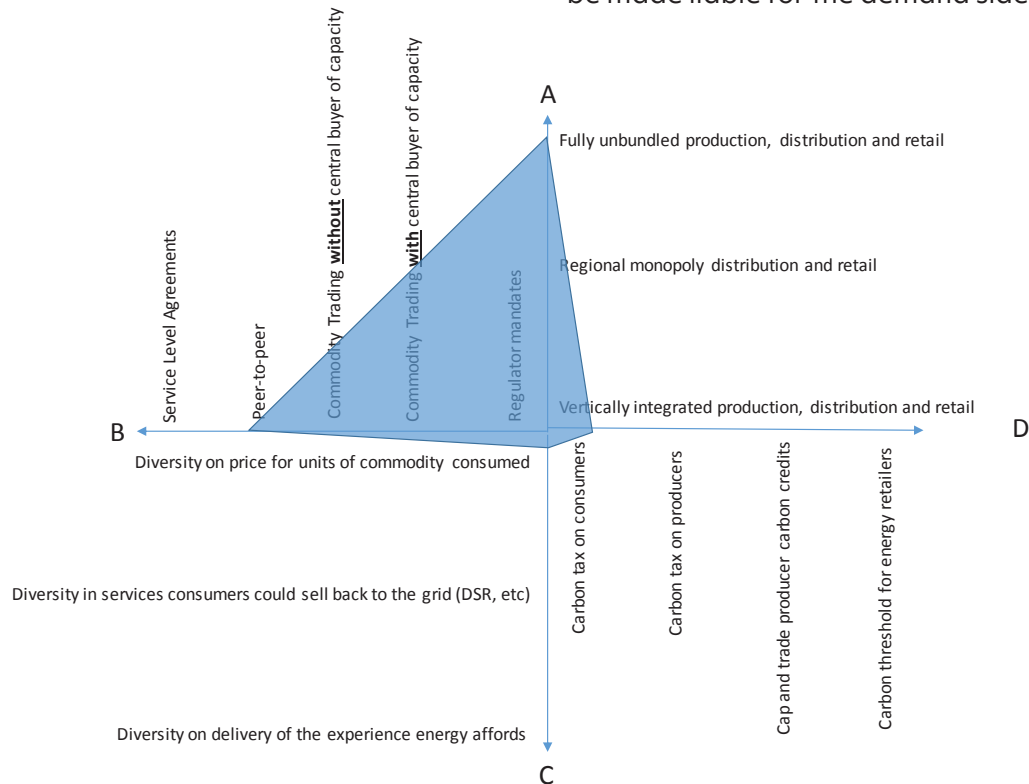
chain development in the automotive sector. It leaves the ESPs free to optimise their portfolio using their deep customer relationships (via the HESG) to shape the demand side and their deep supply chain relationships (via the ERSG) to shape the supply side. Their competitiveness is a function of their ability to navigate uncertainty, deal with integration complexities, invest for the long-term and optimise a portfolio.



Candidate 11 – Peer-to-Peer Market

This concept essentially enables individual Householders and Businesses to assemble the resources required to satisfy their own needs; and for resource providers to sell directly to them, probably in the form of SLAs. For it to work, the Peer-to-peer Trading Platform would need to ensure each consumer had bought the correct supply to meet their own needs and, if not, would

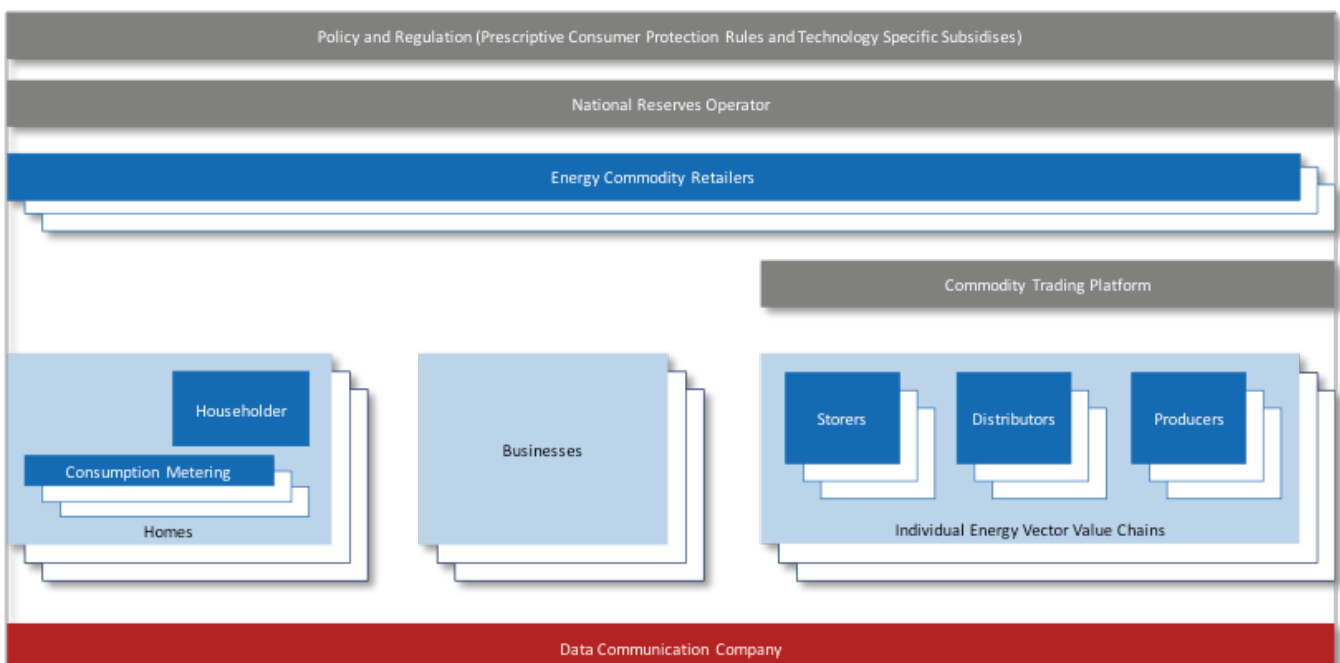
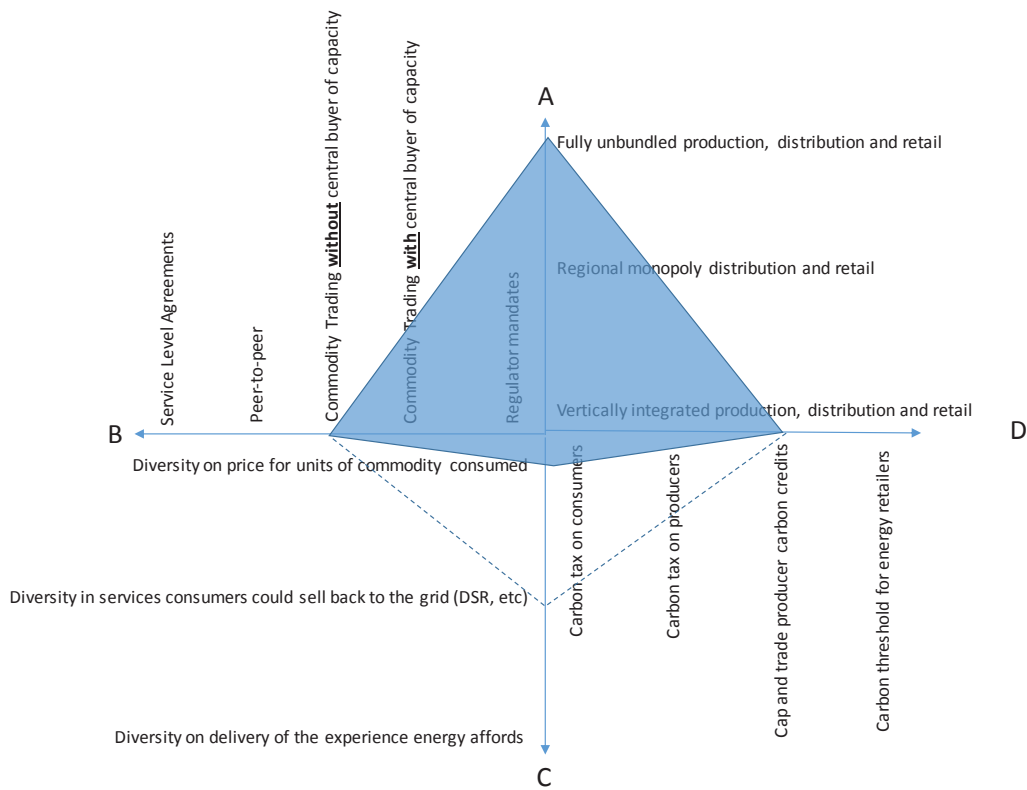
need to have sufficient control to prevent them using more (or less) than they had contracted for. A Data Communication Company would be required to enable any resource provider to access meter data from any consumer that had chosen to buy their resources so as to be able to show that they are providing the supply to match agreed demands; a very different requirement for a DCC compared to other concepts. Resource providers could be responsible for supply side balancing; but it is not clear how consumers could be made liable for the demand side.



Candidate 12 – Fully Unbundled Retail of Commodity consumption, without Central Buyer

This concept is effectively business as usual in the UK today. Encompassed within the Commodity

Trading Platform are the various sub-systems currently implemented to support this function, such as Elexon, Electralink, xoServe, APX Power Exchange, ICE Gas Exchange, etc. although in practice there is very little interaction between them in the energy system today, which would be necessary for multi-vector integration.



Appendix A2: Candidate System of

	1	2	3	4	5	6
	Vertically integrated state company (multi-vector)		Regional companies for distribution and retail (multi-vector)			
	Commodity consumed retail	Experience services retail	Commodity consumption retail			Experience
	Central procurement body for energy production			Production cost recovery via commodity retail fees	Production cost recovery via service level agreements	Central procurement body for energy production
Consumer centricity	X (no insight on consumer preferences)	? (risk of tendency to counter-productive political directives)	X (no insight on consumer preferences)	X (no insight on consumer preferences)	X (no insight on consumer preferences)	? (risk of tendency to counter-productive political directives)
Resource constraints	X (lack of demand side flexibility)	? (lack of competition to drive innovation)	X (achieves capacity investment, but lack of demand side flexibility)	X (evidence so far shows unlikely to secure capacity investment)	X (achieves capacity investment, but lack of demand side flexibility)	? (competition drives supply side innovation; but limited supply side flexibility)
Security and stability	● ● (very few interfaces to expose risks, few supply-demand closed loop risks)	● (few interfaces to expose risks, but introduces closed-loop cyber-security)	● ● (very few interfaces to expose risks, little supply-demand closed loop risks)	X (highly unlikely to build surplus required to give margin needed)	● ● (very few interfaces to expose risks, few supply-demand closed loop risks)	● (limited interfaces to expose risks, but introduces closed-loop cyber-security needing robust architecture)
Commercial alignment	● (commercial interfaces all sub-contracted)	X (requires significant state mandating to ensure devices support service execution despite warranty issues, etc)	● (motives-levers and benefits-liabilities fixed into alignment by regional utilities and central buyer)	X (risks investing in capacity can't be passed on in value chain)	? (requires robust architecture to align motives-levers and benefits-liabilities)	? (requires robust architecture align of motives-levers and benefits-liabilities)
Social objectives	X (fuel poverty dealt with by directives; but carbon unlikely politically viable given lack of ability for consumer focus)	? (fuel poverty dealt with by directives; service model may help with carbon, depending on how motives perceived)	X (fuel poverty dealt with by directives; but carbon unlikely politically viable given lack of ability for consumer focus)	X (evidence so far shows unlikely to secure high capital low carbon asset investment)	X (fuel poverty dealt with by directives; but carbon unlikely politically viable given lack of ability for consumer focus)	? (fuel poverty dealt with by directives; service model may help with carbon, depending on how motives perceived)

Systems Architectures – Evaluation

7	8	9	10	11	12
		Fully unbundled competitive retail			
based services retail		Commodity consumed retail	Experience based services retail	Direct peer-peer (no retail function)	Commodity consumed retail
Production cost recovery via commodity retail fees	Production asset cost recovery via service level agreements			Production cost recovery via commodity retail fees	
<p>?</p> <p>(risk of tendency to counter-productive political directives)</p>	<p>?</p> <p>(risk of tendency to counter-productive political directives)</p>	<p>X</p> <p>(no insight on consumer preferences)</p>	<p>●</p> <p>(improving quality of service delivery drives profits)</p>	<p>X</p> <p>(extremely complex for individual consumers to match supply-demand)</p>	<p>X</p> <p>(no insight on consumer preferences)</p>
<p>X</p> <p>(evidence so far shows unlikely to secure capacity investment)</p>	<p>●</p> <p>(competition drives supply side innovation; SLAs define flexibility supply-demand)</p>	<p>X</p> <p>(lack of demand side flexibility)</p>	<p>● ●</p> <p>(competition drives demand and supply side innovations; and SLAs define flexibility on supply and demand)</p>	<p>X</p> <p>(highly unlikely to secure capacity investment, given lack of any long-term counterparty)</p>	<p>X</p> <p>(evidence so far shows unlikely to secure capacity investment; lack of demand side flexibility)</p>
<p>X</p> <p>(highly unlikely to build surplus required to give margin needed)</p>	<p>●</p> <p>(limited interfaces to expose risks, but introduces closed-loop cyber-security needing robust architecture)</p>	<p>?</p> <p>(many more actors and many more interfaces exposing more risks, but few supply-demand closed loop risks)</p>	<p>??</p> <p>(requires robust architecture for distributed multi-actor complex control)</p>	<p>???</p> <p>(requires robust architecture for distributed multi-actor complex control; lack of clear responsibilities)</p>	<p>X</p> <p>(highly unlikely to build surplus required to give margin needed)</p>
<p>X</p> <p>(risks investing in capacity can't be passed on in value chain)</p>	<p>?</p> <p>(requires robust architecture and transaction gateways to enable alignment of motives-levers and benefits-liabilities)</p>	<p>?</p> <p>(requires robust architecture and transaction gateways to enable alignment of motives-levers and benefits-liabilities)</p>	<p>?</p> <p>(requires robust architecture and transaction gateways to enable alignment of motives-levers and benefits-liabilities)</p>	<p>???</p> <p>(highly unlikely to be possible to align motivations give extremely large number of very low value peer-to-peer transactions)</p>	<p>X</p> <p>(risks investing in capacity can't be passed on in value chain)</p>
<p>X</p> <p>(evidence so far shows unlikely to secure high capital low carbon asset investment)</p>	<p>?</p> <p>(fuel poverty dealt with by directives; service model may help with carbon, depending on how motives perceived)</p>	<p>X</p> <p>(fuel poverty dealt with by directives; but carbon unlikely politically viable given lack of ability for consumer focus)</p>	<p>●</p> <p>(scope for payment on results; enables neutral carbon policy similar to automotive to drive industry investment in low carbon innovation)</p>	<p>X</p> <p>(assumes consumers are 'savvy' enough to sort out issues on their own, given lack of a party taking performance risk)</p>	<p>X</p> <p>(fuel poverty dealt with by directives; but carbon unlikely politically viable given lack of ability for consumer focus)</p>

Appendix B: Holistic Concept of Operations for the Candidate 10 System of Systems Architecture

The following Conceptual Objectives have been developed to explore the operations that need to be performed within Candidate 10 (as set out in Appendix B1) in order to satisfy the Fundamental Principles (as set out in section 4.1). Each Conceptual Objective states an outcome and some high level architectural user stories derived from them. In addition, the Conceptual Logic Sequences are then provided to illustrate the interfaces between various actors within the Candidate 10 System of Systems Architecture to deliver on each whole system Conceptual Objective.

Conceptual Objective 1: Householders finding energy services

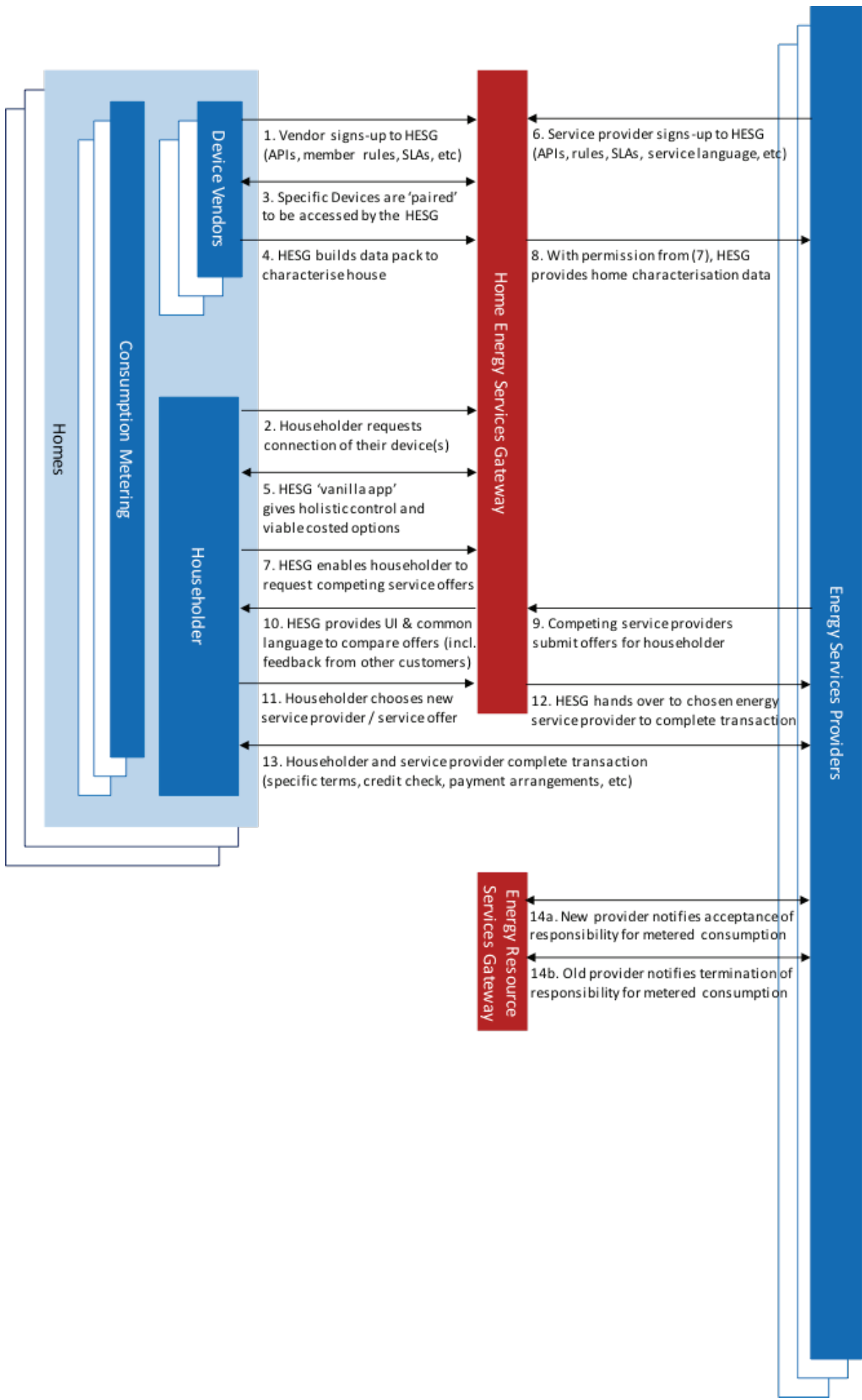
This Conceptual Objective involves itself with enabling many consumers to connect with many ESPs with a shared understanding of the expectations and costs to both parties.

Within this Conceptual Objective, the following Architectural User Stories are covered for particular actors:

A high level logic sequence (to be read in the numbered order as opposed to vertical flow), by which the above Architectural User Stories are achieved within Candidate 10 (as down-selected within Appendix A1 and A2) is outlined below.

If a consumer does not wish to procure a more sophisticated service agreement, they may never enter into this use case; in which case they would continue to pay for energy on a commodity consumption basis. Furthermore, subject to completion of any contractual tie-in period with a given service provider, consumers may revert to step 5 ('vanilla app', independent of any service provider, and the energy provider just bills for units of commodity consumed) or step 7 (choose an alternative service provider).

Actor	#	Architectural User Story
Householder	1-1	As a householder, I want to buy services using a language I can relate to from providers competing to help me get more of what I value and less of what I don't so I'm confident I'm getting good value for money.
	1-2	As a Householder, I want to be able to see feedback from other peoples' experience with a given Energy Service Provider so I can be confident I am making a good decision with a new service selection.
Energy Service Provider	1-3	As an Energy Service Provider, I want to have a common language with which to both understand and to help shape my customers' expectations so I can achieve high levels of satisfaction.
	1-4	As an Energy Service Provider, I want to have sufficient data for a prospective Householder so as to be able to price risk in my offerings.
	1-5	As an outgoing Energy Service Provider, I want to hand-over responsibility for the energy consumed at a given meter point so that I do not incur charges for the usage of resources for which I am no longer responsible.



Conceptual Objective 2: Executing domestic energy services

This Conceptual Objective is concerned with ensuring that operational limits of devices and appliances are not exceeded such that they continue to support the ESP in ensuring that consumer expectations are met.

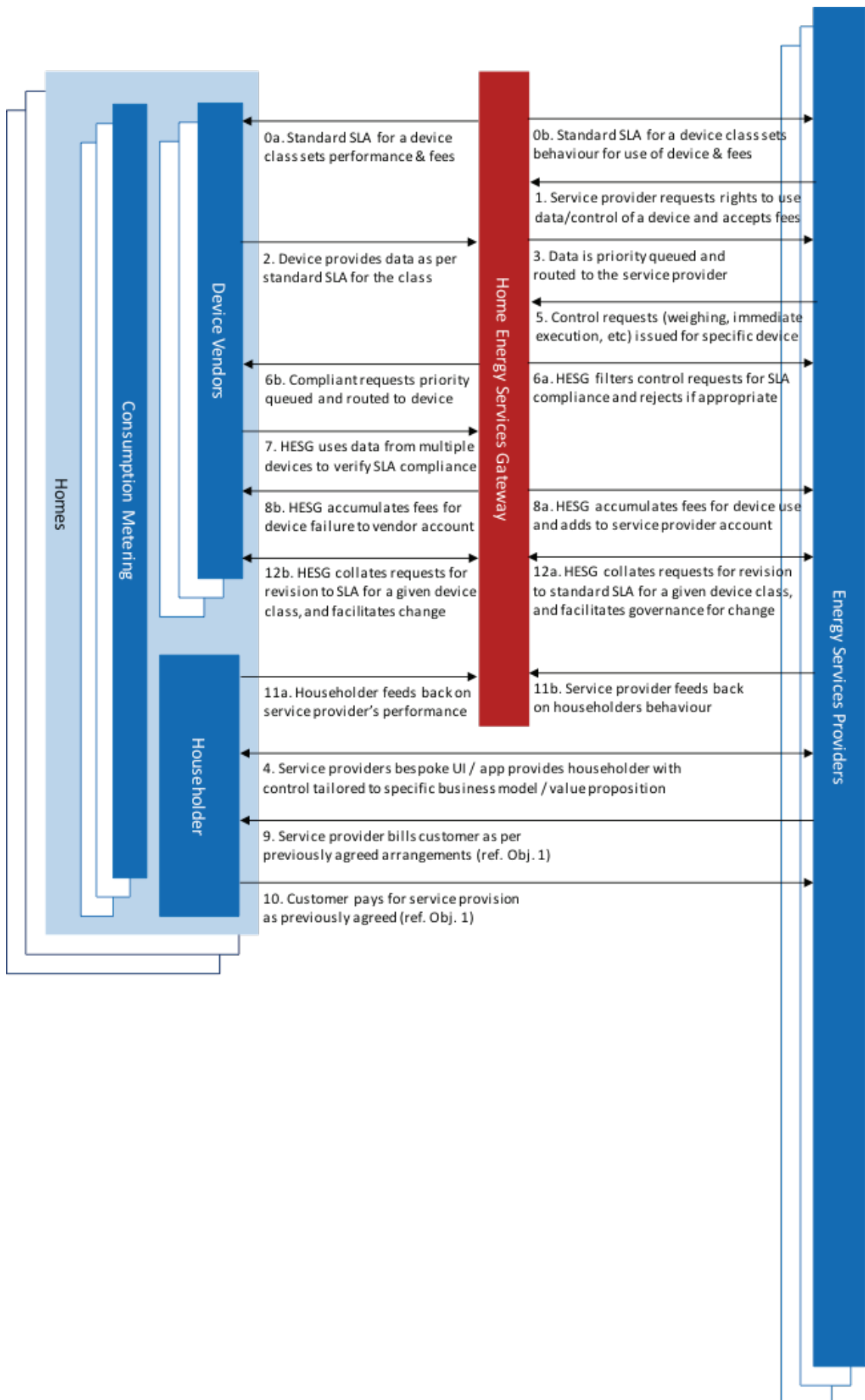
Within this Conceptual Objective, the following Architectural User Stories are covered for particular actors:

voice in the evolution of the SLA for a given class of device. The SLA would define the data that the device will produce, what control inputs the device will accept, the performance of the device in response to such control inputs, the fees that an Energy Service Provider will pay the Device Vendor for use of a given device, the fees that a Device Vendor will pay an Energy Service Provider in the event of failure of a device to meet the terms of the SLA, etc.

Actor	#	Architectural User Story
Energy Service Provider	2-1	As an Energy Service Provider, I want to be confident that devices in my customers' homes will perform in the way that I expect and, if not, I will be recompensed so I can meet my promises to Householders.
Device Vendor	2-2	As a Device Vendor, I want to be confident that my devices will not be used in a way that impacts on reliability so that my reputation is not harmed.
	2-3	As a Device Vendor, I want to capture a share of the value enabled by the data/control capabilities of my products so that I am compensated for the additional competitiveness risks introduced by open standards compliance.
Householder	2-4	As a Householder, I want to be in control of configuring my service (within the terms of service agreed in UC1) so as to best meet my day-to-day needs.

A high level logic sequence (to be read in the numbered order as opposed to vertical flow), by which the above Architectural User Stories are achieved within Candidate 10 (as down-selected within Appendices A1 and A2) is outlined below.

It is unlikely to be desirable to execute the majority of control through immediate execution requests. Instead, some form of weighted probability distribution that can evolve in response to empirical evidence on how the system behaves is more likely to be appropriate. Standard Service Levels Agreements (SLAs) would be defined by the Home Energy Services Gateway for specific classes of device, with appropriate governance to ensure Device Vendors and Energy Service Providers have a



Conceptual Objective 3: Householders raising service complaints

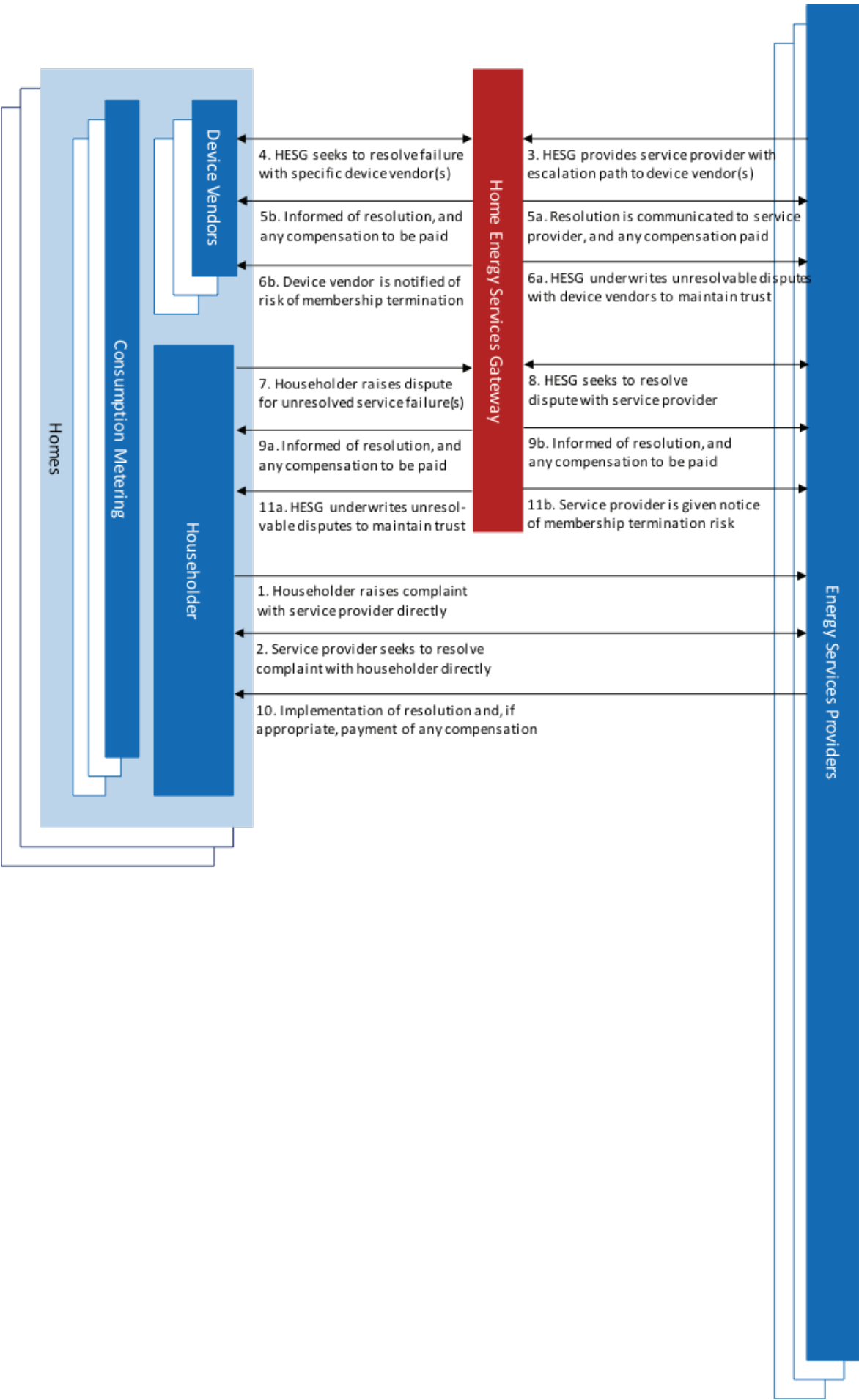
This Conceptual Objective is included to ensure that there is a path to manage complaints where consumer expectations are not met whilst giving the ESP the escalation path with other providers to ensure that matters are adequately managed.

Within this Conceptual Objective, the following Architectural User Stories are covered for particular actors:

Actor	#	Architectural User Story
Energy Service Provider	3-1	As an Energy Service Provider, I want to have the first opportunity to rectify any issues my customers have with my quality of service so that I can maintain customer satisfaction and protect my reputation.
	3-2	As an Energy Service Provider, I want to have an escalation path for issues with the performance of a particular Device Vendor's products that impacts my ability to execute services so I can maintain customer satisfaction.
Householder	3-3	As a Householder, I want to be confident that I have an escalation path in the event that I can't get my complaint resolved by my Energy Service Provider so that I don't get trapped with an underperforming Provider.
	3-4	As a Householder, I want to be confident that, in the event of my Energy Service Provider failing to deliver on its service promises and failing to resolve my complaint, that someone will underwrite my losses.

A high level logic sequence (to be read in the numbered order as opposed to vertical flow), by which the above Architectural User Stories are achieved within Candidate 10 (as down-selected within Appendices A1 and A2) is outlined below.

The majority of services should be executed by service providers without complaint, but where things go wrong the service provider should first be given opportunity to resolve it, which may require the HESG to help with issue resolution where it is caused by issues with one or more device vendors. For the remaining (small number of cases), the HESG needs to provide dispute resolution services which should resolve the majority of any remaining issues. In order to maintain trust, a very small number of residual issues may require underwriting by the HESG.



Conceptual Objective 4: Building up the energy resources supply chain

This Conceptual Objective details how actors co-operate to build up their supply position to support an ESP in delivering on customer expectations.

Within this Conceptual Objective, the following Architectural User Stories are covered for particular actors:

Service Level Agreements via the ERSG to define resource constraints / flexibility to match demand constraints / flexibility agreed with householders via the HESG. The Energy Service Providers are, in effect, the counterparty buying asset capacity (as opposed to business as usual today where this is, in effect, the state). By offering householders different service levels, and buying different resource service levels, revealed consumer preferences drive supply chain evolution (as opposed to business as usual least cost modelling today).

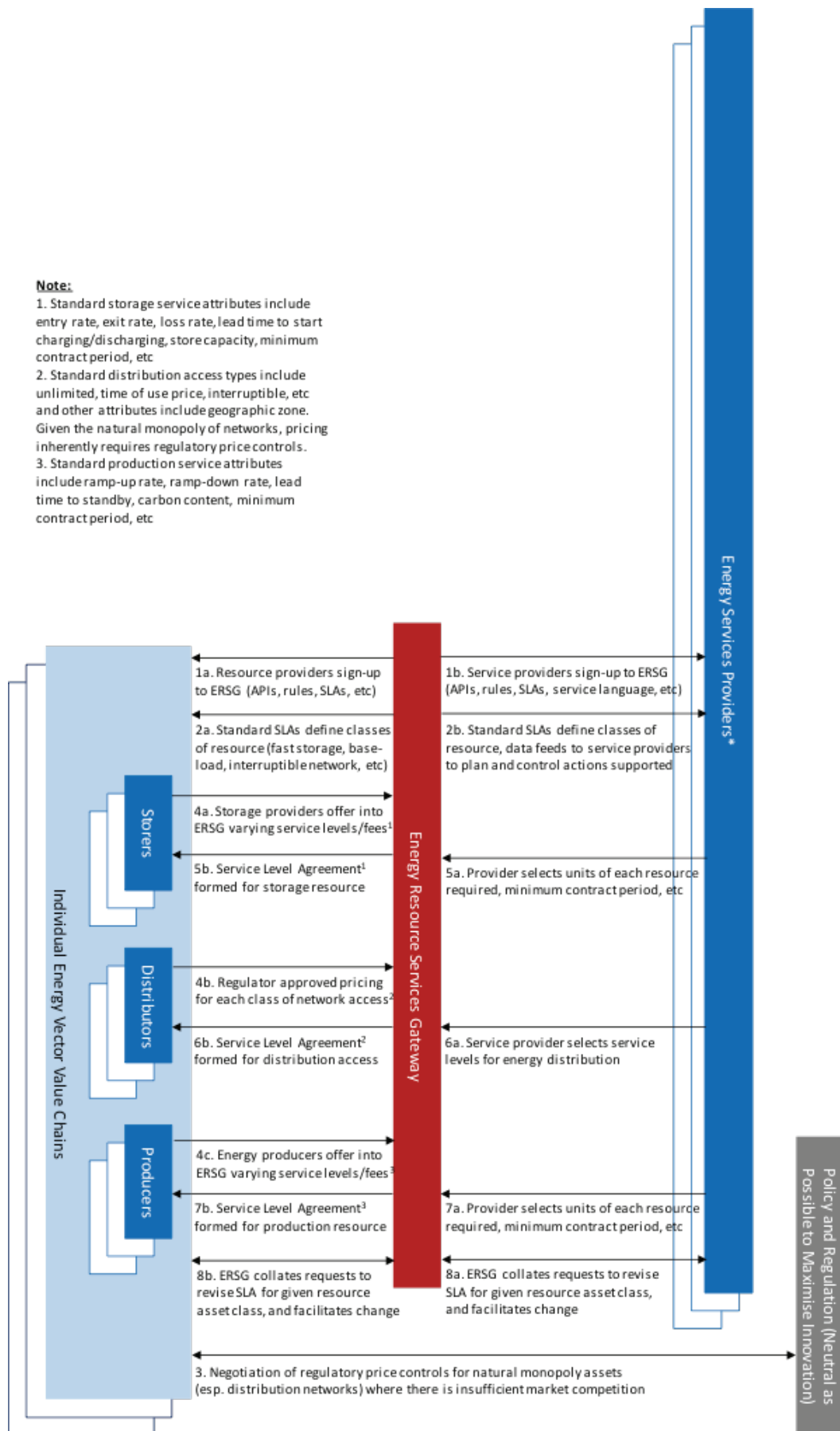
Actor	#	Architectural User Story
Energy Service Provider	4-1	As an Energy Service Provider, I want to build a supply chain with a portfolio of resources that, on aggregate, provide sufficient capacity headroom so I can be confident of meeting service promises I have made to Householders.
Storage Provider	4-2	As a Storage Provider, I want to form an agreement with an Energy Service Provider that articulates the practical constraints of my asset(s) such as entry rate, exit rate, loss rate, lead time to start charging/discharging, store capacity, etc. so I am not obligated to deliver outside my capabilities.
	4-3	As a storage provider, I want to have a sufficiently long duration of commitment from one or more Energy Service Providers to underpin my business case for long-term asset investment.
Distribution Provider	4-4	As a Distribution Provider, I want to be able to offer different levels of network access (unlimited, time of use price, interruptible, etc.) that enables me to reveal consumer preferences on which to base future network plans.
Regulator	4-5	As the Regulator, I want to maintain price regulation for distribution network access given the natural monopoly of a network does not lend itself to a competitive tension, so as to protect consumers.
Production Provider	4-6	As a Production Provider, I want to form an agreement with an Energy Service Provider that articulates the practical constraints of my asset(s) such as ramp-up rate, ramp-down rate, intermittency due to wind availability, lead time to standby, carbon content, etc. so I am not obligated to deliver outside my capabilities.
	4-7	As a Production Provider, I want to have a sufficiently long duration of commitment from one or more Energy Service Providers to underpin my business case for long-term asset investment.

A high level logic sequence (to be read in the numbered order as opposed to vertical flow), by which the above Architectural User Stories are achieved within Candidate 10 (as down-selected within Appendices A1 and A2) is outlined below.

Energy Service Providers optimise their selection of resource assets strategically and well in advance of actual usage to ensure sufficient flexibility to meet service obligations agreed with householders via the HESG; i.e. forming

Note:

1. Standard storage service attributes include entry rate, exit rate, loss rate, lead time to start charging/discharging, store capacity, minimum contract period, etc
2. Standard distribution access types include unlimited, time of use price, interruptible, etc and other attributes include geographic zone. Given the natural monopoly of networks, pricing inherently requires regulatory price controls.
3. Standard production service attributes include ramp-up rate, ramp-down rate, lead time to standby, carbon content, minimum contract period, etc



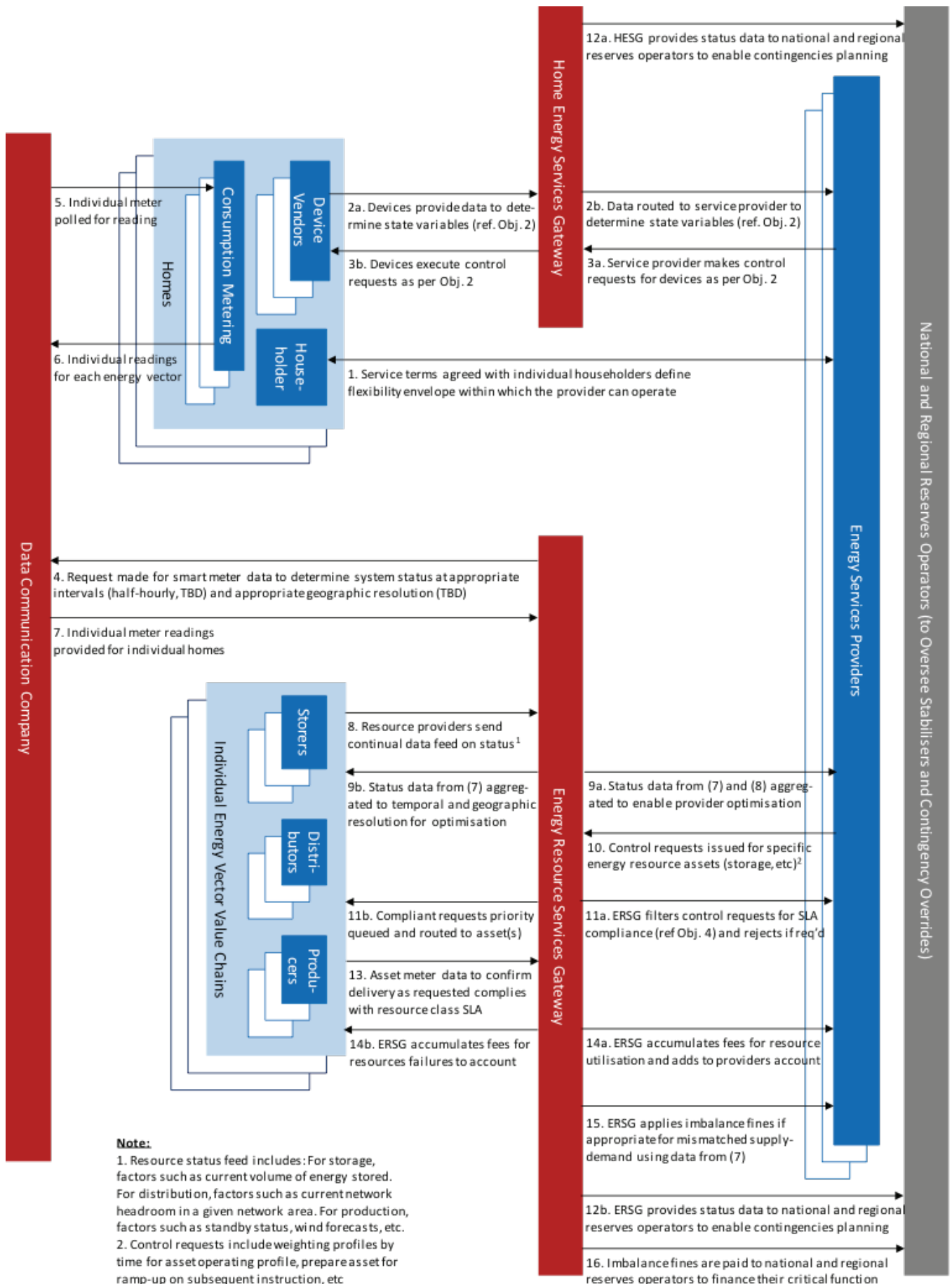
Conceptual Objective 5: Closing out supply-demand

This Conceptual Objective details how actors co-operate to balance supply and demand leaving the reserves operator(s) to manage large scale disturbances only.

Within this Conceptual Objective, the following Architectural User Stories are covered for particular actors:

Actor	#	Architectural User Story
Reserves Operator(s)	5-1	As the Reserves Operator, I want to ensure Energy Service Providers use all levers at their disposal to balance their own supply-demand positions so my role is limited to oversight and intervention only for special contingencies.
	5-2	As the Reserves Operator, I want to ensure I have early visibility of system state so that I can prepare for any special contingency interventions.
Energy Services Provider	5-3	As an Energy Service Provider, I want to have a continual flow of status data (for storage, factors such as current volume of energy stored; for distribution, factors such as current network headroom in a given area; for production, factors such as standby status, wind forecasts) on which to base my operations so I can meet my customer service promises at the least cost.
	5-4	As an Energy Service Provider, I want to have a set of control levers (control levers include: weighting profiles by time for asset operating profile, request to prepare asset for ramp-up on subsequent instruction, etc.) to enable me to optimise the way in which I utilise my chosen supply chain so I can meet my customer service promises at the least cost.
Regulator	5-5	As the Regulator, I want to ensure there is a common 'weights and measures' compliant metering arrangement that achieves transparency to the actions of actors across the system so as to identify and penalise behaviours that seek to destabilise the system for commercial gain.

A high level logic sequence (to be read in the numbered order as opposed to vertical flow), by which the above Architectural User Stories are achieved within Candidate 10 (as down-selected within Appendices A1 and A2) is outlined below.



Conceptual Objective 6: Stabiliser mechanisms and special contingency overrides

This Conceptual Objective details how the reserves operator(s) manage stabilising and special contingency measures and the knock on impacts to other actors.

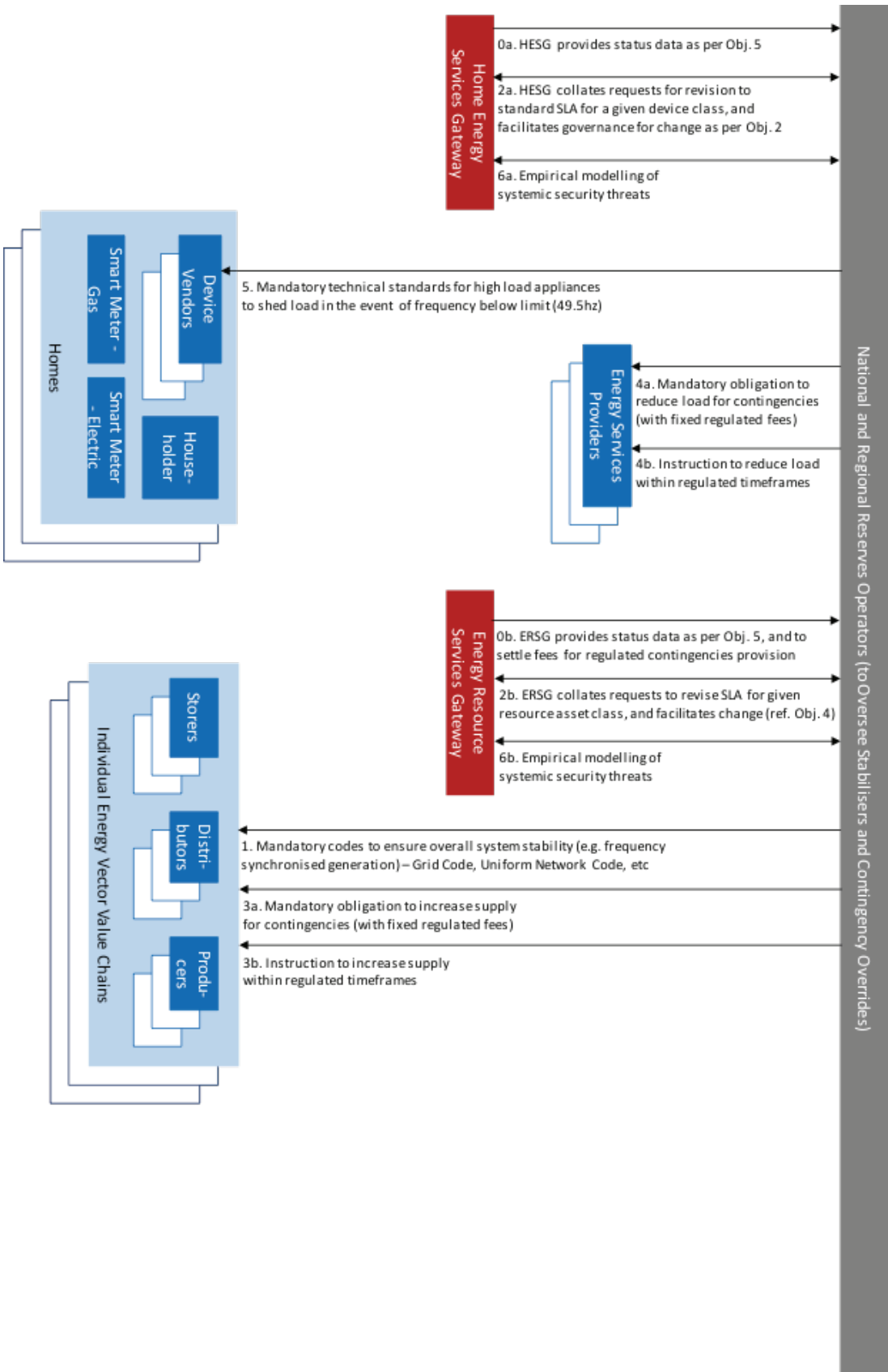
Within this Conceptual Objective, the following Architectural User Stories are covered for particular actors:

position should be punitive to ensure commercial incentive to behave in the collective interest. However, there will remain a need for active stabilisers for second-by-second balancing (e.g. frequency synchronised generation plant), routine contingency measures (e.g. Reserves Operators paying for energy service providers to reduce demand in the event of a short-notice plant failure) and emergency contingency overrides (e.g. frequency responsive appliances to shed load under extreme conditions such as black start).

Actor	#	Architectural User Story
Reserves Operators	6-1	As the Reserves Operator, I want to have a governance role in the key enabling Gateways, especially the Service Level Agreements for the way in which devices (via the HESG) and resources (via the ERSG) can be controlled by Energy Services Providers so as to maintain inherent system stability.
	6-2	As the Reserves Operator, I want to have a governance role in the evolution of mandatory codes (such as the Grid Code, Uniform Network Code, etc.) so as to maintain key stabilisation features of the physical energy chain (such as frequency synchronised generation, frequency responsive devices for critical system events such as a frequency drop below 49.5Hz, etc.).
	6-3	As the Reserves Operator, I need to have sufficiently large levers (much larger than the GBSO has at its disposal today) to compensate for major system failure modes (such as complete failure of the telecommunications infrastructure in a geographic area) so as to avoid catastrophic failures.
	6-4	As the Reserves Operator, I want to have the ability to gather insight on the behaviour of the system so as to identify potential future systemic threats, including cyber-security resilience, and undertake mitigating actions so as to avoid future catastrophic failures.
Energy Service Provider; Storage/ Production Provider; etc.	6-5	As an actor in the system, I want to be financially compensated in the event of major contingency override levers being executed so as to resolve the losses I will have incurred due to customer dissatisfaction, asset failure, etc.

A high level logic sequence (to be read in the numbered order as opposed to vertical flow), by which the above Architectural User Stories are achieved within Candidate 10 (as down-selected within Appendices A1 and A2) is outlined below.

Primary balancing should be achieved by energy service providers, together with stabiliser mechanisms embedded into Service Level Agreements (e.g. randomised delays to control executions) for control of particular classes of device (via the HESG) and resource asset (via the ERSG). Imbalance fines (as per Conceptual Objective 5) for a mismatched supply-demand



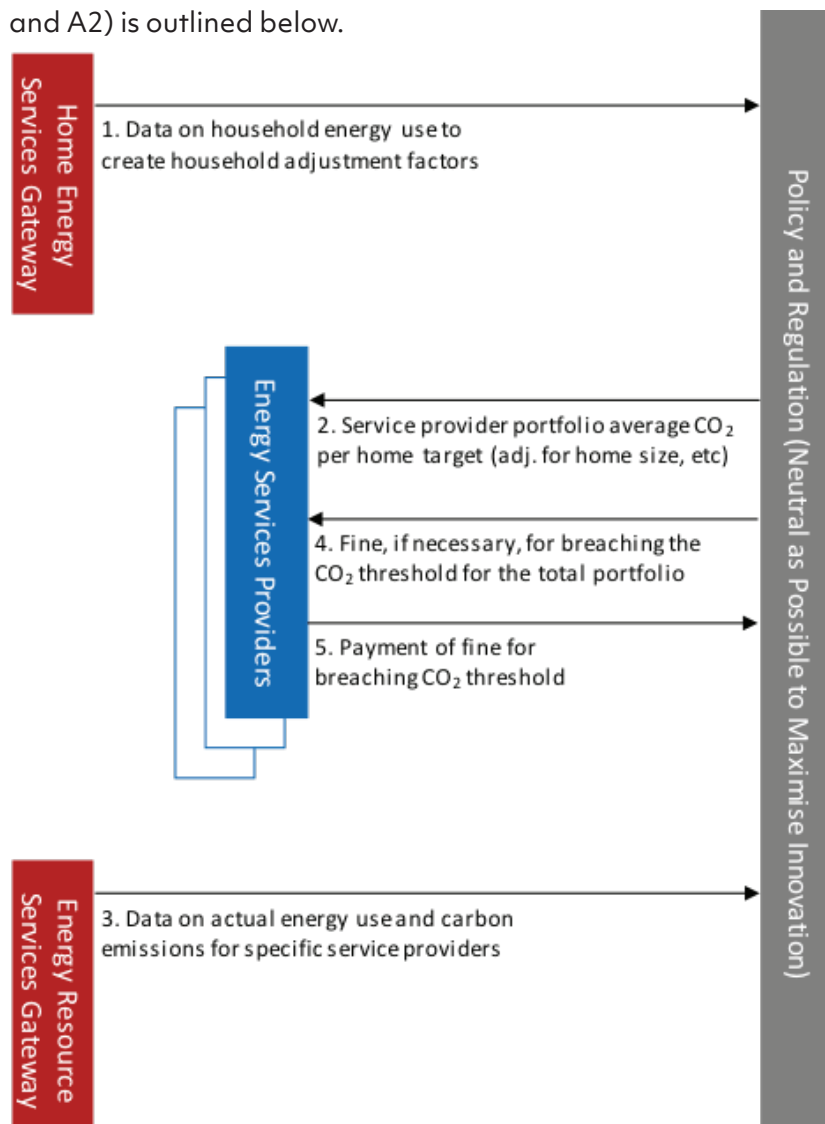
Conceptual Objective 7: Internalisation of carbon costs

This Conceptual Objective details how the policy maker(s) can drive de-carbonisation.

Within this Conceptual Objective, the following Architectural User Stories are covered for particular actors:

Actor	#	Architectural User Story
Policy Maker	7-1	As a Policy Maker, I want to have a technology agnostic means to internalise carbon cost such that Energy Service Providers seek to discover through innovation and competition the best path to zero carbon buildings (including fabric efficiency, appliance efficiency, control optimisation, supply-demand balancing, low carbon energy production, storage, etc.).

A high level logic sequence (to be read in the numbered order as opposed to vertical flow), by which the above Architectural User Stories are achieved within Candidate 10 (as down-selected within Appendices A1 and A2) is outlined below.



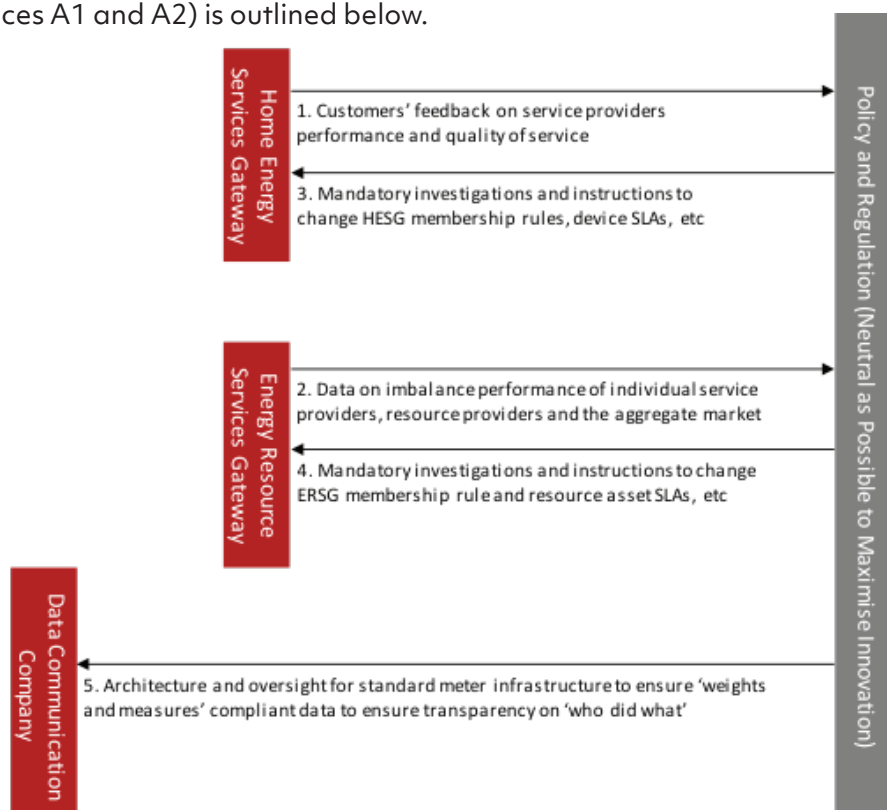
Conceptual Objective 8: Regulatory oversight of market effectiveness

This Conceptual Objective is concerned with how the regulator maintains oversight and control.

Within this Conceptual Objective, the following Architectural User Stories are covered for particular actors:

Actor	#	Architectural User Story
Regulator	8-1	As the Regulator, I want an effective marketplace where Energy Service Providers' performance is transparently available to other customers so I can be confident there is sufficient market pressure to protect consumers.
	8-2	As the Regulator, I want an effective operating environment with sufficient penalties for Energy Service Providers that fail to balance their supply-demand position so as to minimise socialisation of system balancing costs.
	8-3	As the Regulator, I would be able to generate insight on how different customer segments are being treated so as to ensure the most vulnerable are not being exploited by Energy Service Providers.
	8-4	As the Regulator, I would have the ability to undertake investigations and implement mandatory resolutions to ensure the HESG and ERSG both promote innovation while protecting system resilience.

A high level logic sequence (to be read in the numbered order as opposed to vertical flow), by which the above Architectural User Stories are achieved within Candidate 10 (as down-selected within Appendices A1 and A2) is outlined below.

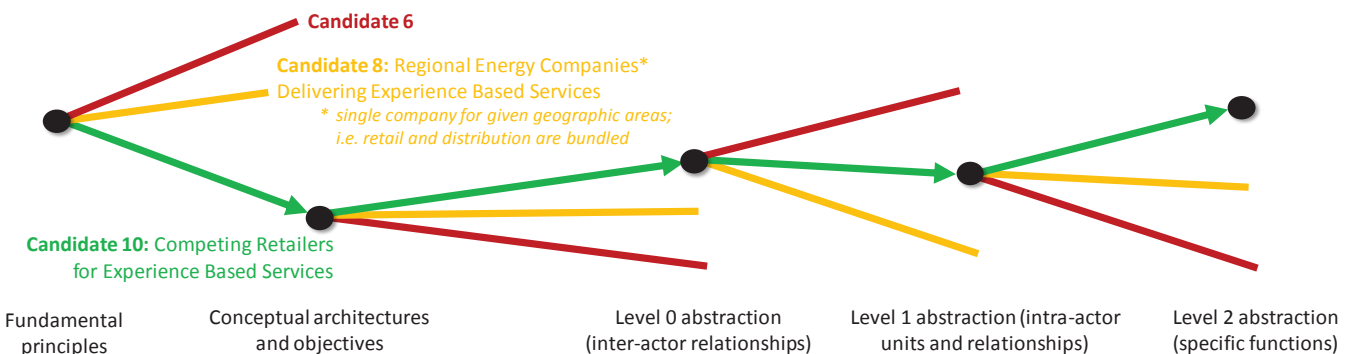


Appendix C: Risk Assessment to Realising Candidate 10

There are some key risks to Candidate 10. Their applicability to the other Candidates and the required approach to risk reduction is outlined below. This table represents an initial start and is not exhaustive, further risks will be discovered as the project unfolds. The risks are being systematically identified and their mitigation should be the focus of the first iterations around the systems integration V model set out on page 2.

Where a risk cannot be solved for Candidate 10 then the decision might be taken to move to pursue more detailed understanding of the next best Candidate, in this case, Candidate 8. Where a risk is currently shown to affect all the down-selected Candidates then mitigating the risk becomes a priority as none of the preferred choices might be viable.

	Applies to Candidate				De-risking approach		
	10	8	6	2	Paper based analysis	Whole systems model	Proto-type and trials
Whether sufficient data quality can be obtained to price risk in experience based energy services	✓	?	?				✓
Whether a shared service language can be formed to describe experience based energy services	✓	✓	✓	✓			✓
Whether the financial motivations of device vendors and service providers are sufficiently attractive to make it a commercially viable business	✓				✓	✓	?
Whether consumers value the advanced services sufficiently to justify costs	✓	✓	✓	✓			✓
Whether weighting profiles can deliver sufficiently predictable aggregate response of distributed devices	✓	?	?			✓	?
Whether energy service providers can build a sufficiently strong balance sheet to be a sufficiently low credit risk for long-term energy resource SLAs	✓				✓		
Whether distributed control can close out supply-demand sufficiently closely to manage system frequency, voltage, pressure, etc.	✓	?	?			✓	?
Whether suitable contingency measures can be implemented, such as frequency responsive devices, to deal with major cyber-security threats	✓	✓	✓	✓		✓	✓



Appendix D: Description of the Actors in Candidate 10

Early work was focused on building a deep internal knowledgebase to adequately understand the problem space as a critical foundation for producing the tangible outputs required of Work Package 3. This included study of electricity, gas and heat system operating dynamics, infrastructure planning policy and processes, carbon policy and investment dynamics, consumer service needs, information systems capabilities, etc.

A set of Fundamental Principles for the Future GB Energy System, summarised in section 4.1, has been created from this deep internal knowledgebase. The Future Power System Architecture (FPSA) project⁶ also identified 35 new ‘functions’ the Power sector needs to provide for in future; which were also accounted for during work on the SSH programme.

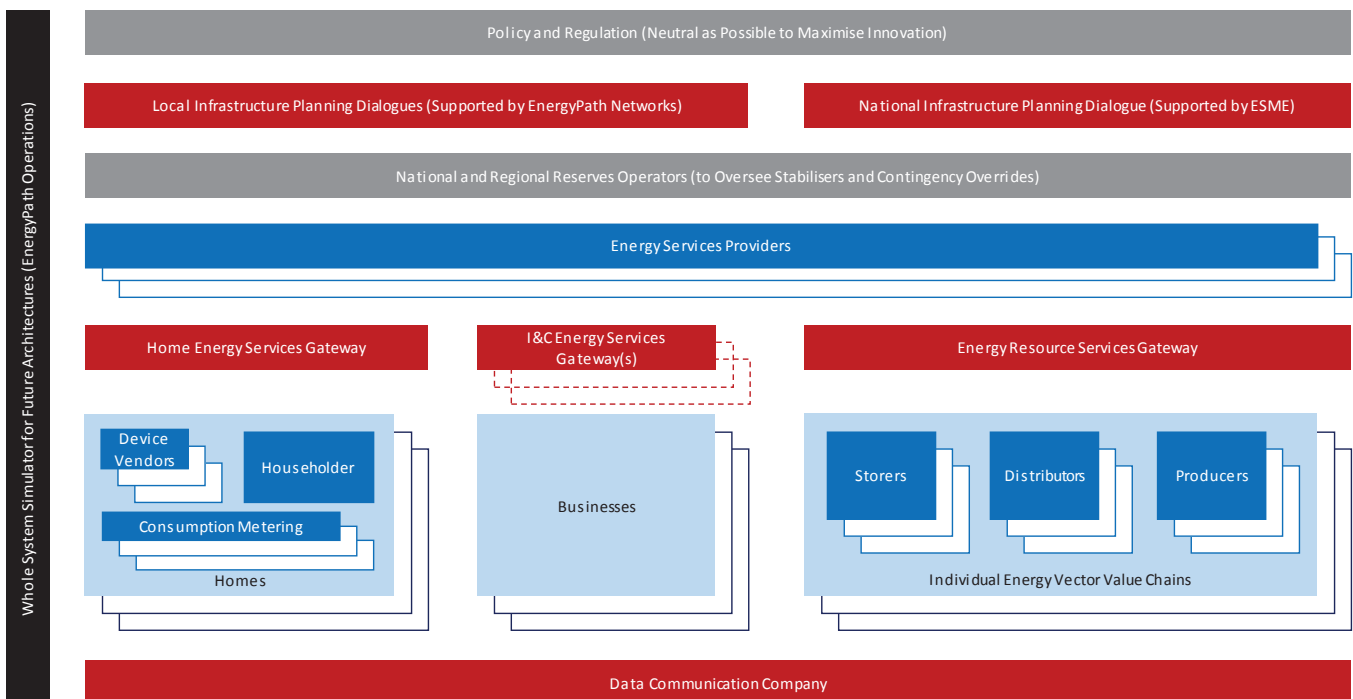
Work to date has identified options for the system of systems architecture, as set out in Appendix B1, which have been evaluated against the above Fundamental Principles, as summarised in

Appendix A2, to select a specific candidate for further detailing to prove the process. Candidate 10 is summarised below.

A holistic concept of operations for Candidate 10 has been described in Appendix C using a set of logic sequences that show how different actors interact with one another to achieve overall ecosystem objectives. As a summary, the key elements are described individually below.

There are risks inherent in down-selecting to a specific candidate, as summarised in Appendix C, and if these cannot be closed out successfully it would be necessary to revert to an alternative candidate.

There are two different types of Enabling Platform within the Shared Ecosystem. The first, Planning Dialogues, enable collective decision making for decisions where competitive market forces are unlikely to play out to any form of effective decision due to natural monopolies; for example, local area network planning. It is critical



⁶ <https://es.catapult.org.uk/projects/future-power-system-architecture-fpsa/>

that these are sponsored by an entity with a democratic mandate to make collective decisions on behalf of end consumers; which means local, regional or national government. It is also critical that the whole process is engaging, transparent and objective to build and maintain trust. The second, Gateways, enable multiple Individual Actors to form commercial value chains where competitive market forces can play out to reach effective decisions that government can hence be largely agnostic about; for example, multiple electricity network operators trading network capacity with multiple Energy Services Providers trading demand flexibility.

Enabling Platform: Home Energy Services Gateway

Many different companies are developing connected home devices, and increasingly the appliances people buy such as boilers, electric vehicles, fridges and ovens are also becoming connected. While the increasing level of information and control is of benefit in and of itself, there is little innovation in the new domestic energy services that will be required to drive elimination of carbon from homes. Indeed, while the number of connected things is on the rise, very few of them are connected beyond the commercial domains of their individual vendor; in other words, they are connected but not available to service innovators. Households value the experiences their use of energy affords, such as a warm home, more than fuel or appliances; in other words, they care about service outcomes far more than commodity inputs. The Home Energy Services Gateway is an open intermediary to connect any Householder to any Energy Services Provider; and any Energy Services Provider to any device from any Device Vendor⁷.

- For Householders, it enables comparison of offers from competing service providers with a comparable language of service attributes and performance levels; and it enables use of their data to drive a market instead of being tied-in

to a limited range of services locked to closed devices.

- For Energy Services Providers, it establishes a common language with which to understand, shape and bound a Householder's service expectations; and it enables access to the critical data and devices Services Providers require to design, price and deliver innovative high value services.
- For Device Vendors, it enables access to a new revenue stream in return for making their devices available to Energy Services Providers for the purposes of executing new services. Device performance, usage permissions and any fees are defined in standard device class Service Level Agreements, as described further under the 'Individual Actor: Device Vendors' heading below.
- For product and service developers it enables revealed consumer preferences to drive investment.

Enabling Platform: Industrial and Commercial Energy Services Gateway(s)

Unlike for homes and, to a certain extent, other low volume consumers with similar needs such as a local clothes shop, industrial and commercial consumers have vastly different needs. For example, managing energy use for a cold warehouse is entirely different from, say, a car factory. There are numerous commercial organisations already providing bespoke energy management services for some Industrial and Commercial (I&C) segments where the use cases are relatively straightforward and the consumption volumes are sufficiently high to pay back on the relatively high costs for these bespoke services. For such services to become more widespread to I&C segments where the use cases are more nuanced and the consumption volumes are insufficient to pay back on bespoke services, the same principle as the Home Energy Services Gateway applies: enabling any Business to

⁷ It should be noted that, while the Home Energy Services Gateway defined here is similar to that in other candidate architectures described in Appendix A1, there are fundamental differences in its business model between the candidates; although the core technical functionality is likely to be very similar between the candidates.

connect to any Energy Services Provider offering propositions relevant to their I&C segment; and any Energy Services Provider to connect to any relevant Plant from any Vendor to deliver that service. The need for standard service attributes and performance levels, and the need for very particular classes of Plant to be integrated, that are specific to a particular I&C segment, may well necessitate a need for multiple I&C Energy Services Gateways. There are already companies providing aggregation services for I&C consumers that may evolve into such open Gateway(s).

Enabling Platform: Energy Resource Services Gateway

The price for a defined product or service provides the critical information on which Individual Actors can make choices in both strategic and operational timeframes. The way in which the product or service is defined is hence critical to whether or not the price information provides the appropriate signals. Service Level Agreements are a key concept to support value chain unbundling. Standard classes of Service Level Agreement comprised of a set of parameterised service attributes and service levels provide consistent commercial terminology to minimise transaction costs between many-to-many Individual Actors. For example, a standard class of SLA for a generating plant would include service attributes such as ramp-up rate and the buyer and seller would agree the service levels for each of the attributes; with higher service levels attracting higher prices, which reveals the value of particular attributes to drive decision making in asset investment time horizons. The capacity of the asset can then be used within the terms of the Service Level Agreement to drive decision making in operational time horizons. There are some specific challenges in the energy system that need to be managed; for example:

- In electricity generation, it is necessary to maintain an operational margin in total capacity, which drives the price for a unit of energy produced towards the marginal cost; inhibiting capital recovery unless capacity is traded.
- In operational optimisation for electricity, the vastly different marginal costs between renewables (e.g. <math><1\text{p/kWh}</math> for wind) and other

plant (e.g. >5p/kWh for a gas turbine) leads to highly volatile spot markets, which means unit commodity price is a poor operational optimisation signal.

The Energy Resource Services Gateway enables any Energy Services Provider to form Service Level Agreements with any Resources Provider for any energy vector. These Service Level Agreements effectively provide the Energy Services Provider with the right to use a certain amount of capacity of a set of a Resource Provider's assets under a defined set of conditions/constraints. The service attributes include:

- Storage: entry/loss/exit rates, lead time to start charge/discharge, capacity, contract period, etc.
- Distribution: access types (such as unlimited, time of use price, interruptible, etc), geographic zone, etc. Given the natural monopoly of networks, pricing inherently requires regulatory price controls.
- Production: ramp-up/-down rates, lead time, intermittency, carbon content, contract period, etc.

The Energy Resource Services Gateway also facilitates bi-directional status and control information flows between Resource Providers and Energy Services Providers to enable the various actors to optimise their operations.

- The resource status feeds include: for storage, factors such as current volume of energy stored; for distribution, factors such as current network headroom in a given network area; and for production, factors such as standby status, wind forecasts, etc.
- The resource control requests include: for storage, factors such as time profile of energy to take-in/-out; for distribution, factors such as network operator requests to curtail demand; for production, factors such as the time profile for energy production, standby preparedness and short-notice requests to increase or decrease production.

Consumption Metering collated via the Data Communications Company enables Service Level Agreement compliance and usage to be traced for the settlement of transactions between Energy Services Providers and their Resource Providers.

Enabling Platform: Data Communications Company

The Data Communications Company enables data from Consumption Meters at the individual Home or Business level to be collated by the Energy Resource Services Gateway in order to verify Service Level Agreement compliance and actual usage for settling transactions between Energy Services Providers and Resource Providers. This may require evolution of existing arrangements.

Individual Actor: Energy Services Providers

Energy Services Providers essentially take responsibility for ensuring agreed service outcomes are delivered to Householders and/or Businesses. They assemble the required supply chains and optimise their day-to-day operations to drive-up customer satisfaction while driving-down costs. They are the counterparty for energy Resource Provider capacity contracts. They are not attached to any particular distribution network, so they must compete with one another. There will be a diverse range of different business models, but they are likely to have some similar general characteristics as outlined below.

- **Focus on customer service outcomes:** the Services Provider takes full responsibility for the units of energy (i.e. kWh) consumed, and the customer pays only for the service outcomes they value (e.g. a warm home on time, a defined time to warm-up on demand, etc).
- **Uses data to underpin customer-centricity:** the Service Provider structures its sales process to elicit customers' willingness to pay for different attributes of service and determine how they expect to use a product or service; and then uses data on how they actually use it to refine its offerings.
- **Integrates low carbon heat components:** the Services Provider would operate a field force, either in-house or outsourced, capable of integrating a set of components in a customer's premises in order to deliver the service outcomes they have agreed with that customer.

- **Provides guarantees on the performance of any installation:** the Services Provider would use data to determine actual performance and compares it with estimates; and so identify quality issues to ensure its business is sufficiently repeatable to guarantee performance/costs.
- **Becomes a technology-agnostic channel to market for low carbon products:** the Services Provider would work with products from a wide range of vendors, provided they are designed to work within an open architecture such that they can be integrated to delight customers.
- **Provides frontline customer support and maintenance:** the Services Provider would be the first port of call for a customer with regard to any issues associated with their use of energy at home.
- **Works to optimise its operations to drive-up customer satisfaction and drive-down cost (and, within the right policy environment to internalise carbon costs, carbon emissions):** the Services Provider would exploit advanced machine learning and big data analytics to identify opportunities to continually improve its business in investment and operational timeframes.

Once Services Providers know how to incorporate risks within the pricing of their services, an innovative new avenue opens up for delivering deep decarbonisation. Essentially, the Services Provider becomes a new channel to market for low carbon options because Householders and Businesses trust them to deliver service outcomes as they have learnt how to integrate multiple components into effective systems. This unlocks benefits to the whole energy supply chain: increased focus on driving-up customer value delivery as well as driving-down cost, reduced cost of sales, reduced risk exposure, greater customer confidence and trust due to real-world data to confirm actual performance, optimisation across vectors, etc. For example:

- Identifying Homes where Households would benefit from investing in fabric retrofit and producing data on effectiveness of measures installed to support performance guarantees.
- Guaranteeing continuation of service performance when a heat pump replaces a

boiler, and financing the asset, maintenance and energy use; avoiding uncertainty for Householders.

- Giving heat network developers confidence that enough households in a given area will be connected quickly enough to repay their capital investment, since the network developer now only need talk to a few Services Providers not every individual Householder. The Local Infrastructure Planning Dialogue (supported by EnergyPath Networks) facilitates this multi-party dialogue.
- Similarly, providing electricity network operators confidence on rate of offtake in a given geographic zone for the major upgrades required to support deep electrification of heat.
- Creating flexibility in how and when energy is delivered to meet agreed service levels⁸, to help Resource Providers integrate inflexible nuclear, manage intermittent renewables, etc.
- Offering performance based contracts to local authorities and/or others for tackling fuel poverty; guaranteeing agreed thermal conditions are achieved for vulnerable citizens.

Each Energy Services Provider will have different but equally sophisticated business models, processes and Information and Computing Technology (ICT) systems for strategic and operational portfolio optimisation.

Individual Actor: Resource Providers (Production, Distribution, Storage for each Vector)

The Resource Providers compete to offer a variety of resource Service Level Agreements to Energy Services Providers, using the standard service attributes and performance levels facilitated via the Energy Resource Services Gateway. Resource Providers actively manage their portfolio of assets, encompassing production, conversion, distribution and/or storage; across the energy

vectors of electricity, heat, gases and/or liquid fuels. Each Resource Provider will have different but equally sophisticated business models, processes and Information and Computing Technology (ICT) systems for strategic and operational portfolio optimisation.

Individual Actor: Device Vendors

The 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 mechanisms for stakeholders to add, modify or retire device classes.

Individual Actor: Householders and Businesses

Generally, Householders and Businesses are likely to buy outcome based services from Energy Services Providers as opposed to input commodities. However, if a Householder or Business wants to remain directly exposed to input commodity pricing then undoubtedly there would be offerings from Energy Services Providers to cater for that. The whole energy value chain in the market arrangements described herein is driven by customer value optimisation, crucially in terms of needs that the use of energy satisfies; to understand it, shape it and deliver on it. Consumers' needs and preferences vary enormously, as do the conditions and constraints of their homes and businesses. Services hence need to be highly tailored.

⁸ Flexibility is created by exploiting storage inherent in fabric of homes, hot water tanks, electric vehicles, etc; and exploiting the ability to switch energy vector in hybrid configurations. This flexibility is a by-product of moving the service relationship away from input commodity use where the Householder takes the risks on how and when energy is used; instead to outcome guarantees where the Service Provider takes those risks.

Enabling Platform: Local Infrastructure Planning Dialogues

Work Package 2 within the Smart Systems and Heat programme has established a new tool, EnergyPath Networks, a methodology/process and the staff expertise for helping a group of stakeholders at the local level to understand their future infrastructure planning choices and to decide on where to focus their efforts over the next five years. This is being tested with three local areas, which is due to conclude at the end of 2017. This is critical for local infrastructure choices where natural monopoly limits the effectiveness of market forces; especially pipes and wires network investments and land use planning for local energy assets. The process is sponsored by local and/or regional government, as the only entity with a democratic mandate to make such decisions, but also needs to engage local network companies and Energy Services Providers with a local presence. It is expected that revealed consumer preferences (willingness to pay for different service attributes) generated via the Home Energy Services Gateway would be aggregated, generalised and anonymised such that local infrastructure planning can be driven toward value optimisation as opposed to just least cost optimisation.

Enabling Platform: National Infrastructure Planning Dialogue

Similarly to the challenge of natural monopoly limiting effectiveness of market dynamics at the local level for certain infrastructure choices, there are certain national infrastructure choices that equally require democratic decision making. For example: transmission network choices, land use prioritisation to enable large-scale nuclear generation, liabilities for long-term CO₂ or radioactive waste storage, etc. A similar national level dialogue is required, sponsored by central government, and supported by equivalent techno-economic analysis capability for the national energy system.

Reserves Operator(s): Stabiliser Mechanisms and Special Contingency Overrides

The Reserves Operator(s) provides two critical functions: to oversee stabiliser mechanisms; and to oversee special contingency overrides. As a result of customer convenience applications, such as remote heating controls, remote plug-in vehicle recharging and pre-heating controls and so on, the traditional view that the GB System Operator holds the only substantive co-ordinated levers for active demand management will be decreasingly the case. The addition of Energy Services Providers with an active customer service execution role and the addition of active Distribution System Operators further increases the number of parties with significant volumes of supply and/or demand under active management. The magnitude of these levers to manipulate supply and/or demand will often far exceed that which the GB System Operator currently has at its disposal. As a trivial example, consider an Energy Services Provider managing 6kW electric immersion heaters in just 500k Homes resulting in 3GW of demand under active management; against the 1-2GW worth of active supply and/or demand the GB System Operator currently has under active management. There are hence two key requirements:

- Stabiliser Mechanisms need to be built-in and maintained through the Gateways described above; for example, by including in a standard device class Service Level Agreement through the Home Energy Services Gateway a random delay function to smooth out execution of demand controls. In addition to synchronised generating plant and other frequency responsive assets, this should ensure the system is sufficiently stable over a sufficient time horizon for the balancing processes of the Energy Services Providers to take effect for bulk supply vs. demand balancing.
- Special Contingency Overrides need to be built-in at the lowest level to deal with major systemic threats; for example, by including a requirement for major energy appliances to respond to

the extreme system frequencies that might be caused by a major cyber-security incident. Resolution of commercial liabilities created by such extreme action would need to be dealt with by regulation.

Frequency responsive appliances at the building level are not presented as a primary system stabilising mechanism, since the frequency of the system is a product of collective action and not a product of any Individual Actor's behaviour. It is essential that, under normal operating conditions, there is clear traceability to the supply vs. demand position each actor is responsible for; especially the Energy Services Providers. The Reserves Operator would be expected to enforce individual Energy Services Providers ensuring their positions are balanced; and the Services Providers would be penalised for any imbalance to minimise socialisation of residual balancing costs.

Policy and Regulation: Ensuring Overall System Effectiveness

Leadership on definition of the policy and regulatory environment is critical, especially with regard to the way in which carbon cost is internalised into the cost base of commercial actors as it sets the context against which those companies create their business models. There are a range of aspects which need to be considered by policy makers, and there are no perfect answers. The architecture described here can enable a highly competed arrangement, where carbon cost is internalised on a technology agnostic basis in order to reward Individual Actors for navigating uncertainty and investing for the long-term in innovation and supply chain development. It can also enable more prescriptive centrally mandated choices at national, regional or local government levels; the configuration is sophisticated enough to support the full range.

The emergence of Energy Services Providers as a point of integration between consumers' expectations and the challenges of the supply chain may open new options for carbon policies with the following general characteristics; but industry, policy makers and regulators will determine the specific solutions over time.

- **Technology-agnostic:** It would focus on applying an economic value to the avoidance of carbon emissions, as opposed to providing subsidies linked to the cost of specific technologies.
- **Drives whole-system optimisation:** It would focus on energy retailers as the obligated party to deliver decarbonisation, ensuring they use their position between customer-side (via HESG) and resource-side (via ERSG) to identify ways to drive-up customer satisfaction and drive-down cost.
- **Long-term:** It would set out a clear and stable framework with a trajectory defined several years in advance, focused on the outcome of reaching specific portfolio level carbon emissions each year; giving confidence for long-term investment in innovation and supply chain development.
- **Avoiding subsidies:** it would avoid subsidy payments, which are inevitably very short-term.
- **Maximises competition:** It would ensure open architectures are adopted to ensure each party with a business motive can effectively trade with those parties holding the required data, relationships and/or levers of control; and customers are not unfairly tied to one provider.
- **Permits long-term deals:** It would permit reasonable long-term consumer service contracts, for example if the capital cost of a heat pump is included and amortised over a five-year period.
- **Fairness:** It would avoid unfairly penalising consumers with limited options to decarbonise through no fault of their own; for example, those awaiting a heat network being built in their area, those without the capital to afford an early heating system replacement, etc.
- **Ensures democratic planning of community-wide choices:** It would empower local authorities to make democratic decisions on network infrastructure evolution, via an open dialogue between energy retailers/service providers (who understand their customers' needs and preferences) and energy network companies (who understand infrastructure options).

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About The Energy Technologies Institute

The Energy Technologies Institute (ETI) is a £400 million industry and Government funded research institute into low carbon energy system planning and technology development to address UK energy and climate change target

For further information please contact:

John Batterbee

Energy Systems Catapult

John.Batterbee@es.catapult.org.uk

Tel: +44 (0)121 203 3700

7th Floor, Cannon House,
The Priory Queensway,
Birmingham, B4 6BS

