DATA & DIGITALISATION STRATEGIES TOWARDS OPEN, SELF-ORGANISING & CIRCULAR SMART ENERGY SYSTEMS

A NEW PARADIGM FOR AGILE AND RESPONSIVE DIGITALISATION ARCHITECTURE FOR THE WHOLE ENERGY SYSTEM

MAY 2022

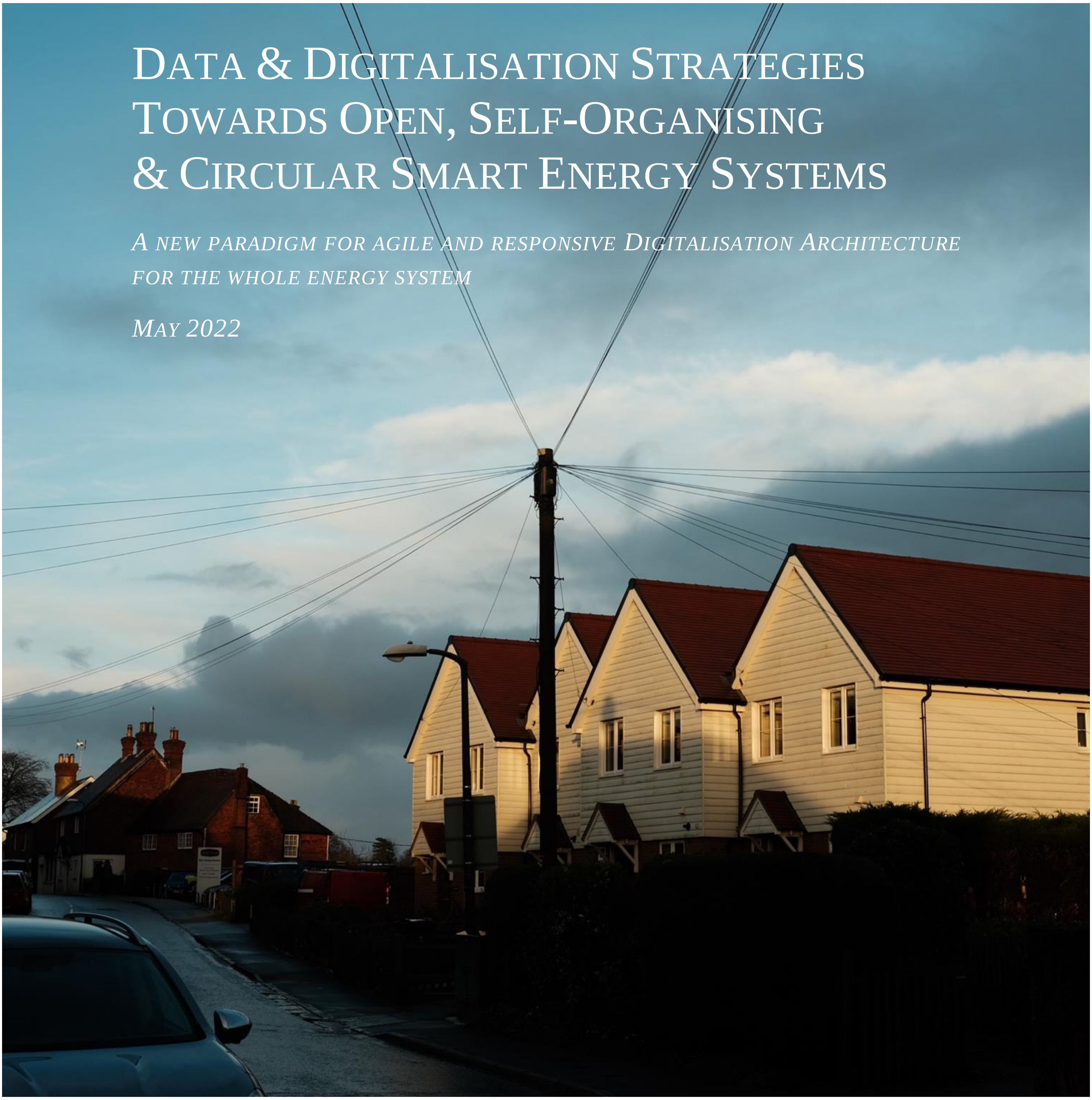

Table of Contents

ACADEMIC AND INDUSTRIAL CONTRIBUTORS

Academic Contributors
Prof **Furong Li**, Electrical Engineering
Dr **Minghao Xu**, Electrical Engineering
Isaac Flower, Mechanical Engineering
Finn Hambly, Computer Science
Dr **Chenghong Gu**, Electrical Engineering
Dr **Yunjie Gu,** Electrical Engineering
Dr **Andy Shea**, Civil Engineering
Dr **Julian Padget,** Computer Science
Dr **Steve Allen**, Civil Engineering
Dr **Xiaoze Pei**, Electrical Engineering
Dr **Kang Ma,** Electrical Engineering
Professor **Chris Brace**, Mechanical Engineering
Dr **Laurent Perge,** WoESTSP Innovation Adviser, University of Bath

Industrial Contributors
Nigel Turvey, Senior Visiting Industrial Fellow, former Network Strategy and Innovation Manager,
Western Power Distribution
John Scott, Visiting Professor, former Technical Director, Ofgem
Lewis Dale, Independent, former Regulatory Director, National Grid
Rob Oldaker, Halo Software
John Hewitt, Hewitt Studios
Chris Harris, Senior Visiting Industrial Fellow, former Regulatory Director, NPower

EXECUTIVE SUMMARY

The UK is leading the world's energy sectors in 'open data'. In 2021, the UK government published its first strategy for digitalising our energy system for net zero [1] — one of the first of its kind globally. Within the country's power and gas sector, significant progress has been made in developing and implementing data/digitalisation strategies focusing on data. Given this focus, there is less emphasis on delivering new application software. This inhibits the integration of existing and new applications across multiple organisations or communities to form whole-system applications that are agile, responsive to rapid changes in the energy landscape, and able to optimise millions of energy assets at kW and GW scale across the whole system to transform energy services to customers.

This data and digitalisation strategy sets out our vision and approach for transforming the energy system into an open 'system of systems' that is agile and responsive. Our data and digitalisation strategy builds on the industry's exciting progress, uses the concept of microservices (widely used by Google and Amazon) to promote open digital architecture, modular and interoperable functions and data to enable agile 'system of systems' operation and development. In a similar way as digitally native enterprises, this strategy promotes modular and interoperable functions that could be independently built from each other, and numerous microservices from the core systems or third-party innovators will then be assembled to create scalable, extendable and complex whole system solutions that are agile to changes. Creating interfaces between subsystems, as well as interfaces between the core energy system and third parties, is key to form whole-system solutions with up-to-date energy assets information. Functions within the "open architecture" can be used more widely and extended, ensuring that the system remains up-to-date and cutting-edge benefits can be realised from wider knowledge and expertise within and outsider the energy sector. The effective management of complex systems will be a key requirement as applications become more distributed, interactions between subsystems increase, and as third parties interoperate more with the core of the energy system.

The aim of this data and digitalisation strategy is to enable:

- **A new digitalisation architecture for the whole energy system** to enable a broad range of organisations and individuals to develop scalable, extendable, and complex whole system solutions, driving for an agile system operation and development in a way that accounts for — and communicates — whole-system impacts.
- **Modular development of scalable and complex whole system solutions** to enable key functions to be readily reused and repurposed. This will increase the pace of development for energy systems facing rapid changes and transform service innovations for energy customers.
- **Creating a system-wide software framework that is open**, allowing third parties to engage in the functionality of system operation and development to substantially reduce the cost and time required for new applications.

A significant outcome of increased functional modularity and interoperability is that it enables proprietary software sitting at different organisations to be combined, while keeping the intellectual property secure. The outputs derived from both proprietary and open-source digital functions can be combined with other applications (via APIs) to conduct real-time operation, offline analyses, and forward planning.

In this initial strategy, we outline a number of use cases: high fidelity heat, power and transport modelling of the last mile of the electrical distribution system; power system resilience; and power system stability. Microservices in these contexts will be an enabler to an open, modular, and interoperable approach leading to scalable, extendible, and complex solutions. This new paradigm will fundamentally transform the relationships between key stakeholders to achieve whole-system optimisation, particularly how the core sub-systems (i.e., transmission systems, distribution systems, vehicle charging systems) may interact with each other, how they interact with traditional or progressive suppliers, and how they interact with external third-party energy players. The resulting architecture's modularity, scalability, and responsiveness is expected to provide valuable insights for the GB Future System Operator.

1. INTRODUCTION

The UK is leading the world's energy sectors in 'open data'. In 2021, the UK government published its first strategy for digitalising our energy system for net zero — one of the first of its kind globally. Within the country's power and gas sector, Innovate UK and the Energy Systems Catapult have enabled significant progress to be made in the past 5 years, from developing data strategies, to standardising energy and system data, establishing comprehensive data catalogues, making data sets available to external parties and issues, and exploring the value of open data [2]. In addition, significant effort was made to both ensure that new data is correctly collected, stored, and maintained together with the cleansing of historic data where this would be useful. Given this focus there is less emphasis on delivering new application software to transform services to customers. Even less is placed on integrating existing and new application software across multiple organisations or communities to form whole-system applications that are agile and responsive to rapid changes in the energy landscape, and able to optimise millions of energy assets at kW and GW scale across the whole system.

This data and digitalisation strategy sets out our vision and approach for transforming the energy system into an open 'system of systems' that is agile and responsive. Our data and digitalisation strategy builds on the industry's exciting progress, uses the concept of microservices (widely used by Google and Amazon) to promote open digital architecture, modular and interoperable functions and data to enable agile 'system of systems' operation and development. The strategy promotes modular and interoperable functions that could be independently built from each other, and numerous microservices from the core systems or third-party innovators will then be assembled to create scalable, extendable and complex whole system solutions that are agile to changes. The strategy focuses on creating interfaces between subsystems, interfaces between the core energy system and third parties such that, proprietary functions sitting at different organisations/communities/companies could be combined and integrated to form whole-system solutions. The resulting whole-system solutions, with updated information, will be able to rapidly respond to changes in customer preferences, generation technologies, network optimisations, energy markets, and business models.

1.1.UK ENERGY LANDSCAPE

Our energy landscape is undergoing profound changes in energy supplies, energy networks, and energy consumption. By 2030, the UK's energy system will look very different. Offshore wind generation capacity will be expanded from today's 11GW to 50GW, solar power will be increased 5-fold. Energy customers are expected to use 10 million more electric vehicles, and 600,000 heat pumps will be installed annually by 2028 [3]. This impressive growth in low-carbon technologies is driven by a range of complementary decarbonisation policies, including the UK Government's *10 Point Plan*, *Smart Systems and Flexibility* plan, *Digitalising Our Energy Systems for Net Zero* plan, as well as *Accelerator of Low-cost Renewable Power*. Amid hiking energy prices and risks to energy security, the pace of clean growth is further accelerated by the Government's latest *Energy Security Strategy*.

Deploying renewable, nuclear, and consumer low-carbon technologies is, however, the first and essential step. The factors that determine when the energy price will stabilised and energy security will be attached are twofold. Firstly, how quickly low-carbon technologies are connected to the grid. Secondly, how successfully energy from intermittent renewables is distributed to and used by end-users' homes, vehicles, and heat pumps without significant back-up sources. These are, in turn, determined by how agile and responsive the energy sector will be to changes in technologies and customer preferences, to flexibility services and to the increasing volatility in energy supply and demand.

To meet the UK's net zero ambitions at the lowest possible cost, the UK's energy system must respond to rapid changes in the energy landscape and optimise millions of assets across the whole energy system. This strategy sets out our vision and approach for an energy system digitalisation architecture — an essential step towards transforming the present energy system to an agile system of systems.

1.2. ADVANCING BEYOND A CENTRALISED SYSTEM ARCHITECTURE

Our physical energy system is interconnected; our digital systems that mimic the real system — to optimise and control it — are not similarly interconnected. This is both due to the sheer size and complexity of the supply systems as well as limited active energy resources at regional, local, and customers levels, limiting the benefits for an interconnected whole-system approach. Consequently, our digital architectures are historically sub-divided into smaller, manageable subsystems hosted by differing organisations, such as the electricity transmission system operator, electricity distribution network operators, and vehicle charging operators. As a way of managing scalability and complexity, they each operate and optimise their subsystems whilst making broad assumptions of the state of the rest of system – a subsystem approach. For example, national energy and system balancing is centrally managed by the electricity system operator, where the state of regional, local, and customer supply and demand that are not visible to the transmission system are managed by forecasting and reserves, to cater for forecasting inaccuracy.

The energy industry functions under an entrenched and centralised system-architecture, with very limited subsystem interactions and coordination for real-time operation or forward planning. To be able to respond to rapid changes in the energy landscape and optimise energy assets across the whole system, it will need a paradigm shift towards an open, and self-organising energy system, enabling agile whole-system solutions to be developed, tested, validated, and deployed. The present energy system falls short in system agility and responsiveness in several ways:

- **Lack of a circular system architecture to enable agility and responsiveness:** The current centralised, top-down system structure poses a key hurdle to develop scalable, maintainable, and complex applications. There is very limited coordination between subsystems (e.g., transmission, distribution, and vehicle charging systems) in real-time, or functional integration across differing organisations to form scalable whole-system solutions. The lack of coordination has severely limited stakeholders' ability to contribute to asset optimisation across the whole system, sharing low carbon responsibilities as well as benefits. As a result, energy balancing and system balancing are the sole responsibility of the transmission system operator, rather than being key factors that affect the behaviours of actors across the whole system.

- **The monolithic approach to application developments:** The current norm for the energy sector has been to develop so called "monolithic" applications where data, graphical user interface (GUI) and code are tightly bound. This makes it difficult to enhance and extend their capabilities to address the challenges presented by our progress to net-zero. An example of this would be transmission boundary capability analyses, where the data, code and GUI are held by a single programme and within the same operating system. Having a fully working program contained within a single program makes development and distribution of the program very straight forward but comes at the cost of the program being locked in. If there is a change in generation, demand, or network connections, key functions throughout have to be modified to reflect the change. Though quick to develop, this monolithic approach prevents useful functions from being scaled or reused for when there are changes in technologies, the energy market, or customer preferences. Such an approach makes it difficult to reuse or repurpose existing functions in a new low-carbon environment, thus slowing down the pace for the industry to respond to evolving technologies, customer preferences, new businesses, and subsystem interactions.

- **A closed system that is expensive for upgrading and extending the functionalities in the new environment**: The closed nature of the energy system makes it difficult if not impossible for third parties to understand the functionality of the complexed system as a whole and, therefore, they can only contribute at the edge of the system in a limited way. Consequently, updating or extending the functionalities of the core systems will have to rely on in-house capabilities and resources, thus increasing the time and expense of creating and integrating innovations.

This deep-rooted, centralised, top-down, and closed supply structure is unfit for managing rapid supply-and-demand dynamics, increasing system complexity, and rising uncertainties. It needs a paradigm shift towards an open, responsive, and self-organising energy system. The Future Power System Architecture (FPSA) projects undertaken by Energy Systems Catapult and the Institution of Engineering and Technology (2015 to 2018) have identified a range of new functions that the power system will need by 2030 [35-36]. This strategy presents possible approach for comple solutions to a complex whole-system problem to be developed, tested, validated, and deployed at scale.

1.3. Our data and digitalisation strategy

This data and digitalisation strategy builds on the industry's impressive new developments. It addresses the urgent needs for scalable and complex whole system solutions that will respond to rapid changes of energy landscape and be able to optimise energy assets across the whole system. This strategy is inspired by a microservice architecture (widely used by Google and Amazon) to transform the present centralised energy system structure to an open system of systems. It introduces a circular, open, self-organising 'system of systems' paradigm to enable an agile and responsive system operation and development. In a similar way to digitally native enterprises, this strategy promotes small, interoperable single function microservices that can be independently built from each other, and numerous microservices from the core systems or third-party innovators will then be assembled to create scalable, extendable, and complex whole system solutions that are agile to changes.

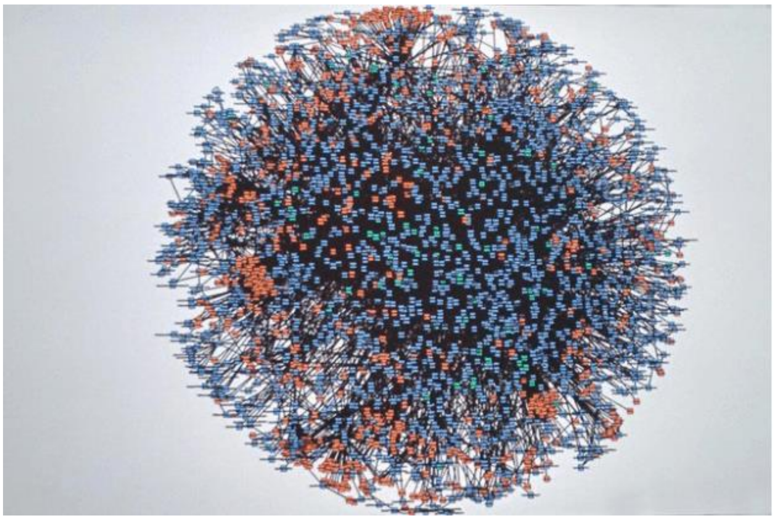

Figure 1-1 Amazon's microservices infrastructure.

The strategy presents initial thinking in three key areas for substantially increasing the energy sectors' agility and responsiveness:

- **Building an open, agile digitalisation architecture for the whole energy system.** It opens elements of digital architecture, functions, and data to outside organisations and individuals to enable a broad range of organisations and individuals to co-develop scalable, extendable, and complex whole-system solutions. It enables an agile and responsive 'system of systems' operation and development in a way that accounts for and communicates whole-system impacts. Complexity management will be key to allow for a subset of functions (potentially sitting at differing organisations or communities) to be combined and integrated, able to rapidly respond to changes in system dynamics, and cope with uncertainties in future energy landscape.

- **Embracing modular development approaches within the core energy system** to enable scalable and complex whole-system solutions. Enabling greater modularity of functions at the core of the energy system will reduce the tight function coupling that is common in energy system applications and, consequently, allow each of the function to be reused, reshaped, and repurposed without impacting the development of other functions.
  - Enabling greater interoperability of these functions of the core system will allow each function to operate across multiple servers and operating systems.
  - The focus on modularity and interoperability will increase the portability of key functions, such that existing functions can be quickly adapted for the low-carbon energy system, substantially reducing the time and resources required to develop whole-system solutions.

- **Creating a system-wide software framework that is open,** by creating an open software development framework to outsiders as well as software-agnostic, organisation-agnostic, and technology-agnostic interfaces, third parties will be able to extend the functionalities of the core system operation and development processes at significantly reduced time and resources.

A key outcome from this open architecture (with increased functional modularity and interoperability) is to enable proprietary functions/software sitting at different organisations/communities/high-tech companies to be combined and integrated to form an agile system to rapidly respond to changes in customer preferences, generation technologies, network optimisations, energy markets, and business models. These agile applications could be formed for real-time operation or offline analyses, for an intact system or a system in stress to improve efficiencies and/or security in fundamentally different ways. This outcome will fundamentally transform the relationships between key stakeholders to achieve whole-system optimisation, particularly, how the core sub-systems (i.e., transmission systems, distribution systems, vehicle charging systems) may interact with each other, how they interact with traditional or progressive suppliers, and how they interact with external third-party energy players.

1.4. High-level architecture for a circular, open, and self-organising energy system of systems

A high-level view of a microservice-based architecture for the entire energy system is shown in Figure 1-2. At the 'national' level, there are services that represent different types of power generation (gas, solar, wind), interconnectors, services that represent national grid operation and development, and services that provides weather information. At the 'local' level, there are separate services for each of the GB DNOs as well as services that can model, optimise, and coordinate demand for power, electric vehicle, and heat pumps.

Each function could be deployed at a separate server but remain loosely coupled to ensure the whole system up to date. Loose coupling between subsystems will enable changes in a technology, market, or customer preference to be immediately felt by the rest of the system, instead of relying on forecasting on the part of the system that is not visible, and backups to cater for inaccuracies.

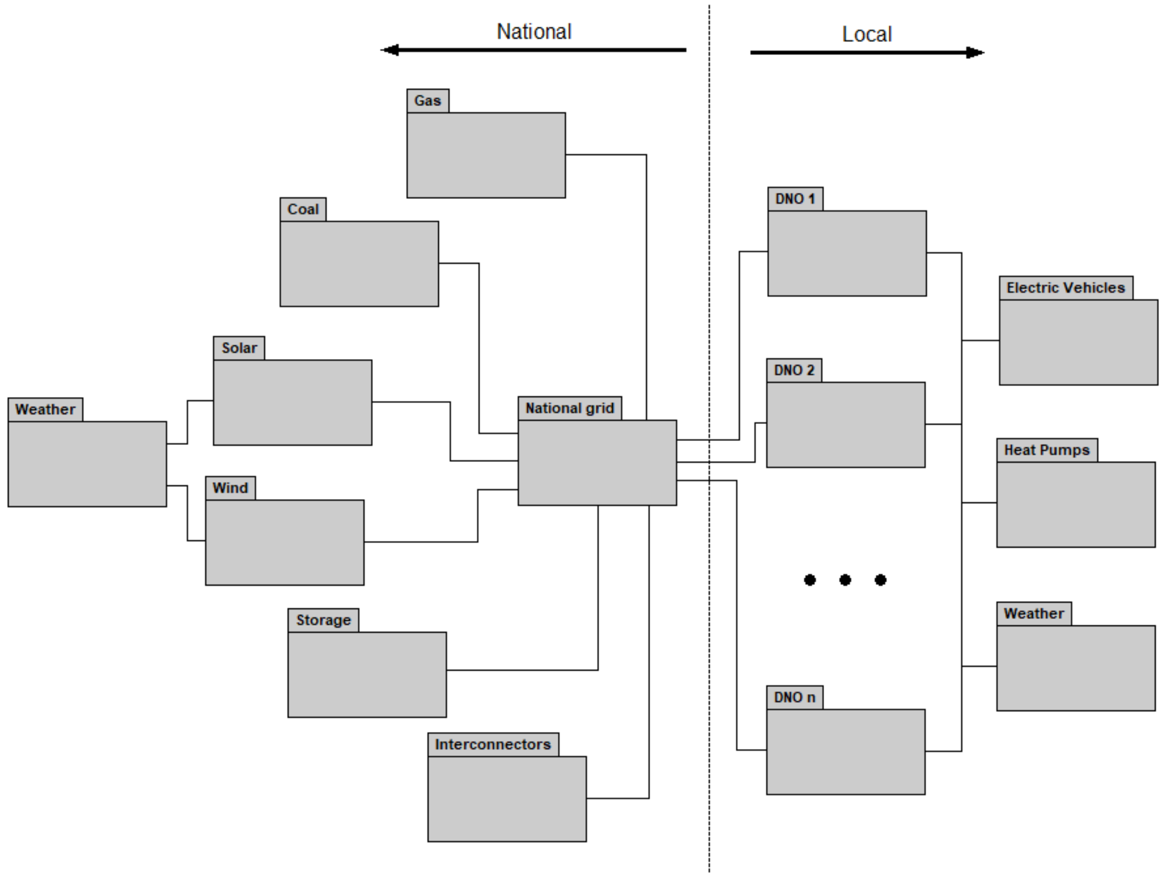

Figure 1-2 High-level overview of microservice-based approach to modelling the entirety of the GB energy system.

2. REVIEW OF TRADITIONAL DIGITALISATION STRATEGIES IN THE POWER AND ENERGY SECTOR

Big data, machine learning, artificial intelligence, and other digital technologies are going to play a vital role in the future energy sector. Almost all these digital technologies and services rely on access to large, representative, and good quality datasets [3]. However, given the age of significant parts of the electricity and other energy networks, data has:

- not been consistently collected,
- been lost or corrupted,
- not transferred to electronic format,
- been transferred into new systems with both data loss and corruption, and
- inaccurately or incompletely collected in the field.

Hence, significant effort is now being made to both ensure that new data is correctly collected, stored, and maintained together with the cleansing of historic data where this would be useful.

The forementioned issues have limited the utilisation of data. To enable digital technologies, much focus is currently on establishing comprehensive data catalogues and making datasets available to external parties. Given this focus, there is not enough emphasis on:

- delivering new or enhanced application software with the vast amount of obtained data,
- integrating existing and new application software — both internally and externally — across different organisations or communities (to transform services for customers), or
- architecting digital and software infrastructure to accommodate and enable more complex analytics and computations for the future energy system.

Other sectors, particularly digital native companies like Amazon and Google, have benefitted from establishing data collection electronically from the start, and hence have been able to progress the services and products for customers at a rapid pace.

2.1. THE STATE OF PLAY IN DATA/DIGITALISATION STRATEGIES AND THEIR KEY LIMITATIONS

2.1.1. PROGRESS SO FAR

In 2017, the UK government and Ofgem jointly published the Smart Systems & Flexibility Plan, with a Progress Update in 2018. An independent Energy Data Taskforce was created as one of these actions, who later published their report [2] in June 2019 which made 5 recommendations and set out a strategy to fill data gaps, improve the quality of data and make data more open. The government is working with Ofgem, Innovate UK, and other industry stakeholders to implement the vision of the Energy Data Taskforce through the Modernising Energy Data programme.

Figure 2-1 Energy Data & Digitalisation Strategy [4].

Network companies have responded to the taskforce's recommendations and published their digitalisation strategies. These demonstrate the progress network companies have already made, but also highlight the need for further effort in this area as energy industry digitalisation progress is behind other major GB economic contributors [5].

2.1.2. *ENERGY DATA TASKFORCE PERSPECTIVE*

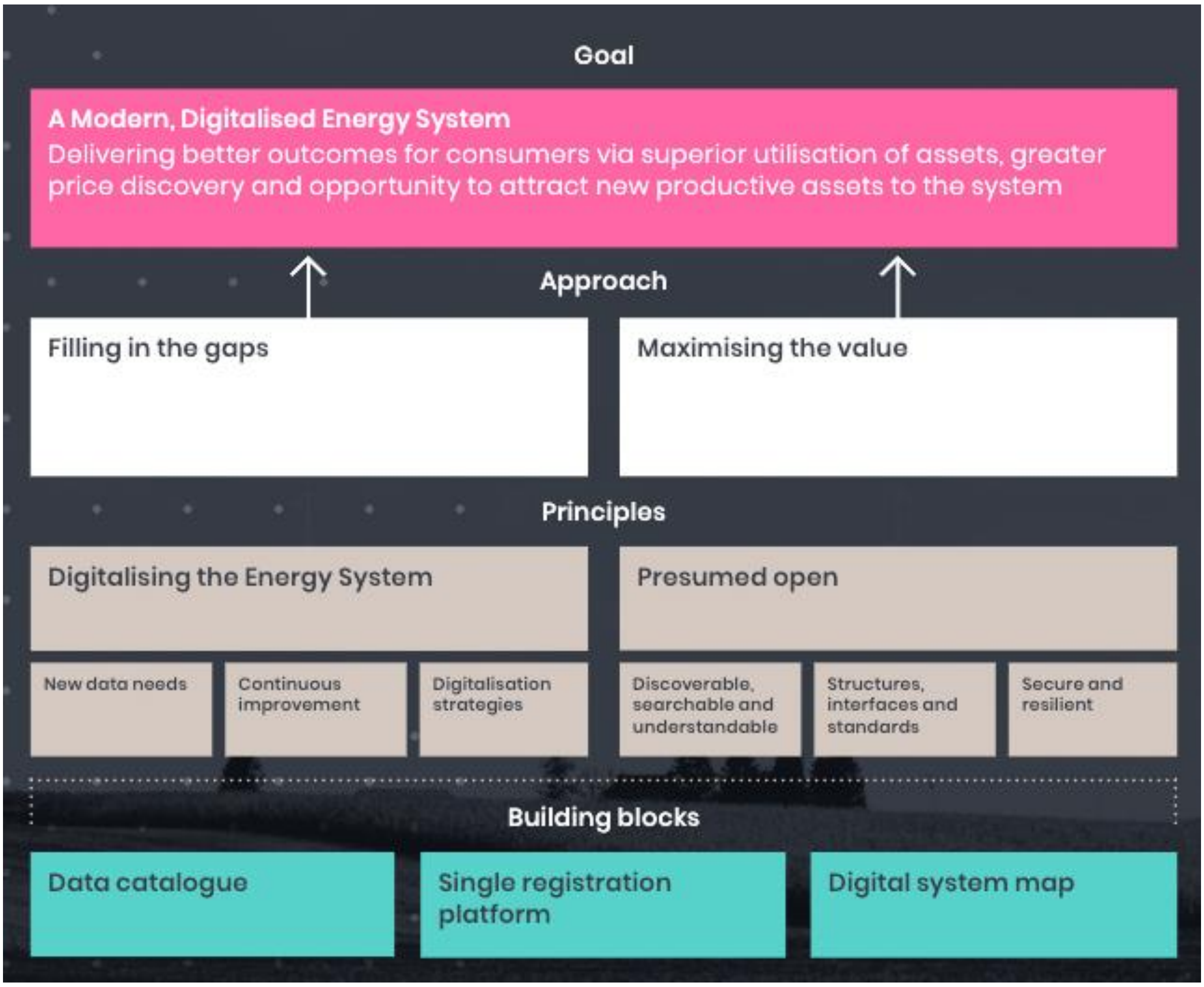

Figure 2-2 Core principles of energy system digitalisation[2].

The Energy Data Taskforce [2] has identified that a staged approach needed to be taken to achieve a Modern, Digitalised Energy System in order to fill the data gaps and maximise data value:

- **Data visibility**: Understanding the data that exists, the data that is missing, which datasets are important, and make it easier to access and understand data.
- **Infrastructure and asset visibility**: Revealing system assets and infrastructure, where they are located and their capabilities, to inform system planning and management.
- **Operational optimisation**: Enabling operational data to be layered across the assets to support system optimisation and facilitate multiple actors to participate at all levels across the system.
- **Open markets**: Achieving much better price discovery, through unlocking new markets, informed by time, location, and service value data.
- **Agile regulation**: Enabling regulators to adopt a much more agile and risk reflective approach to regulation of the sector, by giving them access to more and better data.

Based on those findings, the Taskforce developed five recommendations:

- **Recommendation 1: digitalisation of the energy system** – Government and Ofgem should direct the sector to adopt the principle of Digitalisation of the Energy System in the consumers' interest, using their range of existing legislative and regulatory measures as appropriate, in line with the supporting principles of 'New Data Needs' 'Continuous Improvement' and 'Digitalisation Strategies'.
- **Recommendation 2: maximising the value of data** – Government and Ofgem should direct the sector to adopt the principle that Energy System Data should be Presumed Open, using their range of existing legislative and regulatory measures as appropriate, supported by requirements that data is 'Discoverable, Searchable, Understandable', with common 'Structures, Interfaces and Standards' and is 'Secure and Resilient'.
- **Recommendation 3: visibility of data** – A Data Catalogue should be established to provide visibility through standardised metadata of Energy System Datasets across Government, the regulator and industry. Government and Ofgem should mandate industry participation through regulatory and policy frameworks.
- **Recommendation 4: coordination of asset registration** – An Asset Registration Strategy should be established to coordinate registration of energy assets, simplifying the experience for consumers through a user-friendly interface in order to increase registration compliance, improve the reliability of data and improve the efficiency of data collection.
- **Recommendation 5: visibility of infrastructure and assets** – A unified Digital System Map of the Energy System should be established to increase visibility of the Energy System infrastructure and assets, enable optimisation of investment, and inform the creation of new markets.

2.1.3. RESPONDENT STRATEGIES AND KEY LIMITATIONS

All network companies have published their digitalisation strategies in December 2019 as part of their Business Plans for the next round of RIIO price controls. Their objectives are aligned to the findings of the Energy Data Taskforce and their focuses can be broadly summarised as the following areas:

- Data collection and management
- Data access, openness, and privacy
- Data and IT capacity building (infrastructure and skills)

- Value mining and utilization of data and digital technologies — improve network management and support new business models
- Collaborative and agile working

Almost all the network companies are in the transitioning phase of moving from a legacy analogue system to a digitalised energy system. Consequently, much effort is focused on cataloguing and making data publicly available. Some key limitations and missed out aspects have been summarised as follows:

- Lack of clear pathway for standardising energy data across different network companies.
- Lack of standardised way of sharing data. Some companies use APIs for data sharing and downloading, while others have not specified their planned ways.
- Lack of clear pathway for energy data and technologies to interact with other sectors, such as transportation and heating.
- Lack of strategic design of digital and software architecture to enable and future-proof more complex analytics and computations.
- Lack of standardised way of sharing model and service/computation. All companies have acknowledged the value of sharing data. However, few of them have planned or mentioned the provision of their models and computation service, such as the forecasting models of renewable generation. It is also not clear how such digital technologies will be integrated internally and shared with others externally.

2.2. APPROACH TAKEN BY DIGITAL-NATIVE COMPANIES

Rather than building monolithic applications, digitally native enterprises are increasingly building small, single function microservices, and then assembling numerous microservices to create applications and digital experiences.

These microservices decouple functionality from the application and, as each is independently deployable, developers can work without getting in one another’s way. In the context of energy network companies, an example of microservices is given in Figure 2-3 below.

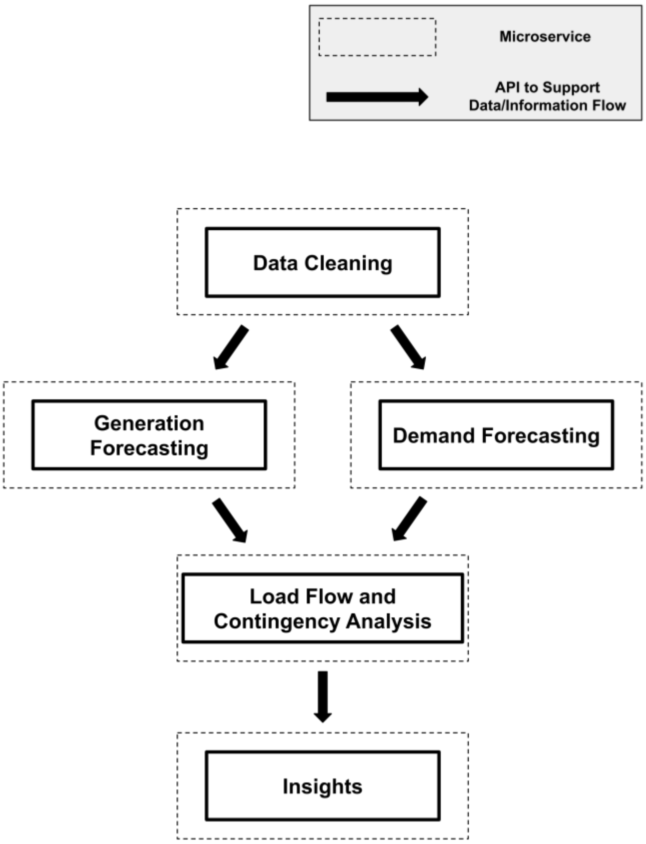

Figure 2-3 Example of microservice based application.

The workflow is built on the invoking of individual function/software via APIs, instead of integrating all functions into one monolithic large software system. By doing so, each sub-module or microservice is separated and can be reused for other functions. This not only greatly reduces the redundancy and complexity of the digital/data flatform, but also improves interoperability and agility.

3. MICROSERVICE ARCHITECTURES FOR WHOLE ENERGY SYSTEMS

Modern energy systems are remarkably complex and complicated systems and, as more renewable systems are being utilised, and electric vehicles and heat pumps become widespread, the complexity increases still further. Renewables' power output is also heavily dependent on environmental factors such as the wind speed and the amount of sunshine, while charging demand of electric vehicles and heat pumps are influenced by human behaviour, and the alignments between renewables and charging demand are additionally impacted by infrastructure network capacity. This presents many challenges to a whole-system approach that will accurately model, analyse, and optimise GW and kW of energy assets system-wide, and act as a self-organising eco-system to readily respond to rapid changes in future energy landscape.

The strategy introduces a circular, open, self-organising 'system of systems' paradigm to enable an agile and responsive system operation and development. In a similar way to digitally native enterprises, small interoperable single-function microservices will be independently built from each other, and numerous microservices from the core systems or third-party innovators will then be assembled to create scalable, extendable, and complex whole-system solutions that are agile to changes. Using microservices is a great way to decompose complex systems into many modular, interoperable, manageable functions. These modular functions can be developed separately and then combined to provide scalable, extendable, and complex whole-system solutions.

3.1. HIGH-LEVEL PRINCIPLES IN DATA/DIGITALISATION STRATEGY FOR AN OPEN, SELF-ORGANISING AND CIRCULAR SMART ENERGY SYSTEM

The key principle behind this strategy is that elements of the system's architecture, functions, and data are open to outside organisations and individuals to use and extend, so that the system is up-to-date and can be operated and developed with an agile and responsive 'system of systems'.

This approach is similar to that of the open source movement in software development which is rapidly becoming the de-facto way that software is developed. Linux and the Android operating system are both examples of successful open-source systems. Linux is run on 96.3% of the world's top 1 million servers and there are over 2.5 billion Android users worldwide.

Microsoft has open-sourced its flagship development framework, .net, and its class leading development tool Visual Studio Code. Both last two systems are examples where outside users can develop and share their own "extensions" (Visual Studio Code) or "libraries" (.NET) that extend the functionality of the core system. For Visual Studio Code, this has meant it is now the most popular development tool on the Stack Overflow survey being used by 72% of all developers and with over 30,000 extensions available.

The key to allowing a system to be extended in this way is the use of strict Application Programming Interfaces (APIs), a set of definitions and protocols for building and integrating application software that provide a "contract" to which both the system and the outside organisation/entity adhere to. The API defines the protocol to use, what functions are available and, importantly, the data structures used to share information. The API allows many applications to interoperate instead of integrating all functions into one large monolithic piece of software. They decouple back-end complexity from front-end development, abstracting that complexity into an interface that users can use for new applications and experiences, even if they are unfamiliar with underlying technical minutiae.

3.2. Overall architecture, key components and their interactions

This is an overview of the various software components that will make up the system.

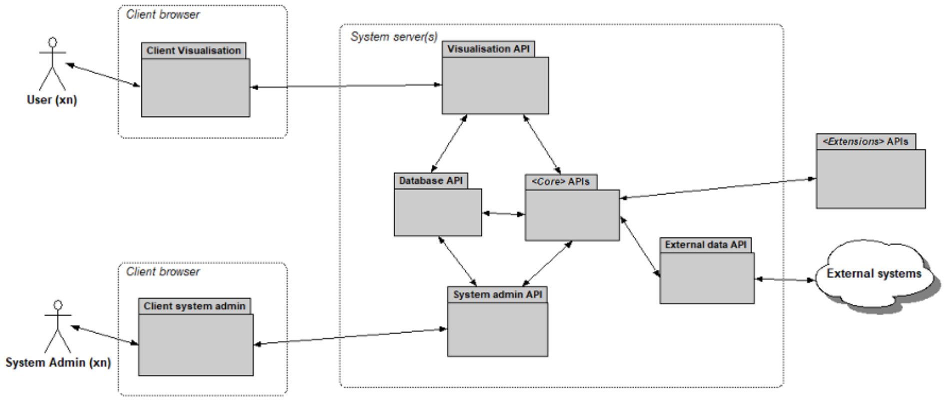

Figure 3-1 Example of microservice architecture.

The above architecture is an example of the microservices architecture for developing scalable, maintainable, and complex applications. The system architecture makes extensive use of APIs. These APIs define a clear and unambiguous contract about how each component will interact with each other and provide the bedrock upon which the system will be developed and extended. By taking this modular approach, each submodule or microservice is separated and can be reused for other functions. This not only greatly reduces the redundancy and complexity of each individual application, but also improves interoperability and agility, able to self-organising energy assets in line with changes in supply/demand dynamics to maximise efficiency and ensure supply security and resilience.

Below, in Table 3-1, is a comparison of a traditional centralised application and a microservices-based application.

Table 3-1 Comparison of monolithic and microservices applications

Monolithic applications	Microservice-based applications
Built as a single unit	Functionality is de-coupled and modular
Implementation is straightforward	Implementation takes longer
Dependencies not explicit	Dependencies are explicit
Interfaces are code based and often opaque	Interfaces defined by data schemas and public APIs
Not easily scalable since will involve code changes	Easily scalable by deploying on more servers.
Management is straightforward	Management requires third-party tools to automate tasks across servers.

3.3. Our vision of a microservices-based architecture for the whole energy system

This data and digitalisation strategy sets out our vision and approach for data and digitalising the energy system to transform the present energy system to an open system of systems. It has the key feature of being agile and responsive to rapid changes in energy landscape and able to optimise energy assets across the whole system. This strategy is inspired by microservice architectures, opening up elements of architecture, functions and data to outside organisations and individuals, enabling scalable, extendable and complex whole-system solutions, and promoting an agile system operation and development. The strategy focuses on creating interfaces between subsystems, interfaces between the core energy system and third parties such that, proprietary functions sitting at different organisations/communities/high tech companies could be combined and integrated to form whole-system solutions. Compared with a subsystem solution, the whole-system solutions with updated information can rapidly respond to changes in customer preferences, generation technologies, network optimisations, energy markets, and business models, and to cope with major uncertainties in forward planning.

This strategy presents initial thinking in three key areas for substantially increasing the energy sectors' agility and responsiveness, follows:

- An agile, transactive, open architecture for the whole energy system to enable agile system of system operation and development
- Modular and interoperable functions within the core systems to enable scalable and complex whole system solutions
- Enabling third parties to extend the functionality of the core system
- Potential hurdles.

3.3.1. An agile, transactive, open architecture for the whole energy system to enable agile system of system operation and development

Developing a scalable, extendable, and complex applications under a microservices architecture will enable an agile and responsive system operation and development. This will require paradigm changes to the existing relationships between the core subsystems (i.e. transmission, distribution, and charging systems), where there are very little information exchanges for real-time operation between subsystems and for forward planning in both operational and investment timescales. An open, circular, and self-organising system architecture will enable loose coupling between core subsystems to form whole-system solutions with up to date information, such that a change in customers' vehicle charging will be immediately felt by the whole system in real-time. Conversely, a change at GW scale in renewable generation investment, infrastructure investment, or alternative market arrangements will be translated into energy costs, energy availability and carbon intensity for the end consumers.

Through an open system architecture, further use and extension of capabilities will be enabled to ensure that the system remains up-to-date, and the benefits of cutting-edge technologies can be realised from the knowledge and expertise that this open architecture brings.

Complexity management will be key to allow for a subset of functions (potentially sitting at differing organisations or communities) to be combined and integrated. These whole system solutions will be designed to rapidly respond to changes in system dynamics, and cope with uncertainties in future energy landscape. The complexity management will transform the relationship between key stakeholders and, particularly, how the core sub-systems (i.e. transmission systems, distribution systems, vehicle charging systems) may interact with each other, how they interact with traditional or progressive suppliers, and how they interact with external third party energy players to achieve whole-system optimisation.

3.3.2. *Modular and interoperable functions within the core systems to enable scalable and complex whole system solutions*

Enabling greater modularity of functions at the core of the energy system will reduce the tight function coupling that is common in energy system applications and, consequently, allow each of the function to be reused, reshaped, and repurposed without impact the development of other functions.

Enabling greater interoperability of these functions of the core system will allow each function to operate across multiple servers and operating systems.

This focus on modularity and interoperability will increase the portability of key functions, such that existing functions can be quickly adapted for the low-carbon energy system, substantially reducing the time and resources required to develop whole-system solutions.

3.3.3. *Enabling third parties to extend the functionality of the core system*

By increasing the modularity and interoperability of the core system and software-agnostic interfaces, the core energy system can make a great use of external third parties' innovation and capabilities to extend the functions of the core system. This will allow the energy sector to tap into the strengths and knowhow beyond the traditional remit of the energy sector to co-develop complex whole system solutions. Further integration will benefit from whole-system applications that are organisation agonistic, community agnostic and technology agnostic.

3.3.4. *Potential hurdles*

Microservices provide many benefits over traditional centralised applications but also present a number of hurdles that need to be overcome before their benefits can be fully realised.

Functional partitioning

One of the key starting points when designing a micro-services system is to partition the functionality so that it can be implemented piecemeal by separate co-operating services. Choosing the functionality of each service is important to get right and will ensure that the finished system works well and accrues the benefits that the system is designed for.

API definition

It is important to apply some thought up front to the APIs each service will offer and the data schemas that will be used to exchange data. These can be thought of as "contracts" that will need to be adhered to and any changes will likely break existing code. If it is found that the API and data schemas are too complex it may mean that the functional partitioning needs to be adjusted.

Service management

The management of services is a challenge to be resolved since they will be remotely deployed on one or more servers and the tasks needed to manage them will soon become a headache if they cannot be automated. Luckily there are third-party tools that can help in this regard such as Kubernetes and Docker that can provide the necessary tools to automate this process.

3.4. ARCHITECTURE

A high-level view of a microservice-based architecture for energy system is shown in **Error! Reference source not found.**. At the 'national' level, there are services that represent different types of power generation (coal, solar, wind) and interconnectors, services which represent the national grid operation and development, and services that provides weather information. At the 'local' level, there are separate services for each of the GB DNOs as well as services that can model, optimise, and coordinate demand for power, electric vehicles, and heat pumps.

Each function could be deployed at a separate server but loosely coupled to ensure the whole system remains up to date. Loose coupling between subsystems will enable changes in a technology, market, or customer preference will be immediately felt by the rest of the system, instead of relying on forecasting on the part of the system that is not visible, and backups to cater for inaccuracies.

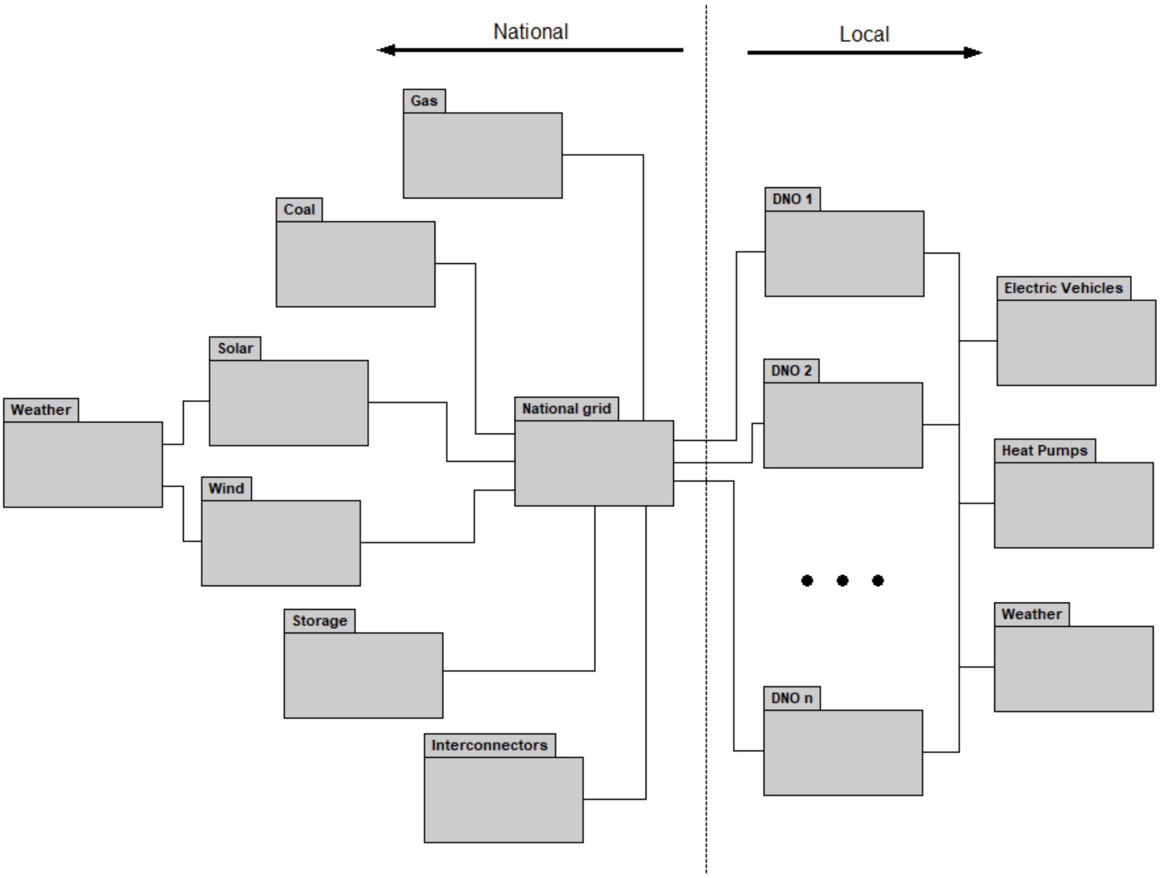

Figure 3-2 High-level overview of microservice-based approach to modelling the UK energy system.

4. USE CASES OF A WHOLE-SYSTEM MODELLING APPROACH

Our physical energy system is interconnected; our digital systems that mimic the real system — to optimise and control it — are not, however. This is both due to the sheer size and complexity of the supply systems as well as limited active energy resources at regional, local, and customers levels, limiting the benefits for an interconnected whole-system approach. Consequently, our entire digital system is sub-divided into smaller, manageable subsystems hosted by differing organisations, such as the electricity transmission system operator, electricity distribution network operators, and vehicle charging operators. As a way of managing scalability and complexity, they each operate and optimise their subsystems whilst making broad assumptions of the state of the rest of system – a subsystem approach. For example, national energy and system balancing is centrally managed by the electricity system operator, where the state of regional, local, and customer supply and demand that are not visible to the transmission system are managed by forecasting and backups, to cater for forecasting inaccuracy.

An open, agile, self-organising energy system of systems will comprise of millions of distributed microservices, making it possible to operate and optimise the system as a whole. Each microservice will be hosted at differing organisation, each with up to date information and appropriate 'contracts'/APIs signed up. Through APIs and complexity management, these microsevices will be combined and integrated to form a variety of applications that are able to respond to changes in dynamics of supply and demand, such as real-time whole system energy flows, carbon flows, locational marginal prices, system stability or resilience, or longer term investment at the transmission or distribution, and vehicle charging levels or use of system charges. The contracts/APIs with the outsiders of the core system will enable the key functions of the core systems to be extended by third parties such as aggregators, virtual power plant operators, low carbon heat providers, vehicle charging providers, high-tech companies specialising energy applications. The microservice based system architecture will shift the centralised operation and development to a paradigm that enables a co-develop of the smart, flexible energy system of systems with greater agility and responsiveness in system operation and development, able to respond to rapid changes in our current and future energy landscape.

A whole system simulator that emulates an agile and responsive system operation and development, where numerous microservices will be developed and ran in parallel. They can then be integrated to form scalable and complex whole-system solutions and be reused in a new environment. A whole system simulator will be able to assess a wide range of options at customers levels and how they may impact on the whole-system performance and development. Conversely, it will also be able to assess the impact to energy customers from a range of the system options, such as infrastructure development, system operation, market design and operation. An example of a microservice based whole energy system digital simulation platform is shown in Figure 4-1.

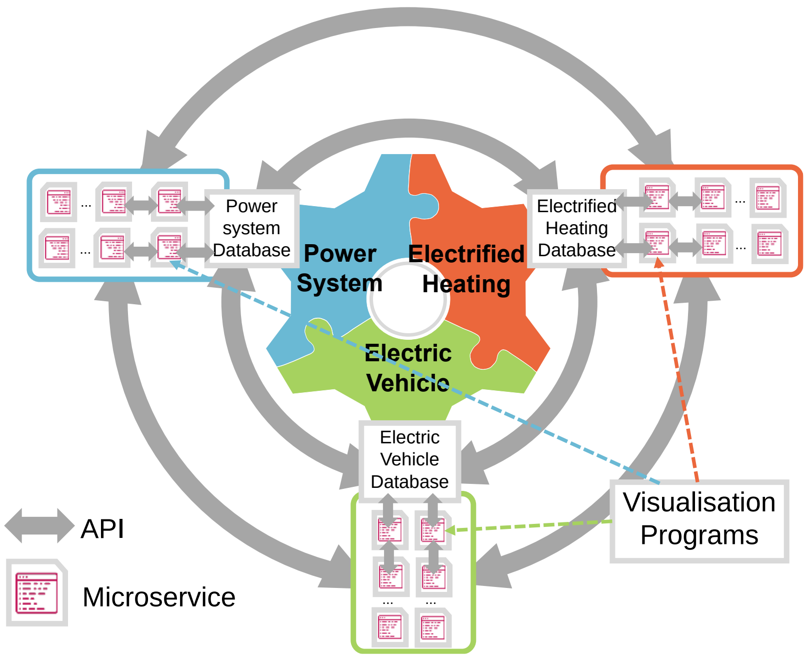

Figure 4-1 Example of a microservice based whole energy system digital platform.

Potential applications can be broken down into customer facing and system facing are included in Table 4-1.

Table 4-1 List of customer-facing and system-facing applications of whole-system modelling

Customer Facing		System Facing	
Grid integration of EVs/HPs	Tool for Local Authorities, EV charge point providers, HP installers to understand where installations could be made where the impact, and hence cost of connection, would be the lowest	Cost-reflective network pricing methodologies	Modelling of the impact of different use of system charging methodologies and connection charging policies to customer groups with differing EV/HP uptakes and flexibilities
High fidelity power, heat and vehicle charging modelling, optimisation and control	Ability to model power, flexible heating and vehicle charging in detail through modelling and integration dynamic behaviour of flexible customers and static behaviour of fixed customers	Efficient granular energy pricing	Modelling of granular locational marginal energy pricing, understand the likely customers responses and the trade-offs between renewable utilisation and network constraints
System impact from EV/HP integration	Ability to map the impact of the installation of electric vehicles and heat pumps or other electricity-based heating and vehicle charging system on the network to allow reinforcement of the network where necessary or an understanding of the control systems that would be needed to manage the network.	System needs and product development (thermal, frequency, stability, resilience)	Understanding of the times, volumes and locations of demand side services that would benefit the network and provide lower cost solutions compared to reinforcement
Community energy, local energy and flexibility markets	Understand changes to customer/community's flexibilities and energy behaviours from introducing local energy and flexibility markets for reduce system peak, and/or increasing demand for renewable energy, and strike the balance between sophistication and simplicity	Impact assessment to network investment from customer and system flexibility	Modelling of the customer and system flexibility and their effects in delaying and deferring future network investment
Rapid assessment of EV/HP installation projects	Ability to quickly assess individual applications for the installation of EV chargers or heat pumps.	Rapid assessment and ranking innovation projects	Modelling of potential or proposed innovation projects to understand likely impact and hence speed up the assessment and prioritise which project should go forward first

4.1. HIGH FIDELITY MODELLING OF ELECTRIC VEHICLE AND HEAT PUMP DEMAND

4.1.1. BACKGROUND

In an effort to decarbonise, the UK is expected to see a rapid increase in the uptake and usage of low-carbon technologies (LCTs), such as electric vehicles (EVs) and electric heat pumps (EHPs) which poses numerous challenges to the country's low-voltage (LV) distribution networks.

In 2016, the transport sector contributed 16.2% of global greenhouse gas emissions (CO_2 eq), with road transport alone contributing 11.9% to the global output [6]. To reduce their overall CO_2 output, many countries, including the UK, have announced a ban on the sale of new fossil fuel-powered vehicles between 2030 and 2040 [7]. As a result, the need to supply energy to a rapidly growing fleet of EVs presents major challenges for the automotive and energy sectors. In their Global EV Outlook [8], Bloomberg NEF project that the market share of EVs could be as high as 28% of all new vehicles sold in 2030 and 58% by 2040. The most significant change will be an increase in evening peak loads as drivers return from work and plug in their vehicles to charge. This will be most problematic at the LV level, due to the variable distribution of EV charging hot spots. Subsequently, the peak load increases resulting from uncontrolled EV charging could surpass the capacity of local transformers, thus requiring expensive grid upgrades. McKinsey estimates that, without corrective action, the total grid investment needed could exceed several hundred euros per EV [9]. In their 2014 report on the 'Impact of Electric Vehicle and Heap Pump loads on network demand profiles' [10], UK Power Networks highlighted the importance of using demographic information to indicate areas with anticipated EV uptake.

The impact of adding EHPs to the electricity distribution system is also set to be highly significant with the UK government aiming to install 600,000 heat pumps annually by 2028 [7]. At a national level, Love et al. estimate that a 20% uptake of heat pumps nationwide would lead to a 14% increase in the UK's peak load in the evening [11]. Additionally, Cooper et al. find that 80% uptake could lead to peak net-demand to double (100% increase) [12]. When considering the uptake of LCTs at the distribution substation level, Navarro-Espinosa and Ochoa find that EHPs could lead to thermal and voltage problems in over half of the UK's feeders [13].

As well as needing to meet the increased electricity demand and changing consumption patterns, electricity distribution infrastructure must also be able to handle increasingly high levels of renewable energy penetration. This includes a planned quadrupling of offshore windfarms by 2030, as well as the deployment of distributed generation (DG) devices across LV networks, such as photovoltaic (PV) panels and wind energy resources. Therefore, our work on modelling EV and EHP uptake in LV networks must account for these changes in technology and ideally enable their efficient usage.

Therefore, distribution network operators (DNOs) and planners need to consider their network options to meet the rapidly increasing activity on LV distribution networks, without committing to wasteful investments that needlessly raise costs for consumers. In the absence of cost-reflective price signals on the LV network, costly consumption and generation patterns are currently not appropriately disincentivised. This is compounded by the fact that these patterns are changing in unpredictable ways, due to the heterogeneous introduction of LCTs. To meet the nation's decarbonisation goals, investments into distribution networks will need to be made to ensure the uptake of LCTs is neither prohibited nor damaging.

4.1.2. WHY DO WE NEED MODULAR HIGH-FIDELITY MODELLING?

When forecasting which parts of the network are at risk of thermal and voltage violations, the combined uptake of EVs, EHPs, and DG devices must be considered, as their joint interactions dictate the shape of electricity load profiles and, subsequently, peak demand. To model the impact of these technologies, their uptake must be forecasted at a high spatial resolution as the uptake of these technologies is expected to be clustered. Additionally, since the rates of EV charging, EHP usage, and distributed generation will change over a day, load profiles with a high temporal resolution are necessary to forecast the peak daily demand at each distribution substation. Therefore, a high-fidelity whole-system model is required to pinpoint precisely where on the network issues could arise and provide confidence in peak demand estimates resulting from the concurrent use of LCTs.

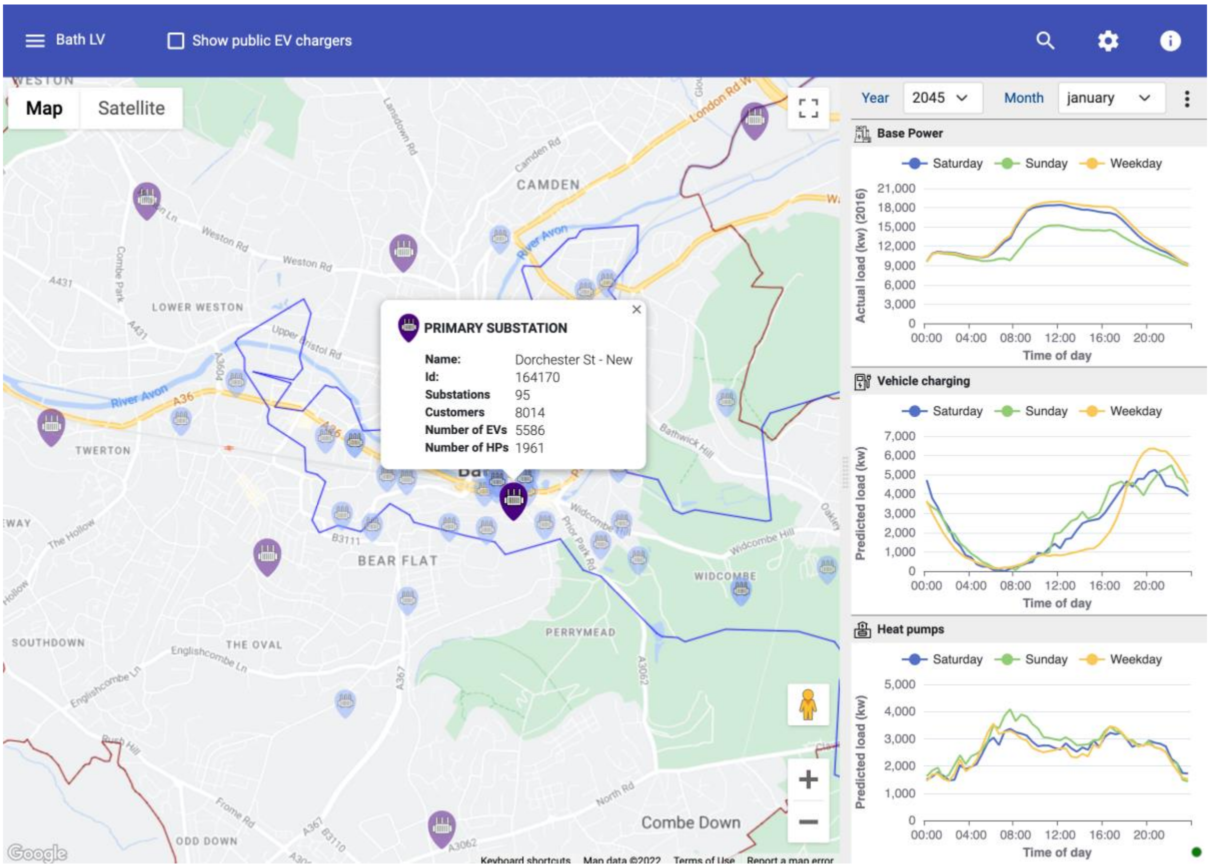

Figure 4-2 A screenshot of our interactive map, displaying high-fidelity load profile forecasts for power, heat, and transport. These daily load profiles can be examined at the distribution substation level. This tool can be accessed here.

Here, we focus on modelling the impact of EHP and EV uptake which require subtly different modelling methodologies for accurate forecasting. However, these technologies must be considered in combination to understand the emerging challenges for the UK's LV networks. Therefore, a modular approach is required to appropriately manage these different modelling methodologies. By taking a modular approach to high-fidelity modelling, we can create tools to help DNOs plan network interventions in a manner that accurately accounts for these changes. When used for real-time data analysis and forecasting, the utilisation of microservices will enable these different modular models to interact cohesively. We illustrate our application of mciroservices on Bath's LV network modelling.

The use of different datasets for both EVs and EHP modelling further highlights the importance of this modular approach. The ability to integrate and update technology-specific datasets to each module separately increases the overall model's flexibility. The use of open datasets ensures our approach to high-fidelity modelling is scalable. For EVs, we have focused on demographic factors contributing to a clustered uptake of EVs and modelled their uptake in a manner that can be scaled nationwide, while still accounting for their likely spatial heterogeneity. For EHPs, our work has focused on modelling the changing nature of demand profiles — from distribution substations to primary substations to regional demand.

A summary of the datasets used in our initial modelling is shown below:

Table 4-2 Summary of datasets used for EV and EHP modelling

Type	Dataset	Application
Spatial	WPD – Primary substation geospatial data	All
	WPD – Distribution substation geospatial data	All
	Office for National Statistics – Output Area Boundaries	All
	WPD – Distribution Future Energy Scenarios	All
Demographics	2011 Census Data	All
	WPD – LV Customers and EAC	All
	Department for Transport – Licensed vehicles by postcode district and body type (ve0122)	EV
	Department for Transport – Licensed ultra low emission vehicles by postcode district: United Kingdom (ve0134)	EV
Trials	WPD – Electric Nation trial data	EV
	Renewable Heat Premium Payment scheme data	HP
	Low Voltage Network Template	Power

4.1.3. *HIGH FIDELITY EV CHARGING DEMAND MODELLING*

Current state of play

In the last decade, there has been a significant focus on estimating the effect of EV charging on the power network. Early research into EV charging behaviour relied on probabilistic models of non-EV driving behaviour to characterise charging sessions, due to a lack of real-world EV data resulting from low EV penetration. This was performed by estimating arrival and departure patterns, energy requirements and the covered distance in between trips. However, more recently, the rapid increase in EV uptake and improved availability of EV charging datasets has allowed researchers to use real-world data-driven approaches to model EV charging behaviour. Studies tend to gravitate towards either data-driven or agent-based modelling (ABM) approaches. ABMs are becoming more frequently used to model and predict EV charging demand due to their ability to capture the complex interactions between members of heterogeneous populations.

A handful of papers provide very comprehensive high-fidelity models for charging behaviour by leveraging real-world census data to create synthetic populations and activity. Plagowski et. al. [14] quantify the impacts on hourly powerline loads from charging a car fleet with an 8.5% Battery Electric Vehicle (BEV) share for the real distribution grid in the canton of Zurich which is intended to represent a likely future scenario in 2025. The simulation includes approximately 3.5 million car-driving agents at a temporal resolution of one second. The authors assume that neighbourhood clustering has a significant effect on BEV uptake. Using a combination of socioeconomic and behavioural characteristics from a synthetic population and the current locations of existing BEV owners, they consider new BEV owners to (i) live near current owners of BEVs; (ii) possess a driver’s license; (iii) commute by car to/from work; and (iv) have sufficient income to buy a BEV. Whilst Plagowski et. al. model the impact of EV charging, Adenaw and Lienkamp [15] focus on modelling charger utilisation and user behaviour. The authors employ a co-evolutionary learning model for adaptive charging behaviour and verify their simulation framework using the city of Munich as a case study. They aimed to realistically reproduce current EV charging behaviour and spatiotemporal charger utilization. However, they do not attempt to provide medium to long-term forecasts for EV charging demand.

Both models utilise high-fidelity input data for activities, travel, EV ownership and socioeconomic demographics which enable them to accurately simulate real charging behaviour. However, the availability of this high-fidelity data outside of the case-study regions might be restricted or absent entirely, thus limiting the scalability and versatility of these models. Therefore, in our approach to high-fidelity modelling, the use of open datasets that span whole regions or countries is important to perform whole system modelling on the distribution and transmission system.

Spatial data

To forecast future demand at the distribution substation level, we estimate the demographic data associated with each substation. However, the highest resolution of publicly available demographic data from the 2011 census is recorded at the Output Area (OA) level. Since OAs do not directly correspond to Distribution Substation Areas (DSAs), geospatial analysis is required to estimate DSA demographics from the census data. Geospatial data for Bath distribution substations were accessed and filtered from the Western Power Distribution (WPD) collection of spatial datasets. In total, 668 distribution substations were included in this analysis.

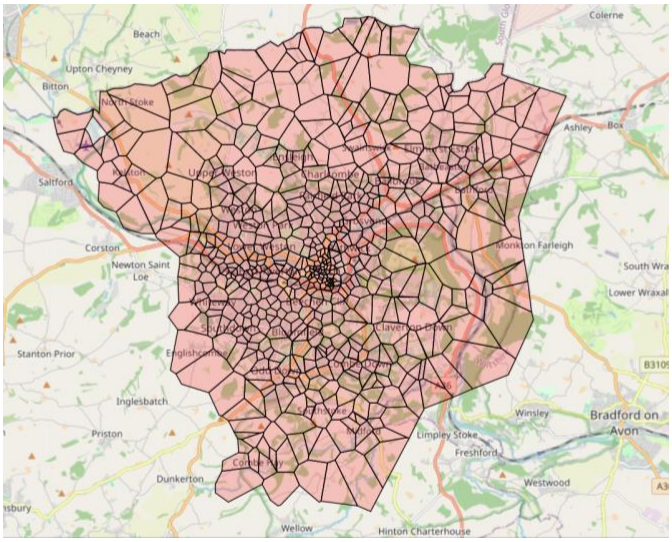

Figure 4-3 Map of Bath distribution substation areas (DSAs).

Next, the OA geospatial data was retrieved from the office for national statistics and filtered to only include OAs in Bath and North-East Somerset. Demographic data for each OA was taken from the 2011 census.

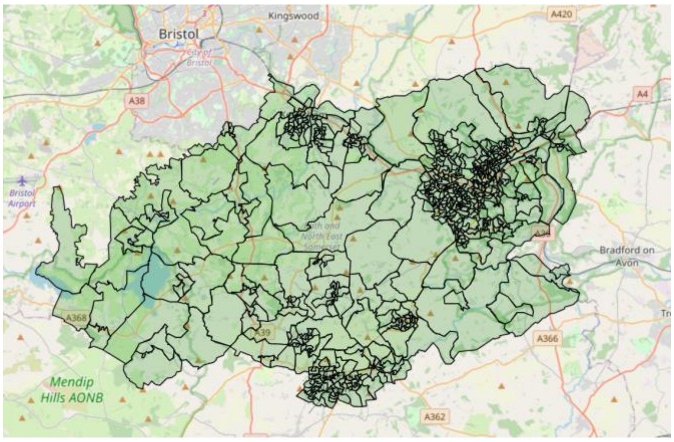

Figure 4-4: Map of Bath and Northeast Somerset Output Areas (OAs).

Here, it was assumed that the demographics of a DSA are approximately equal to that of intersecting OAs, where larger intersections led to greater contributions from the OA. Therefore, for each DSA, intersections with OAs were recorded and the intersectional areas, relative to the size of the OA, were calculated.

EV uptake forecasts

The demographic data for a DSA was calculated as a weighted sum of the demographics from all intersecting OAs. A key demographic of interest was the number of cars and vans in the area, a choropleth map of which is shown below.

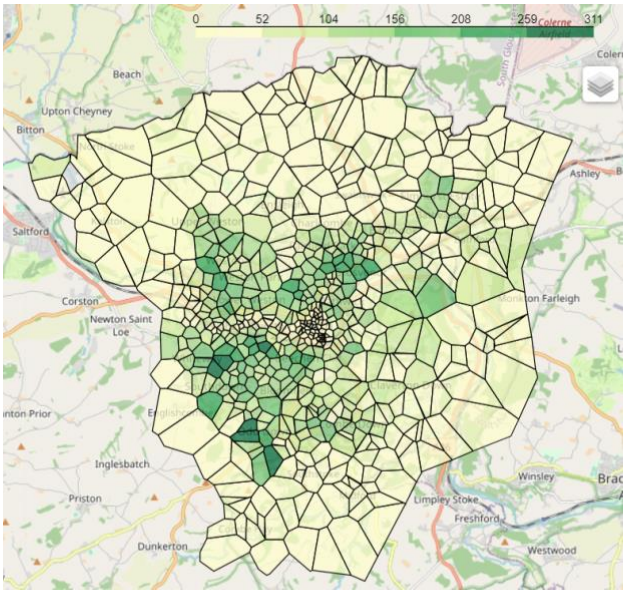

Figure 4-5: Choropleth map of the estimated number of cars and vans in each DSA.

This demographic can help to estimate the current level of EV uptake in each of the DSAs. The total number of registered Battery Electric Vehicles (BEVs) and Plug-in Hybrid Vehicles (PHEVs) in BA1 and BA2 (Q3 2021) was retrieved from the Department for Transport. The number of all licenced cars (Q3 2021) was used to calculate the level of EV penetration.

Table 4-3: EV penetration by Bath postcode (Q3 2021)

Postcode	No. BEVs	No. PHEVs	No. Cars	BEV Pen (%)	PHEV Pen (%)
BA1	286	147	17,688	1.62%	0.83%
BA2	425	260	33,191	1.28%	0.78%

WPD's 'Best view' distribution future energy scenario (DFES) has forecasts for BEVs and PHEVs at the Electricity Supply Area (ESA) level. DSA forecasts were generated by scaling the associated ESA forecast to match the current number of EVs DSA. This ensured that the trend of a DSA followed the trend of its parent ESA.

Generating EV load profiles

Charging session data from the WPD Electric Nation trial was used to develop the EV load profiles. It was assumed that the vehicles began actively charging when they plugged in and ignores the use of timers. An approximation for charging duration and charging end time was calculated by dividing the total energy consumed by the vehicle's nominal charging rate.

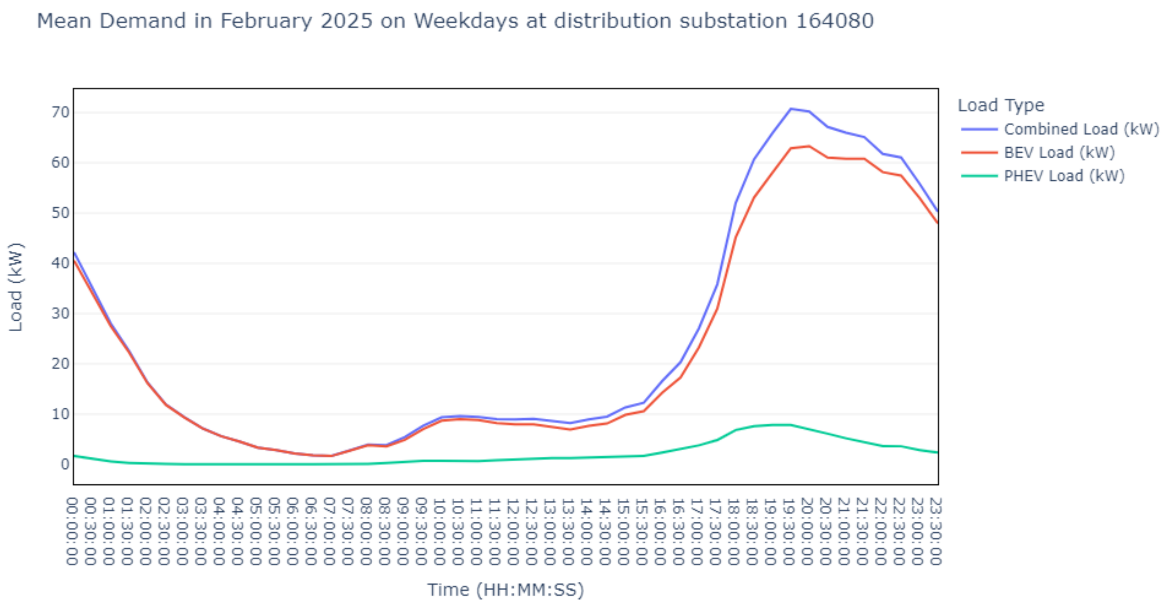

Figure 4-6: Example forecast for the daily load profile at a single distribution substation due to EV charging.

Overview

The key differentiating part of this methodology is the mapping of Census and EV data to distribution substations through geospatial analysis. This approach to high-fidelity EV charging demand modelling is appealing because it leverages completely open datasets which are updated periodically and are available for the whole of the UK which makes this approach potentially. These factors make this approach both scalable and robust to future changes to the data. We plan on using census data and current EV penetration data to identify the key drivers for EV uptake.

4.2. COMBINED MODELLING OF EVS AND EHPS

State of play

Existing research on the impact of EVs and EHPs on electricity distribution often use representative networks, rather than real LV networks, as the information necessary for creating a bottom-up model is not available. While helpful, we are seeking to use high-fidelity modelling that can map impacts onto real networks for direct applicability, built from power demand modelling from LV Network Template project [37-38]. Motivated by similar reasoning, Navarro-Espinosa and Ochoa conduct bottom-up modelling of real UK LV networks by assigning photovoltaic systems, micro combined heat and power units, EVs, and EHPs to feeders at different uptake levels [13]. This research exemplifies the power of high-fidelity modelling for determining future challenges to LV networks, but the authors' use of a single monolithic model for modelling the whole system prevents their approach from being scaled across other networks and is not able to use our best forecasts for assigning LCTs heterogeneously across the network.

Assigning EHPs across Bath's LV network

While EV uptake relies on socioeconomic factors, the driving factors used for forecasting the future uptake of EHPs are naturally quite different. As the installation of EHPs is far more likely to depend on the tenure and characteristics of the dwellings in each area. Properties that are less likely to be connected to the gas network, are more modern (and thus better-insulated), and owner-occupied are all more likely to install an EHP in the coming years.

We use WPD's 'Best View' Future Energy Scenario to inform EHP-uptake. We modulate these uptake rates at the distribution-level according to driving factors available from Census data and property information from the Valuation Office Agency and Office for National Statistics. This enables us to assign EHPs to households according to our best available forecasts.

Modelling aggregated demand profiles for different numbers of users

To model EHP usage behaviour, data from the UK Government's Renewable Heat Premium Payment (RHPP) scheme was used [11]. This scheme provided homeowners and landlords subsidies to install air-source, ground-source, and hybrid EHPs, and data was collected on the electricity usage associated with these devices. Data was collected at two-minute intervals from 700 device installations from November 2013 to April 2015.

In order to model the additional demand resulting from these devices, a probabilistic model was created for each type of EHP so that an arbitrary number of EHP-associated demand profiles could be generated in a manner that accurately represents their diversity. Generative sampling from these representative distributions enables our high-fidelity model to capture the effects of having limited diversity located at the feeder level of the network. High rates of coincidence are more likely to be observed among smaller populations and, as a result, peak demand per household increases as we model electricity consumption with greater spatial resolution. This is compounded by the clustering of dwelling characteristics, tenure types, and demographic factors which are likely to result in a clustering of EVs and EHPs at the feeder level of the network.

Combining this with WPD's 'Best View' scenario, the impact of ASHPs, GSHPs, and hybrid heat pumps (with no complementary heat storage devices) has been mapped onto Bath's LV network (and can be trivially expanded to the rest of WPD's service areas).[1]

Combining models

By taking a modular approach that will enable the use of microservices in the future, we must be able to combine our models which will allow us to both observe their combined effects and alter the underlying factors that drive changes across technologies. We simply integrate technologies at the distribution substation level by aggregating their combined demand profiles.

The level of EV and EHP uptake was calculated slightly differently. The number of EVs in each DSA was derived from the estimated number of cars registered in each OA, whereas the number of EHPs was derived from WPD's 'Best View' scenario and assigning heat pumps according to the number of customers connected to each distribution substation. This difference in approach was primarily because the level of vehicle ownership in an area might vary depending on the parking availability and so the density of EVs won't necessarily correlate strongly with population density.

The load profiles for EVs and EHPs were both derived from trial data. EV load profiles were calculated using session data (i.e., start time, end time, quantity of energy delivered) whereas the load profiles for EHPs were calculated from meter data. Since EV charging data is often in the form of session data, it was logical to develop a workflow that could easily enable the addition of other EV datasets.

4.2.1. NEXT STEPS

For EV modelling, the next steps will be to identify key demographical drivers for EV uptake and charging behaviour using the DfT data that covers the entire UK, and Electric Nation trial data from WPD. In addition, the use of public charging infrastructure should also be incorporated into the model.

For EHP modelling, the next steps will be to model EHP uptake and behaviour according to dwelling characteristics and demographics. The model should also be expanded to consider other types of heat pumps such as district heating, in addition to modelling the impact of storage on load profiles.

Overall, the high-fidelity load profiles will be made probabilistic such that the load at a given time is expressed as a probability distribution rather than a point estimate. Furthermore, we plan to combine the effects of supply deficits and surpluses at both distribution and transmission systems by vertically integrating these models with Lewis Dale's practical electricity transmission system models, and over time with gas transmission system model, electricity and gas distribution system models, as shown in Figure 4-7. Under the microservices paradigm, this approach to whole-system modelling is uniquely powerful since a change in one set of forecasts, technological characteristics, or expectations of consumer behaviour does not require the full, highly complex model to be re-simulated.

[1] Modelling storage technologies is a crucial next step in this research

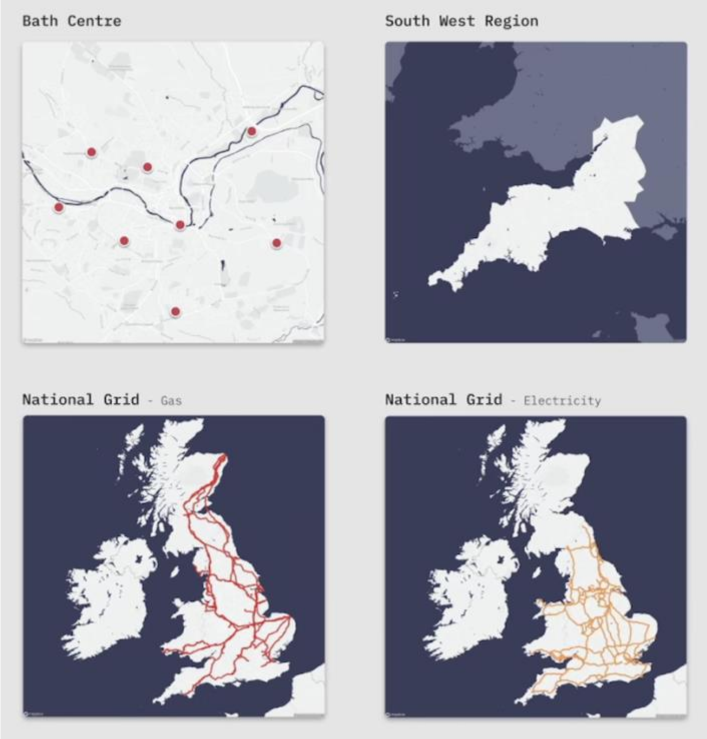

Figure 4-7: A Sample Illustration for the Whole Energy System Visualisation.

4.3. ENERGY SYSTEM RESILIENCE UNDER EXTREME WEATHER

4.3.1. BACKGROUND

The resilience of energy systems in responding to various extreme events, either natural or man-made, is essential for ensuring energy access by the society. The UK energy system is vulnerable to many weather events and power cuts/outages hit the system nearly every winter. The latest outage was caused by storm Arwen in winter 2021. Ofgem recently initiated a review into the response of the power industry to Storm Aware. UK government also recently published a report of Energy Emergencies Executive Committee Storm Arwen Review to summarise the key learnings and implications of energy system resilience.

In reality, many extreme weather events can impact the energy system, but the relative importance diversifies. According to the Climate Change Adaptation Report by ENA, the main weather impacts on UK gas and electricity networks from the latest independent Met Office UKCP18 climate change projections are [16], [17]:

- Temperature—predicted increase.
- Precipitation—predicted increase in winter rainfall and summer droughts.
- Sea level rise—predicted increase.
- Storm surge—predicted increase.
- Increasing wet – dry cycles leading to ground movement.
- Increasing windstorm frequency (particularly when following high intensity precipitation).
- Significant cold spells – predicted decrease but more severe.
- Wildfire.

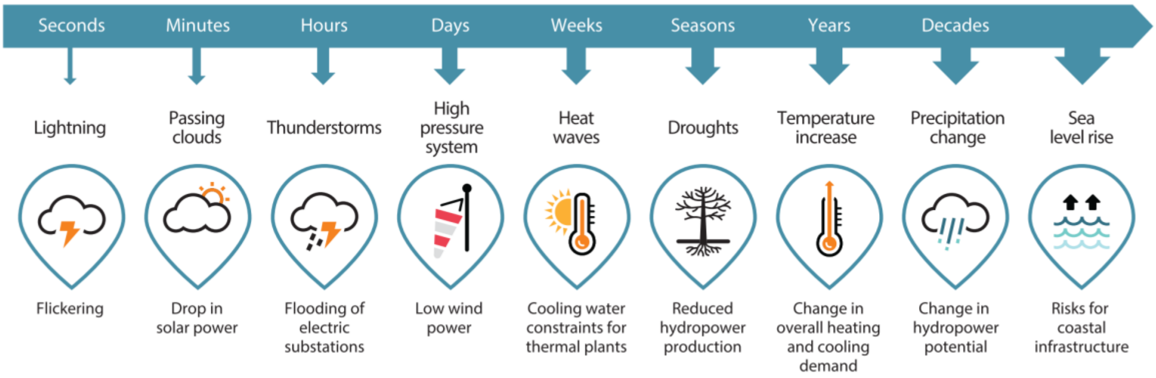

Figure 4.7 Weather and climate on energy system on all time scales [18].

It is noted that these weather events have dramatically different time scales, varying from seconds to years. However, weather events that are significant to UK energy systems, flooding, extreme temperature, and storm, have very short time scales. The impact can build up within minutes or hours and propagate within the systems quickly. The duration of extreme weather events can disappear after hours or days, but the consequences could last for a very long time, days, weeks and even months. It means that network operators should take quick actions in predicting issues, preparing resources, and recovering their networks as prolonged outages can cause severe consequences.

4.3.2. Current Practices and Benefits of Microservices to Support Resilience

Network operators normally have their climate response plans in place. Ahead of winter 2021, they carried out several activities in line with their established pre-winter checks and preparations. These activities are mainly concerned with preparation long before the events, which could include:

- Delaying major planned outages to increase network resilience.
- Undertaking tree cutting programmes to clear trees from the vicinity of overhead lines.
- Undertaking inspections of substations and overhead circuits ahead of and throughout winter periods.
- Undertaking checks on the availability of key external resources such as helicopters, vehicles, mobile generators or staff with specialist skills.
- Ensure enhanced contingency arrangements are in place, to cover an often-busy winter period, which includes having extra staff and resources on duty or stand-by.

Network operators are all in receipt of 10- and 5-day advanced weather forecasting, as well as detailed near-term forecasts. They can access information via very limited channels regarding their systems. The SCADA system is mostly used, but the problem is not all assets can be real-time monitored. Therefore, network operators need to rely on customers to report outages and then engineers can work out the location and seriousness of faults. Then, they should stand up their responses to the severe weather warnings for extreme weather. This involves moving field teams into areas most likely to see impacts and relocating critical resources into the most appropriate locations. In some unusual cases, if the extreme weathers are higher than the normal/expected thresholds, there will be insufficient time to mobilise additional response beyond what was typical for the severe amber weather warnings [19]. It is noted that all these functions of data acquisition, processing and decision making are developed as a whole in their energy management systems. However, there are many problems with this business-as-usual practice:

- The methods are still rudimentary, to some extent, based on past experiences or rules of thumb, but the emerging data from all sources concerning resilience is not well utilised;
- This centralised architecture is vulnerable to faults and cyber-attacks, as everything is centrally controlled and managed;
- The computational process and communication are a huge burden as all tasks and inquiries need to be processed by the energy management systems;
- Some data essential for energy system resilience cannot be directly collected by the systems deployed by network operators, such as weather information;

To address the above challenges and make the best use of data to facilitate resilience, microservices can work as promising solutions to further promote the functionality, robustness, and efficiency of solutions. Microservices can decouple the whole decision-making into different modules, such as data collection processing, knowledge learning, and decision-making, and microservice modules can be developed for specific purposes, or assets, or scenarios. Each module can be developed separated and then be integrated to form the data acquisition, assessment, and decision platform. There are many benefits to this architecture for resilience prediction, analysis, and management, including

- **Agility**: because microservices are deployed independently, it's easier to manage problem fixes, feature releases, and function expansion.
- **Robustness**: if an individual microservice becomes unavailable, it will not disrupt the entire application, as long as any upstream microservices are designed to handle faults correctly.
- **Scalability**: services can be scaled independently, letting operators scale-out subsystems that require more resources, without scaling out the entire application.
- **Data isolation**: it is much easier to perform schema updates and data protection because only a single microservice is affected.

The following sections will discuss the data architecture which can work together with microservices to facilitate energy system resilience.

4.3.3. DATA ARCHITECTURE FOR ENERGY SYSTEM RESILIENCE

An energy system is a source of rich multi data, owning a vast amount of diversified data collected via SCADA, PMU, WAMS. In addition, satellites, planes, drones, sensors and robotic devices are some of the geospatial tools that now can provide cost-effective, automated and continuous data collection beyond human capability. Data and data analytics can facilitate the assessment and management of energy system resilience. They can dramatically overhaul the current practices in assessing asset health, predicting the severity and features of weather events, preparing and recovering networks, and managing resources. By fusing data and information from various sources and extracting useful insights, network operators can then make the best use of them to inform more robust decisions. It is essential to leverage the data to make fast predicting resilience and take robust decisions to protect the system, and to mobilise resources to recover energy systems. Thus, we should leverage the potential of digitalisation to support the resilience of energy systems to extreme weather.

In general, there are three groups of data, which can be utilised to further enhance the assessment and management of energy system resilience, including

- Climate data, which should have a fine spatiotemporal resolution to characterise the ambient environment of energy systems
- Historical failure data, which is used to learn how weather events affect the whole energy systems

- Energy system data, which describes the structure, states and resources of energy systems and assets

The problem is that these datasets dramatically diversify from many aspects, including: 1) various sources, within the energy system, ambient environment, supply chain, etc.; 2) different sizes, bytes, kB, MB, GB, TB, etc; 3) temporal resolution, second, minutes, and even years; 4) different format, pictures, text, spreadsheets, and inputs of professional software, etc.; 5) different quality; 6) accessibility. In addition, these datasets should be integrated and fused together on a common platform so that they can provide useful insights from a different perspective to support robust and flexible decision making. From this perspective, digitalisation technologies and microservice can help in the following areas.

4.3.4. DIGITALISATION FOR ENERGY SYSTEM RESILIENCE VIA MICROSERVICES

Data analytics and machine learning play a pivotal role in exacting valuable information, insights, and supporting decision making. By piecing together data and information from various sources, it is possible to obtain a more complete picture of the system, which will enable network operators to make better decisions. By using the concept of microservices, it is possible to disaggregate the problem into different dedicated modules, which would be able to produce more robust, efficient, and scalable solutions.

Data module

As discussed before, data is the key to making fast and accurate assessments on energy system resilience. The data can be in many different formats and collected from various sources. Thus, the data module can be working as the host for the data and data processing functions can be developed. Some automation can be embedded in this layer to pre-process data, including

- Data cleaning, which includes handling missing entries and noisy entries
- Data transformation, which contains feature construction and data normalisation
- Data integration, which includes data merging and knowledge integration, data reduction

Knowledge learning module

At the knowledge learning module, various data can be fused and integrated together to produce new knowledge and insights, which is not possible preciously. They will then be utilised for modelling various system assets, technologies, events, and the integration between different events. These data can be utilised for generating knowledge that cannot be acquired by purely using data from one source. Various machine learning methods can be for information exaction and knowledge learning:

- **Big data analytics** (pattern mining, rule association, clustering, classification, regression, etc.) to handle large-size data acquired from energy systems on a real-time basis that describe the states of key elements and assets
- **Machine learning** (LSTM, reinforcement learning, extreme learning machine, etc.) approaches to identify the relation between ambient climate and states of elements and assets
- **Heterogeneous data fusion** to extract knowledge (stage-based, feature-based, semantic meaning based, etc.) from multi-source data

Decision-making module

At the decision-making module, the data and modelling developed in the previous two modules can be used for informing effective measures and solutions to protect energy systems from extreme weather and mobilise resources to recover the systems from the events quickly and effectively. Apart from that, such module can also help develop what-if scenarios, i.e. to assess system performance under various plausible scenarios which could happen in the future. The outcome will inform network operators to make better planning and operation decisions in responding to extreme weather.

- Edge-cloud architecture to support fast decision makings in network operation and resource allocations in response to extreme weather conditions.
- Support the digital twin development of energy systems by feeding in real-time data from energy systems and the ambient environment
- Local market design and resources integration to support network resilience.

4.4. CIRCULAR STABILITY SERVICES FROM INVERTER-BASED RENEWABLE RESOURCES

4.4.1. *BACKGROUND*

The drive to decarbonise electrical energy is progressing quickly around the world with large volumes of renewable capacity added each year [20], [21] and several systems that were fossil-fuel operating at times with more than half of production from renewable sources [22]–[25]. Several planning and operation challenges have had to be confronted to get to this point and others remain to reach higher penetrations [26]. Many of those challenges relate to the variable nature of the resource of wind and solar but other challenges relate to the inverters used to interface wind, solar and battery systems to the grid [27]. These are known as inverter-based resource (IBR) or converter interfaced generation (CIG).

As the numbers of inverters in power systems have grown concerns have grown over changes to system dynamics and stability [28]. There have been several incidents reported where inverters are implicated in threats to system stability. Some relate to transient stability issues such as disconnection of inverters where fault-ride-through was expected [29], [30], and poorly damped reactions to voltage dips have been observed in large wind farms [31]. A particular problem has been recognised of instability in phase-locked loops (PLLs) of inverters in weak grids [32], [33]. Some system operators have reported emergence of poorly damped oscillatory modes under certain operating conditions when inverters are dominant in an area and for which further investigations are now needed to establish the root-cause [34]. The stability challenges may become more significant in the future when IBRs take a dominant role in a carbon-neutral power system.

Inverters have decidedly different characteristics to conventional synchronous generators. Inverters lack intrinsic over-current capacities and energy storage components, resulting in a drastic reduction of physical strength, including short-circuit levels and inertias. On the other hand, inverters have programmable behaviours that can be flexibly shaped and re-shaped, which can be exploited for versatile stabilisation services that is beyond the current categories. To make the best use of the flexibilities in control and avoid the deficiencies in physical strength, a new paradigm is needed for stability design and system operation. In this section, we envisage such a new paradigm and illustrate how it can be integrated with the microservice architecture described above, as a user case for the digitalisation strategy.

4.4.2. *CIRCULAR STABILITY: A NEW PARADIGM*

The changing landscape of power systems with inverter-based renewables poses challenges but also opportunities to rethink power system stability. A conventional power system features centralised stability management to tackle the tight dynamic coupling of generators across the entire system, mainly due to the uncontrolled angle swing of rotors. This methodology should no longer be continued in an inverter-based renewable power system, due to the following reasons:

- The decentralised distribution of resources makes centralised management extremely expensive and unreliable if not impossible
- Inverters lack intrinsic physical strength underlying the operating principle of conventional grids
- Inverters offer controllability to mitigate the uncontrolled angle swing in a conventional grid, based on which a new paradigm of stability management is possible.

As a user case for the digitalisation strategy, we explore the possibility of circular stability services from inverter-based distributed resources. Our vision is as follows:

- To establish a theoretic framework to push the stability boundary to the physical boundary of power transfer, and thus remove the stability barrier, by exploiting the controllability of inverters.
- Based on the new framework, to establish an abstraction layer where the stability control is encoded as technology-neutral stabilisation services.
- To design the interoperation and inter-trading mechanism of the stabilisation services and plug it into the wider circular smart energy system.

4.4.3. Stability as Services

Stability in its original form is a single technical problem and is maintained by an operator alone with natural monopoly. This monopolistic approach worked well but may result in insufficient competition. There is an ongoing trend to re-formulate stability requirements as technology-natural services, and an operator procure stability services in an open market to provide incentives for competition and innovation. Some forms of stability services have been well established, such as inertia or primary response as the main form of frequency stability services. The new behaviours of IBRs introduce new categories of system dynamics which should be addressed by new stability services. On the other hand, the programmability of inverters may also supply new stability services. Our vision is to establish a theoretical framework to understand the behaviour of inverter-based power systems, and on top of that to define services in all categories of stability across all timescales. Such services will be an abstract layer between physical technology and market-based operation.

4.4.4. Software Defined Hardware

As discussed above, the behaviour of inverters is largely defined by their control, i.e., the software defined dynamics. The stability services will be provided in the form of re-configurable and re-programmable control software embedded into inverters. The re-programmable embedded software will be a part of the microservice software architecture and be the "last mile" of the microservices in a digital energy network, linking the digital and physical worlds. The software defined hardware will be the enabler of the circular stability paradigm and may be extended to provide more versatile functions beyond stability.

5. CONCLUSION

The pressures from energy security, sustainability and affordability will intensify energy system decarbonisation and decentralisation. The present subsystem approach to system operation and development will need to change to cope with increasing and diversified energy technologies, growing energy players and progressive energy markets.

A whole-system approach is an essential step to decarbonise our energy system and deliver energy security and affordability, allowing high fidelity modelling, analyses, optimisation, and control to be exercised across the whole system. Moving to a whole-system approach will result in changes in a subsystem being immediately experienced by the entire system, with the benefit that energy assets across the whole system can be optimised to cope with rapid changes in customer requirements, system dynamics, and uncertainties in the future landscape.

This strategy presents our initial thinking of transforming the present energy system to an open, agile, and responsive system of systems, where functions sitting at differing organisations can be combined to form scalable and complex solutions and extended by both dominant and third-party energy players.

However, the energy sector is unlike digital natives. It has the challenges of legacy systems and software applications designed to work on a subsystem level, modified over the years to account for increasing renewables, electric heat and transport demand, new markets, and new energy players. It is not possible to introduce modularity, interoperability, and open framework everywhere and overnight, but should be considered as a T+10 years endeavour.

The initial focus could be on areas where the greatest benefits could be created by decoupling some central monolithic applications to create modular, interoperable, and open functions, such as GB system forecasting, power flows and contingency analyses. This will allow the energy companies seamlessly to adapt a small subset of the functions in response to significant emerging changes and enable third parties to integrate their innovations to improve the speed, performance and/or the stability of core system functions.

6. References

[1] Department for Business, Energy, & Industrial Strategy, ‘Digitalising our energy system for net zero: strategy and action plan’, Jul. 2021. Accessed: May 27, 2022. [Online]. Available: https://www.gov.uk/government/publications/digitalising-our-energy-system-for-net-zero-strategy-and-action-plan

[2] L. Sandys, R. Dobson, E. Brown, G. Graham, R. Lane, and J. Verma, ‘A Strategy for a Modern Digitalised Energy System: Energy Data Taskforce Report’, 2019.

[3] A. Rhodes, ‘Digitalisation of energy’, *Imp. Coll. Lond. Lond. UK*, 2020.

[4] C. Gibbard, ‘Journey towards the UK’s first Energy data & digitalisation Strategy’, 2021.

[5] S. Steer and Ofgem, ‘Review and next steps: RIIO digitalisation strategies’, Jun. 10, 2020. Accessed: May 27, 2022. [Online]. Available: https://www.ofgem.gov.uk/publications/review-and-next-steps-riio-digitalisation-strategies

[6] CLIMATE WATCH, ‘World Greenhouse Gas Emissions in 2016’, *World*, 2016.

[7] *The Ten Point Plan for a Green Industrial Revolution*. Accessed: Aug. 25, 2021. [Online]. Available: https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution/title

[8] BloombergNEF, ‘Global EV Outlook 2020’, Bloomberg New Energy Finance, 2020.

[9] H. Engel, R. Hensley, S. Knupfer, and S. Sahdev, ‘The Potential Impact of Electric Vehicles on Global Energy Systems’, McKinsey Center for Future Mobility, 2018. Accessed: Apr. 28, 2022. [Online]. Available: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-potential-impact-of-electric-vehicles-on-global-energy-systems

[10] UK Power Networks, ‘Impact of Electric Vehicle and Heat Pump loads on network demand profiles’, pp. 32–37, 2014.

[11] J. Love *et al.*, ‘The addition of heat pump electricity load profiles to GB electricity demand: Evidence from a heat pump field trial’, *Appl. Energy*, vol. 204, pp. 332–342, Oct. 2017, doi: 10.1016/j.apenergy.2017.07.026.

[12] S. J. G. Cooper, G. P. Hammond, M. C. McManus, and D. Pudjianto, ‘Detailed simulation of electrical demands due to nationwide adoption of heat pumps, taking account of renewable generation and mitigation’, *IET Renew. Power Gener.*, vol. 10, no. 3, pp. 380–387, 2016, doi: 10.1049/iet-rpg.2015.0127.

[13] A. Navarro-Espinosa and L. F. Ochoa, ‘Probabilistic impact assessment of low carbon technologies in LV distribution systems’, *IEEE Trans. Power Syst.*, vol. 31, no. 3, pp. 2192–2203, 2015.

[14] P. Plagowski, A. Saprykin, N. Chokani, and R. Shokrollah‐Abhari, ‘Impact of electric vehicle charging ‐ An agent‐based approach’, *IET Gener. Transm. Distrib.*, vol. 15, no. 18, pp. 2605–2617, Sep. 2021, doi: 10.1049/gtd2.12202.

[15] L. Adenaw and M. Lienkamp, ‘Multi-Criteria, Co-Evolutionary Charging Behavior: An Agent-Based Simulation of Urban Electromobility’, *World Electr. Veh. J.*, vol. 12, no. 1, p. 18, Jan. 2021, doi: 10.3390/wevj12010018.

[16] ENA, ‘Written evidence submitted by Energy Networks Association’. 2022. [Online]. Available: https://committees.parliament.uk/writtenevidence/106681/pdf/

[17] ENA, ‘Adaptation to Climate Change Task Group’. 2021. [Online]. Available: https://www.energynetworks.org/assets/images/CCRA3%20report%20v1.0%20final.pdf

[18] EEA, ‘Adaptation challenges and opportunities for the European energy system — European Environment Agency’, Publication, Jan. 2019. Accessed: May 27, 2022. [Online]. Available: https://www.eea.europa.eu/publications/adaptation-in-energy-system

[19] BEIS, ‘Storm Arwen electricity distribution disruption review: terms of reference’, Energy Emergencies Executive Committee, Feb. 2022. Accessed: May 27, 2022. [Online]. Available: https://www.gov.uk/government/publications/storm-arwen-electricity-distribution-disruption-review/storm-arwen-electricity-distribution-disruption-review-terms-of-reference

[20] IEA, “Global Energy Review 2021,” 2021. [Online]. Available: https://www.iea.org/reports/global-energy-review-2021/renewables

[21] ‘Trends in Renewable Energy’, *IRENA*, 2020. https://www.irena.org/Statistics/View-Data-by-Topic/Capacity-and-Generation/Statistics-Time-Series (accessed May 27, 2022).

[22] '2020 greenest year on record for Britain | National Grid Group'. https://www.nationalgrid.com/stories/journey-to-net-zero-stories/2020-greenest-year-record-britain (accessed May 27, 2022).
[23] Eirgrid Group, 'All Time Record for Wind Generated Electricity Broken', *EirGrid Group*, 2017. https://www.eirgridgroup.com/newsroom/wind-record/ (accessed May 27, 2022).
[24] 'South Australia sets world record in solar generated electricity, says SA Power Networks - ABC News'. https://www.abc.net.au/news/2021-11-04/sa-generates-more-electricity-than-it-consumed/100595636 (accessed May 27, 2022).
[25] 'Solar reaches 110 per cent of South Australia demand as more records tumble | RenewEconomy'. https://reneweconomy.com.au/solar-reaches-110-per-cent-of-south-australia-demand-as-more-records-tumble/ (accessed May 27, 2022).
[26] L. Bird, M. Milligan, and D. Lew, 'Integrating variable renewable energy: Challenges and solutions', National Renewable Energy Lab.(NREL), Golden, CO (United States), 2013.
[27] A. Hoke, V. Gevorgian, S. Shah, P. Koralewicz, R. W. Kenyon, and B. Kroposki, 'Island power systems with high levels of inverter-based resources: Stability and reliability challenges', *IEEE Electrification Mag.*, vol. 9, no. 1, pp. 74–91, 2021.
[28] J. Matevosyan *et al.*, 'A future with inverter-based resources: Finding strength from traditional weakness', *IEEE Power Energy Mag.*, vol. 19, no. 6, pp. 18–28, 2021.
[29] North American Electric Reliability Corporation and Texas RE Staff, 'Odessa Disturbance - Texas Events: May 9, 2021 and June 26'. Accessed: May 27, 2022. [Online]. Available: https://www.nerc.com/pa/rrm/ea/Pages/May-June-2021-Odessa-Disturbance.aspx
[30] J. NERC, '900 mw fault induced solar photovoltaic resource interruption disturbance report', *North Am. Electr. Reliab. Corp.*, 2018.
[31] N. ESO, 'Technical report on the events of 9 august 2019', *Natl. Grid ESO*, 2019.
[32] J. Z. Zhou, H. Ding, S. Fan, Y. Zhang, and A. M. Gole, 'Impact of Short-Circuit Ratio and Phase-Locked-Loop Parameters on the Small-Signal Behavior of a VSC-HVDC Converter', *IEEE Trans. Power Deliv.*, vol. 29, no. 5, pp. 2287–2296, 2014.
[33] Q. Hu, L. Fu, F. Ma, and F. Ji, 'Large signal synchronizing instability of PLL-based VSC connected to weak AC grid', *IEEE Trans. Power Syst.*, vol. 34, no. 4, pp. 3220–3229, 2019.
[34] M. O'Malley and J. Leslie, G-PST/ESIG. *Research Agenda for Transformed Power Systems*, (Nov. 30, 2021). Accessed: May 27, 2022. [Online Video]. Available: https://www.esig.energy/event/webinar-research-agenda-for-transformed-power-systems/
[35] Energy System Catapult, 'Review of Future Power Systems Architecture (FPSA) Functions, https://es.catapult.org.uk/report/review-of-future-power-system-architecture-fpsa-functions/, 2019.
[36] Institute of Engineering and Technology and Energy System Catapult, 'Fast Track to Britain's Future Power System', https://www.theiet.org/media/9408/fast-track-to-britains-future-power-system.pdf, 2019.
[37] R. Li, C. Gu, F. Li, et al, 'Development of Low Voltage Network Templates-Part I: Substation Clustering and Classification', IEEE Transaction on Power Systems, 2015.
[38] Western Power Distribution, 'Low Voltage Network Templates' https://www.westernpower.co.uk/projects/network-templates, 2015.