Catapult Energy Systems

BEIS Energy System Digital Twin Demonstrator

9th August 2022

Department for Business, Energy & Industrial Strategy

The Alan Turing Institute

CITYSCAPE DIGITAL

Contents

Disclaimer

Foreword

It really has been a great pleasure to have sponsored this project. Decarbonising our economy is the transitional challenge of our age. It's also very likely we will face further demands to understand the energy and emissions system in more detail as we chase down the mega-tonnes of greenhouse gas on our way to Net Zero. A digital twin could prove to be a great way to provide the:

- level of detail we desire;
- visualisations that make it seem real; and
- interfaces that allow our customers to interact directly with our models.

It wasn't clear, when we started the project, whether it would be possible to apply the concepts of digital twins to the whole energy system. They have been used successfully for single or small groups of assets but was it possible here? The two demonstrators described in this report are the first exciting step to answering this question and I am looking forward to the rest of the journey.

– Alec Waterhouse MSc, FORS, Companion of the OR Society

This has been a fantastic project. It has clearly demonstrated the value of digital twins for the energy system, and it has underlined that great collaboration is key to success. So, I'm delighted to see this report and excited to consider where this approach could go next. In particular, it would be brilliant to begin unlocking the promise of 'an ecosystem of connected digital twins'.

The value of individual digital twins is in helping us to make better decisions faster, and federating digital twins promises even greater value by enabling us to understand systems better and to intervene more effectively. For example, making connections between digital twins of the energy and transport systems could help us to optimise the role of electric vehicles in both systems. Connecting digital twins is all about interoperability – enabling secure information flow across organisational and sector boundaries.

All this is hugely exciting and has enormous potential value, but technical solutions alone will not be sufficient. Put simply, our complex physical infrastructure systems are massively interconnected, but our organisations operate in silos. Therefore, we need to frame this agenda in terms of socio-technical change and address the all-important human and organisational factors.

The lessons learned from this project hugely help this journey. Massively well done to the team.

– Mark Enzer OBE FREng

Acknowledgements

We have been extremely grateful for the knowledge, expertise and guidance provided by our steering group throughout this project, and their ongoing endorsement of the outputs of this demonstrator project has been greatly appreciated. Populated by experts in digitalisation from across a range of industries, steering group members have shared experiences and lessons learned from their respective journeys, which helped to guide the structuring of the use case and the development of the demonstrators.

Felix Wisby – BEIS

Soheila Amin-Hanjani – BEIS

Mark Enzer – Centre for Digital Built Britain

Peter Van Manen – Frazer Nash Consultancy

Rhiannon Calado – National Grid ESO

Chris Dent – The Alan Turing Institute

Nina Klein – National Grid ESO

Jim Hall – Data & Analytics Facility for National Infrastructure (DAFNI)

Thanks also to Dr Zoya Pourmirza, Security and Resilience Lead at Centre for Energy at Newcastle University, for the expert contribution in writing section 7.4 on cyber security, detailing the security implications associated with moving through the roadmap from digital model to digital twin. Dr Pourmirza' s work was supported by the EPSRC Impact Acceleration Account.

1. Executive Summary

To decarbonise the energy system by the year 2050, it is crucial that decision-makers are equipped with the insights they need to ensure their decisions are effective and influential. The challenge of providing relevant and timely information is compounded by the increasing decentralisation of the energy system, with more assets interacting with it now than ever before. These assets are increasingly under the control and monitoring of digital systems, making available valuable streams of data on the real-time status of the system. This enables decision-making relating to the longer-term strategic decarbonisation policy environment.

Digital twins have long been spoken about as one of the key solutions benefiting from the increased digitalisation of systems, empowering their users with the information and insights they need to make more informed decisions. This project explored the feasibility of creating a digital twin of the energy system, which would be able to provide in-depth analytical information on the system, while also being easy to interact with for both technical and non-technical users. Due to constraints within the project, two demonstrators have been produced: an analytical version for technical users, and the visual element of twinning for non-technical decision-makers, to give the assurance needed that the modelling makes sense. These two aspects have been addressed by creating two proof-of-concept digital models, one focused on visual presentation and one on technical functionality. The visual presentation vividly shows the impact that policy decisions are likely to have on the decarbonisation of domestic properties. The demonstrators show illustrative values for metrics related to the UK's decarbonisation activities, representing the effects of policies as changes to uptake and usage of energy-related technology types, at both a household and a national level, while also giving the user the ability to 'travel' backwards and forwards in time, to see changes in the energy system play out in front of their eyes.

Video walkthroughs of the two proof-of-concept demonstrators – visual and technical – can be found on the ESC site dedicated to this project.[1] The visual demonstrator was developed in a collaboration between ESC, The Alan Turing Institute and CityScape Digital, and provides compelling and accessible visualisations of outputs from the BEIS National Buildings Model[2] using a visual interface written in the Unreal Engine 3D graphics system.[3] This demonstrator provides users with the ability to explore how policy decisions will impact the UK at a national, regional and local level in a much more intuitive way than the current suite of models allow. The technical demonstrator (developed by ESC and CityScape Digital) explores how some of the current suite of spatially and temporally disaggregated models can be interconnected to visualise modelling results under a variety of user-selected scenarios.

These demonstrators begin to paint a picture of how digital twins could be used to support decision-making within the energy sector. However, further work is needed to ensure that the outputs meet user needs and augment the portfolio of pre-existing modelling tools. This project highlights that questions remain around the technical and privacy challenges associated with granular data ingestion and how these should be appropriately mitigated within digital twin solutions, in order to provide full benefit to users.

1 https://es.catapult.org.uk/project/energy-system-digital-twin-demonstrator-project/

2 https://data.gov.uk/dataset/957eadbe-43b6-4d8d-b931-8594cb346ecd/national-household-model

3 https://www.unrealengine.com/en-US/

2. Glossary and Digital Twin Definition

The term 'digital twin' is currently used as an umbrella term throughout industry to describe anything from a virtual model to a digital system which can incorporate a two-way data exchange with a real-world object. There are numerous definitions, and some examples are listed below.

- A digital twin is a realistic digital representation of something physical[4]
  – Cambridge Centre for Digital Built Britain
- A digital twin is a near real-time digital image of a physical object or process that helps optimise business performance[5]
  – Deloitte
- A digital twin is a digital representation of a real-world entity or system. The implementation of a digital twin is an encapsulated software object or model that mirrors a unique, physical object, process, organisation, person, or other abstraction. Data from multiple digital twins can be aggregated for a composite view across a number of real-world entities, such as a power plant, or a city, and their related processes[6]
  – Gartner
- A digital twin is a virtual model of a process, product, production asset or service. Sensor-enabled and IoT connected machines and devices, combined with machine learning and advanced analytics, can be used to view the device's state in real-time. When combined with 2D and 3D information, a digital twin can visualise the physical world and provide a method to simulate electronic, mechanical and combined system outcomes[7]
  – Microsoft
- A digital twin is a virtual representation of a physical product or process, used to understand and predict the physical counterpart's performance characteristics[8]
  – Siemens

---

4 https://www.cdbb.cam.ac.uk/DFTG/GeminiPrinciples

5 https://www2.deloitte.com/content/dam/Deloitte/kr/Documents/insights/deloitte-newsletter/2017/26_201706/kr_insights_deloitte-newsletter-26_report_02_en.pdf

6 https://www.gartner.com/en/information-technology/glossary/digital-twin

7 https://info.microsoft.com/The-promise-of-a-digital-twin-strategyBest-practices-for-designers-Registration-ForminBody.html

8 https://www.plm.automation.siemens.com/global/en/our-story/glossary/

For the purposes of this report, we will be using the following working definitions for digital twin technologies.

Digital Model – A digital representation of a physical system or object, e.g. a network infrastructure map which utilises data from a fixed point in time.

Digital Shadow – A digital model which integrates automated one-way data flow from the physical system or object, e.g. a network infrastructure map which pulls data from the system to dynamically update inventory, asset state and constraints.

Digital Twin – A digital model which integrates two-way data flow between the model and a physical object or system, as shown in Figure 1, where making a change to one can change the other, e.g. a control centre's network map, which displays real-time system status and enables engineers to control assets to mitigate issues.

Based on these definitions, the proof-of-concept demonstrators produced in this project are digital models, where static datasets are being used to better visualise policy decisions over time and illustrate the ways in which Net Zero can be reached more efficiently throughout the UK.

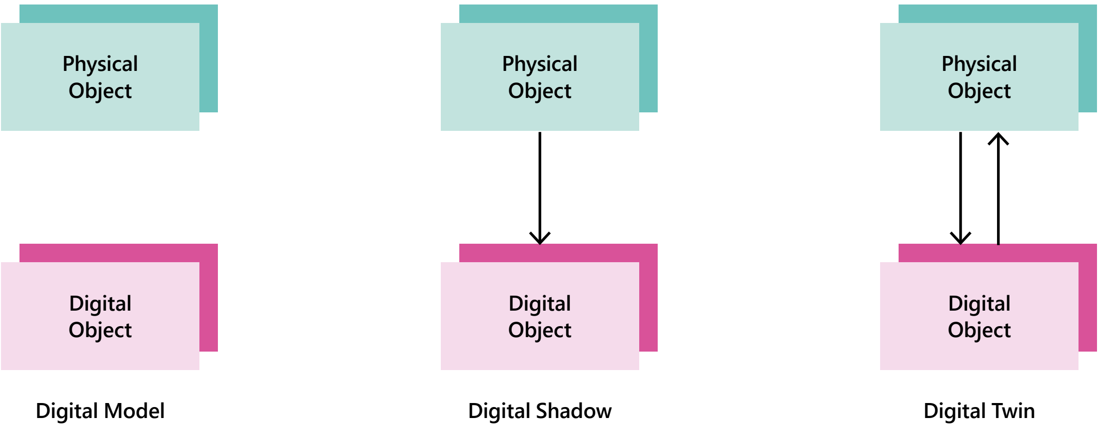

Figure 1: Distinguishing features of digital model, shadow and twin

3. Introduction

3.1. Problem Statement

To support achieving Net Zero by the year 2050, increased datasets from across a wide range of sectors within the UK will need to be more effectively gathered, with accelerated digitalisation efforts providing much of the infrastructure to enable this to happen. Many organisations are exploring how they use and share this data in a way that can provide benefit to both their own organisations and in the longer term the overall system.

In the energy sector in particular, there has traditionally existed a clear division of information across differing organisational silos, making the roll-out of more innovative solutions, and ultimately the transition to a cleaner energy system, much more challenging. Robust digitalisation and data sharing efforts have been shown to begin to bridge the gap between organisations, such as the Modernising Energy Data[9] programme, curating a culture of collaboration throughout the sector and improving the ways in which the whole sector shares and utilises key datasets. These programmes have begun to show the benefits of increased data visibility, demonstrating more accurately how wider access has been crucial to generating a more accurate picture of the ways in which the sector works, and the interactions between the parties within it. However, increasing access to these data types has only been part of the problem and it is the innovative digital infrastructure that will need to be focused on to ensure that this data continues to provide value to those working within the energy sector.

A digital twin is a 'much discussed' concept for integrating and using digital information. The components that support digital twinning have been used in many sectors over the last few decades. Building Information Management (BIM)[6] systems have been early adopters because it enables collaboration through digitalisation. BIM sought to standardise the ways stakeholders involved in a project collect, manage, store, share and use building data and the model used to view the information. This meant that those involved within the building's project lifecycle, from planning to maintenance to decommissioning, could access the same project information and have the ability to adapt the model in real-time, reducing costs, time spent and the risk of different teams working from out-of-date and inconsistent project information. In this process, it is the data owner's responsibility to ensure that they are working towards an open data standard and that their data is accurate and accessible across the asset lifecycle.

One of the main advantages of BIM was its ability to transform the approach to infrastructure design. BIM moved from lifetime construction project information being stored in separate locations, to one where all information is contained in a single integrated framework. This means users can work within a single information space and dive into the deeper elements of information as needed.[10] Digital twins build on these capabilities, providing deeper insights into system interactions, not just for buildings, but for a variety of different sectors.

9 https://www.gov.uk/government/groups/modernising-energy-data
10 https://www.thenbs.com/knowledge/what-are-bim-objects

A digital twin has traditionally been seen as a virtual representation of a real-world asset or set of assets, such as bridges, buildings or wind turbines. However, they should now be considered as a complex system, able to incorporate assets, markets and people. Digital twin solutions can use data and model these assets using the concepts of big data, artificial intelligence (AI), machine learning (ML) and the Internet of Things (IoT).[11] Digital twins are beginning to become feasible in the energy sector because digitalisation can provide a holistic view of the energy system, gaining insight into the ways in which various elements are able to interact with each other.

Some of the benefits of a digital twin include:

- The ability to join data sources and subsequently open up data silos, through the utilisation of common datasets.
- Improved data accuracy, through automating data transformation methods and synchronisation. In the energy sector, this is particularly relevant to the case of consistency in energy network models.
- Reduced likelihood of operating or planning errors, through the ability to better update models to account for changes in the real-world system.
- Reduced time and effort to monitor, manage and control equipment, through the automation of methods.
- More seamless and strategic incorporation of Low Carbon Technologies (LCTs) into the energy system, enabling long-term decarbonisation strategies.

Digital twins could provide a significant opportunity to support aspects of the energy system's transition to Net Zero, such as strategic national and regional level planning and modelling. However, to date their potential has not been fully achieved as they have traditionally been applied for the optimisation and remote operation of smaller groups of physical assets in near-real-time. For digital twins to be successful, it is crucial that commercial actors and technology companies can not only optimise their portfolios of assets within today's market rules but also understand how the constraints applying to their assets might change in the future.

Usable demonstrators have been harder to come by, despite digital twins being one of the most talked about digital solutions within the energy industry in recent years. There are many models within the energy sector which seek to answer a large number of questions in this area; however, the challenges of joining these outputs together and investigating how temporal and spatial outputs can be aligned are substantial.

This project explores how digital twin technologies can be applied in the energy system with an emphasis on using this to understand decarbonisation. The aim was to integrate information from different models and present it in a variety of ways to provide insights and technical analysis. This has involved: identifying a specific use case; exploring the data and models relevant to that use case; and constructing proof-of-concept demonstrators that address the chosen context.

11 https://www.cdbb.cam.ac.uk/what-we-do/national-digital-twin-programme

3.2. Project Phases

This project was split into three core delivery phases, outlined below.

Phase One

Phase One identified and shortlisted use cases for digital twins in the energy sector, down-selecting to one use case to be explored in detail during this project, utilising engagement from the energy sector and adjacent sectors to do so. A steering group was formed of industry experts, who helped to prioritise and define the use case, with domestic decarbonisation being identified as the most relevant and interesting use case.

Phase Two

Phase Two carried out a deep-dive into the data and technology options for a digital twin for the domestic decarbonisation use case. A methodology and scope were proposed for the construction of an energy system digital twin demonstrator during Phase Three, and the ways in which the demonstrator would be run were explored.

Phase Three

Phase Three built the demonstrators. The visual demonstrator was built in a collaboration between Energy Systems Catapult, The Alan Turing Institute and CityScape Digital. The technical demonstrator was built by Energy Systems Catapult and CityScape Digital. Alongside building the demonstrators, the project team engaged with different stakeholders to carry out assurance and user-acceptance testing, incorporating and documenting changes in an agile format.

4. Project Requirements

Defining decarbonisation targets within the energy sector, and indeed other industries, sets the scene for ambitions; however, developing realistic sector level decarbonisation pathways is much more difficult. In the UK, carbon budgets[12] are used to set a cap on the amount of greenhouse gas emissions produced by the country and can highlight the sectors in which the largest change is required.

The sixth carbon budget,[13] covering 2033–37, acknowledged that the energy system's role in reaching Net Zero is heavily reliant on the significant expansion of low carbon generation and other low carbon technologies. As part of the process through which the carbon budget was created, BEIS set the strategic direction needed to meet the budget and used their suite of models to a) identify whether what was set out was achievable and b) provide indications on where assets can be optimised to reach decarbonisation targets more effectively. This culminated in the 'Sector Pathways to Net Zero' defined in the published carbon budget.

Through discussions with BEIS, it was identified that the largest problem faced when looking to tackle the above challenge was developing a holistic view of the outputs produced by different models. Government departments' suite of models spans many sectors. Currently, joining these together, seamlessly sharing assumptions and outputs with each other, is a time-consuming and semi-manual process. This means that developing national and local views, or both present-day and future-facing views, is also time consuming and presents risks.

The task set out by BEIS was to create a proof-of-concept 'demonstrator' for a digital twin to explore the benefit of getting different models to interface and share data with each other. It was also key that what was produced could be easily interpreted by a variety of users, from technical analysts to non-technical policy developers, breaking down the silos of information currently existing between various model users. The aim was to explore the 'art of the possible' in terms of integrating models and visualising data, using values that are plausible enough to illustrate the functionality i.e. BEIS did not set out to produce a rigorously grounded and actionable model for immediate use.

Two subtasks focused on different aspects of the problem: a visual demonstrator and a technical demonstrator. These were envisaged to be separate investigations with the aim that the results could inform future work to create a single cohesive prototype. Since the result of development was intended to be a proof-of-concept only, the accuracy of the demonstrators' outputs was not a key consideration. Accordingly, for both demonstrators, there was a need to communicate to users that the outputs are for demonstration purposes only and do not necessarily reflect the 'real world'.

12 https://www.gov.uk/guidance/carbon-budgets

13 https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf

4.1. Visual Demonstrator

The visual demonstrator aimed to produce a system to provide a user with a fully immersive view of the impact of policy decisions on the UK, at national, regional and street view levels, over time.

The visual demonstrator requirements were:

- The design of the interface should be user-centric and intuitive, enabling a user to navigate through the demonstrator with ease. Colour schemes used in the demonstrator should be both accessible to all user types and consistent between differing spatial granularities.
- Users should be able to investigate the impact of differing policy measures on the UK, at national, regional and street view levels, where it is assumed that each policy incentivises the deployment of a different combination of low carbon technology measures. Displayed metrics should reflect data drawn from the BEIS National Buildings Model.[14]
- The low carbon technologies that should be represented are rooftop solar photovoltaic panels, heat pumps, electric vehicle chargers and external wall insulation. These should be reflected in averaged metrics shown on 2D maps in the national and regional views, and in 3D on homes in the street view, with the user being able to step forwards and backwards in time to see changes in the uptake of low carbon technologies.

4.2. Technical Demonstrator

The technical demonstrator investigation aimed to use more real-world datasets and integrate existing models to generate insights into ways in which differing policy measures will affect UK households. The outputs should be able to demonstrate the power in integrating different models, in terms of producing results on different spatial and temporal levels, and should illustrate how the standardisation of data used within these models is a key enabler to unlocking holistic insights.

The technical demonstrator requirements are outlined below:

- Users should be able to select between different policy scenarios that will have different technology uptakes associated with them.
- The technical demonstrator should be accompanied by a visual interface, which should be able to give analytical outputs in the form of graphs or tables. This interface should allow the user to travel forwards and backwards in time, to see the effect of policies, and to dive into different geospatial levels to investigate CO_2-equivalent emissions.
- The technical demonstrator should cover scenarios that:
  - Result in different uptakes of electrical home heating, heat networks and hydrogen home heating.
  - Show the effects of different generation mixes for electricity.
  - Show the effects of different uptakes of heating flexibility.

14 https://data.gov.uk/dataset/957eadbe-43b6-4d8d-b931-8594cb346ecd/national-household-model

5. Chosen Use Case for the Energy System Digital Twin

5.1. Defining the Use Case

Around 40% of UK carbon emissions originate in the home.[15] Therefore, decarbonising homes is essential for delivering a Net Zero economy by 2050. For the government to successfully influence homeowners and landlords to deliver this decarbonisation, an understanding of the impact of different decisions regarding regulatory options and policy levers is required. This is the use case chosen to be addressed by the digital twin demonstrators developed through this project.

This use case is intended to build on current BEIS modelling capabilities to better understand the impact of national domestic decarbonisation policies at a more granular level. Key elements of this use case are to demonstrate how the baseline position of UK homes could be better understood and how the impact of policies could be analysed in a more refined way with the output made more tangible to stakeholders at all levels.

5.2. Challenges Associated with the Use Case

Domestic decarbonisation is a key area within the energy sector, with numerous unresolved challenges. Some of these are relevant to the development of digital twin systems oriented towards this use case – from the need to obtain and manage fine-grained data while protecting individuals' privacy, to the complexities of representing realistic household behaviour. This section details some of the challenges and how they have been addressed within this project.

5.2.1. High Granularity Energy Data and Privacy

A large amount of time on this project was spent identifying the appropriate data required to answer the question of how we more effectively decarbonise homes.

To construct digital twins representing local areas, energy data that is highly granular in space and time is going to be needed to accurately reflect changes at a household level. The ideal source of this data is half-hourly data from smart meters in domestic properties. However, it is highly likely that this data would fall under the personal information classification, and thus data privacy is one of the biggest challenges associated with the domestic decarbonisation use case. Understanding the ethical and social implications of data gathering is key to ensuring that data is collected, handled and stored to fulfil the best interests of both the intended users and consumers. To manage the potential privacy impact and protect consumers, appropriate anonymisation techniques are needed.

Anonymisation refers to the removing or altering of any features of data which may be used to directly or indirectly identify an individual. Another method for retaining privacy of individuals is pseudo-anonymisation, which is the practice of replacing identifiable features with a unique identifier across the dataset but removed from real-world identity. However, care must be taken as even pseudo-anonymised data can still be classed as Personally Identifiable under GDPR.[16]

15 https://www.theccc.org.uk/wp-content/uploads/2016/07/5CB-Infographic-FINAL-.pdf

16 https://es.catapult.org.uk/report/smart-meter-insight-paper/

Some examples of anonymisation techniques are outlined below and are further discussed in Ofgem's Energy Data Best Practice Guidance.[17]

Redaction – The activity of removing or overwriting selected features

Noise – The activity of combining the original dataset with random data, in order to conceal features of the data

Delay – This involves deferring from publishing any results from the data for a set period of time

Differential privacy – The method of applying an algorithm or model which is able to obscure the original data, but limit re-identification

Data masking – The activity of hiding the original data within modified content

Aggregation – The method of combining data to reduce granularity of resolution, time, space or individual

The smart metering framework defines the levels of access to energy data that different organisations can have, and the conditions that they must fulfil in order to receive that access, from energy suppliers to energy network operators. Organisations that do not have direct access to the smart metering system may also receive anonymised data from those that do have access if circumstances permit.

To work around the challenges associated with access to these dynamic data streams, this project has focused on static data sources, particularly those gathered from previously run modelling scenarios.

A full data landscape is included in Appendix 1, and the main types of static data used are outlined below.

- Geographic boundaries of Manchester (at the Lower Layer Super Output Area (LSOA)[18] level)
- Housing archetypes
- Building dimensions (height, roof elevations, orientation)
- Data on building construction
- Data on cladding, solar panels or external fixtures to buildings.

It is recognised that to move towards a full digital twin with two-way data flow between households and models, appropriate privacy-preservation techniques will need to be established, utilised and prioritised throughout the sector.

5.2.2. Modelling Consumer Behaviour Patterns

To fully realise the use case of a digital twin for domestic decarbonisation, consumer behaviour will need to be considered in the models. Modelling simulations of households only tell part of the picture when it comes to how effective decarbonisation will be, as there is no guarantee that consumers will be willing, or able, to change their behaviours to fully realise the benefits of low carbon technology.

Models such as Home Energy Dynamics (HED)[19] can simulate the efficiency and cost-effectiveness of low carbon technologies using several different data sources, including consumer preference surveys. Although these are still static datasets, by ingesting these preferences into a digital twin, the model would give an idea of how households are going to change and decarbonise, as an improvement over generic assumptions of how an 'average' household ought to behave. In this project, generic assumptions have been used regarding the behaviour of consumers in terms of low carbon technologies. Section 7 of this report outlines the next steps needed to realise a 'full' digital twin with dynamic consumer datasets and the technologies that would need deploying to enable this.

---

17 https://www.ofgem.gov.uk/sites/default/files/2021-11/Data_Best_Practice_Guidance_v1.pdf

18 LSOAs are geographical subdivisions defined by the Office for National Statistics which are used for many national statistics. More information: https://www.ons.gov.uk/methodology/geography/ukgeographies/censusgeography

19 https://es.catapult.org.uk/tools-and-labs/our-place-based-net-zero-toolkit/home-energy-dynamics/

5.2.3. Data Security

Digital twins make use of simulations in an environment that is more directly linked to the real world than is the case for traditional models. As a result, their methods of data ingestion from differing technologies and resources can make them susceptible to cyber risk and data hacking. This is particularly the case for use cases around domestic housing, since as stated above this area relies on the use of personal data.[20] A systematic cyber security strategy is needed to help eliminate any weaknesses in security that could occur at the interface between the real and virtual worlds.

There are two security accreditations that should be incorporated when deploying digital twin systems:

ISO/IEC 27001[21]
This is the international standard for information security management, ensuring that organisations are establishing, implementing, maintaining and continually improving an information security management system.

SOC 2[16]
Established by the American Institute of CPAs, SOC 2 defines the criteria for managing customer data based on five trust service principles – security, availability, processing, integrity, confidentiality and privacy.

A full breakdown of the security challenges associated with digital twin implementation is outlined in section 7.4 of this report.

20 https://www.slingshotsimulations.com/technical/how-secure-is-your-digital-twin/

21 https://www.iso.org/isoiec-27001-information-security.html

6. Building the Demonstrators

As discussed within section 4, two proof-of-concept demonstrators were built with the following aims:

- Visual demonstrator: Producing dynamic visualisations of the impact of policy decisions using a visual, interactive and immersive interface
- Technical demonstrator: Meshing together models and outputs to demonstrate the benefits of being able to better analyse policy impacts across different temporal and geospatial scales for the UK.

Both demonstrators were planned and built using agile delivery methods. Demonstrator requirements and functions were prioritised in the form of user stories using MoSCoW (Must, Should, Could, Would) analysis, and dataset requests were categorised into in-scope and out-of-scope, based on viability within the project timeframes.

6.1. Visual Demonstrator

The visual demonstrator was built in a collaboration between ESC, The Alan Turing Institute and CityScape Digital. A key early design decision was to use Unreal Engine,[22] to create the immersive experience that digital twins promise users. Unreal Engine is a computational 3D graphics engine, for which the source code is available for inspection,[23] and which can be used to create complex digital twins and to visualise assets, processes and workflows in real-time. It has a broad user base, with multiple applications in games, film, television, virtual reality, architecture and design, and it was used in this project to produce a visualisation of a selected real street within the area of Greater Manchester, where decarbonisation options applicable to homes could be visualised.

BEIS suggested that it would be appropriate to use data derived from the National Buildings Model (NBM)[14] within this demonstrator and supported accessing model outputs. Since the NBM is intended to represent the national building stock at a fixed point in time, it was necessary to add time dynamics to this dataset. The codebase of the RangL project[24] was developed at The Alan Turing Institute to facilitate the incorporation of dynamics in industrial decision-making problems such as Net Zero planning, in a manner suitable for the application of Reinforcement Learning. The team at QMUL created middleware code which deployed the RangL codebase to incorporate these dynamics in the NBM data.

22 https://www.unrealengine.com/en-US/
23 https://www.unrealengine.com/en-US/ue-on-github
24 https://www.turing.ac.uk/research/research-projects/ai-control-problems

6.1.1. Visualisation Build and Considerations

For this demonstrator, the assumption is that the user is looking to understand the effects of levels of investment in different energy policies, which have different foci in terms of the low carbon technologies they support. Three indicative energy policies were defined, with the names 'Thermal Comfort', 'Mass Electrification' and 'Energy/Home Resilience'. Each policy is assumed to direct associated investment in different proportions towards supporting uptake of four selected low carbon technologies (solar PV, heat pumps, EV charge points and external wall insulation). The split of investment between technologies for each policy are shown in Table 1. The user's choice is then whether to apply low, medium or high investment to each policy, with 'high' and 'medium' effort representing respectively a trebling and doubling of modelled investment in absolute terms relative to 'low', which represents a nominal baseline investment level. Total investment in each technology across all policies is then translated to a profile of uptake of the associated technology within the UK's housing stock over time from the present to 2050. Illustrative regional variations in uptake were created based on distributions observed in sample data, represented as 'Progress towards target'.

Policy → Technology Ratios			
	Thermal Comfort	Mass Electrification	Energy/Home Resilience
Solar PV	0%	30%	0%
EV Charge points	0%	20%	10%
Heat Pumps	80%	50%	0%
External Wall Insulation	20%	0%	90%

Table 1: Assumed proportional splits of financial investment between technologies for each example policy. Columns sum to 100%.

6.1.2. Technical Challenges

The format of the NBM dataset represents the national building stock at a fixed point in time, and so middleware was used to create the ability to 'travel' backwards and forwards in time within the demonstrator. The RangL middleware developed by The Alan Turing Institute is able to create these time dynamics, as part of its existing functionality to transform data into a form suitable for the application of Reinforcement Learning. Another task for the demonstrators was formatting the data in a way to represent policy as a combination of different technology implementation amounts, which has been outlined within Table 1.

Some examples of the transformations within the middleware code are:

- NBM data is based on generic house archetypes. Therefore it cannot be directly linked to a real house or a street. The NBM data was mapped to each house in the chosen street based on its identifiable features such as size, age and type. For the regional view, a random weighting parameter is used to create a realistic average.
- The NBM data does not contain separate parameters for electricity and gas usage, but instead provides a total energy usage parameter. To visualise the impact on electricity and gas usage of the technologies, a method for disaggregating energy use between vectors was needed. For illustrative purposes, it was assumed that overall energy use (on a kWh basis) is 60% electricity and 40% gas in all years and for all policy choices; while substantially different from the present-day split in the UK, this was viewed as more representative of the overall period under consideration due to future electrification trends.
- It is assumed that the total number of buildings in the UK is 25,000,000 and that the rated power of each domestic electric vehicle charging point is 7.2kW.

6.1.3. Demonstrator Outputs

Initial Interface

The initial interface of the visual demonstrator gives insights into how changes will be reflected on a national scale. As discussed above, the policies visualised within the demonstrator are given the illustrative names of 'Thermal Comfort', 'Mass Electrification' and 'Energy/Home Resilience' and hovering the cursor over the information icons for each gives further insight into how choices of investment intensity for each policy can change the investment in each technology as shown in Figure 2.

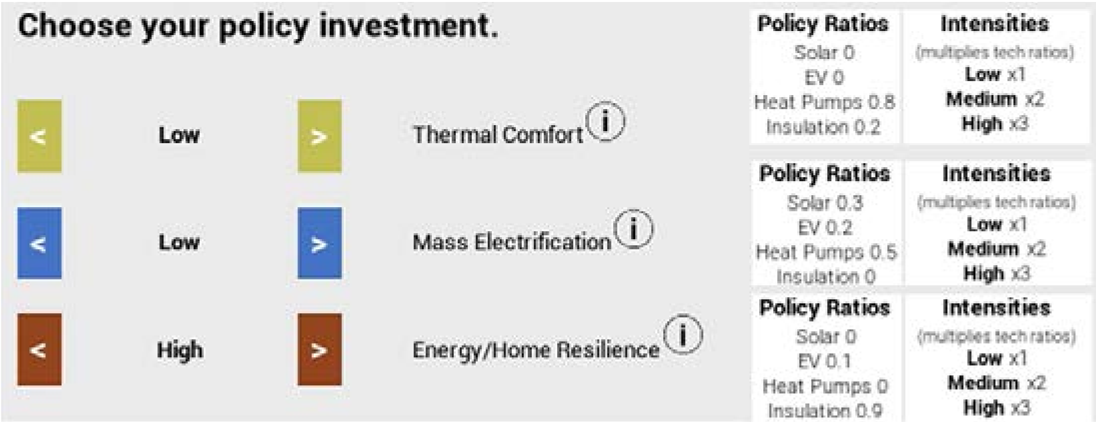

Figure 2: Policy investment intensity and related technologies

Changing the policy investment from low to medium or high levels is reflected both in a colour-coded national map as shown in Figure 3, where the colour indicates the relative level of uptake of a user-selected low carbon technology, and in the CO_2 and total emissions bar charts given at the top of the interface as shown in Figure 4. The user can apply a combination of investments across different policies to investigate the resulting changes, and the slider under the national map enables this change to be seen over time.

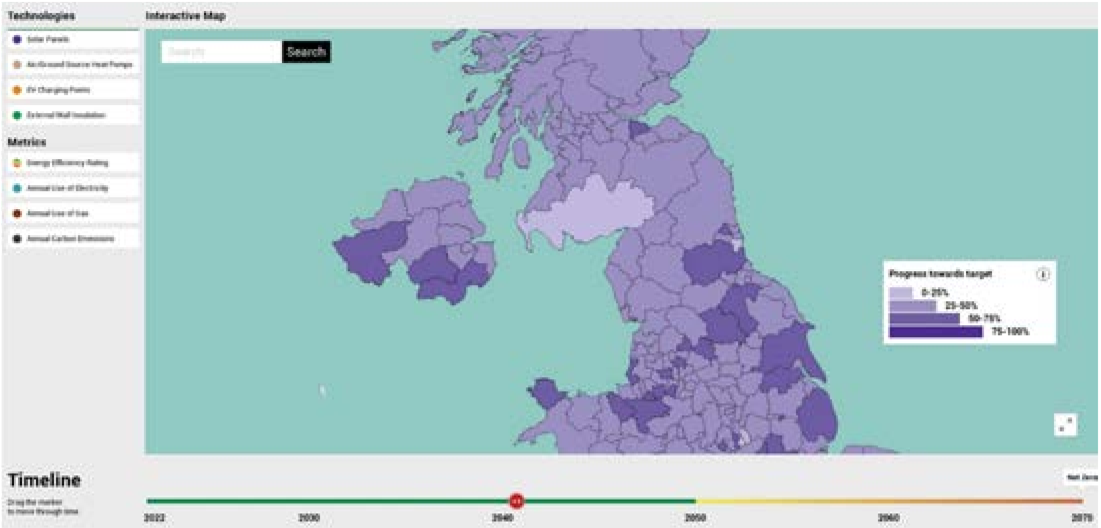

Figure 3: UK view of deployment of solar panels in the year 2041

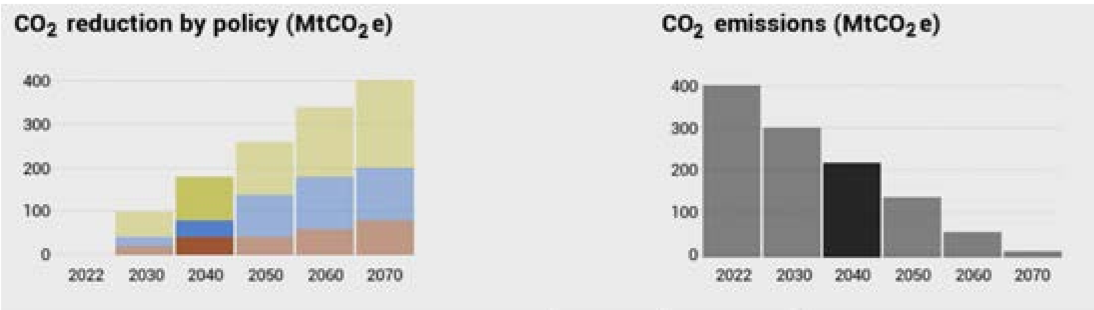

Figure 4: CO_2 reduction and total emissions bar charts

The main analytical output from the demonstrator is an understanding of the level of policy investment intensity required to deliver Net Zero by 2050, and the impact this will have on the look of a typical residential street. The Technologies tab gives an indication of the scale of change in the energy system under consideration by showing how much new technology has been installed by the chosen date, for comparison against the system-level outcomes achieved, as shown in Figure 5.

Figure 5: Technologies tab showing scale of installation of low carbon technologies by the chosen date

Local Area Representation

The Visual Demonstrator also allows policy impacts to be visualised at a more local scale. Greater Manchester was selected as a candidate local area, with individual LSOAs being outlined within the demonstrator. The same policy investment effects are carried through from the national view, giving a more granular view on how technology implementations and resulting metrics will change for a local area. The user can continue to investigate these dynamics both forwards and backwards in time as shown in Figure 6.

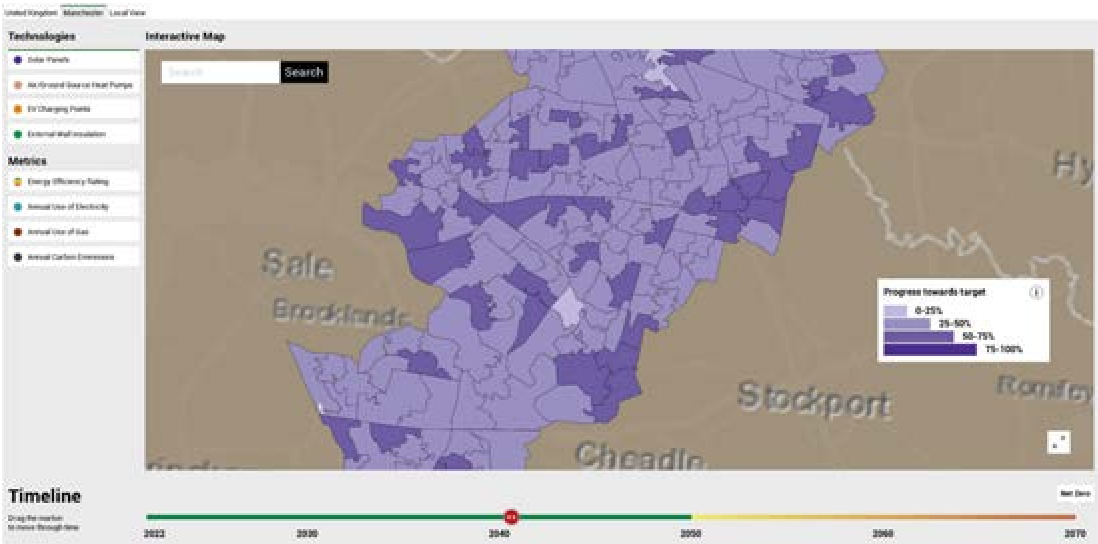

Figure 6: Manchester view of deployment of solar panels in 2041

The street-level view allows the user to observe how policy impacts are likely to be seen on individual UK households. Changes are presented visually as well as quantified by the same metrics as above, but now available at the level of individual buildings. The scene is a stylised representation of a selected real street in Manchester. Going forwards in time from the present, the user can see solar panels and heat pumps being installed on homes, EV chargers being placed in driveways, and the installation of external wall insulation as shown in Figure 7. The user can click on individual homes to investigate energy consumption and efficiency changes with the addition of these technologies.

Figure 7: Street view in the year 2041. Solar panels are highlighted in purple, as the user has selected those in the sidebar. Other low carbon technologies are also shown: external wall insulation is indicated by light purple colouring of houses, and an EV charging point is visible as a short post next to the driveway of one house. Heat pumps are also shown in this view, but none are visible in this screenshot.

6.1.4. User Workflow

The user can choose their level of 'investment' in each policy and explore the impact on low carbon technology uptake and energy metrics over time to understand the required investment to reach a certain goal. The national and local map views show the varying impact across different geographical scales based on their household make-up and housing density. The street-level view is a powerful tool to show how our street landscape will change with increasing low carbon technology uptake.

6.1.5. Demonstrator Implementation and Supporting Material

Supporting material for the visual demonstrator can be found on the ESC Digital Twin project page,[25] which provides links to the visual demonstrator, as well as a video walk-through guide. Visual demonstrator access requires a licence, with five having been made available for demonstration purposes. For access to the actual demonstrator, please contact ESC.

6.2. Technical Demonstrator

The technical demonstrator processes large amounts of data to allow characteristics of a local energy system to be viewed under multiple scenarios. The data provided to the visualisation tool is aggregated at different spatial scales, with a temporal component to display changes occurring over time for a given scenario. This was done by bringing together data from three models developed by ESC: Local Energy Asset Representation (LEAR),[26] EnergyPath Networks (EPN)[27] and EnergyPath Operations (EPO).[28]

LEAR integrates currently available datasets, including for example data from Energy Performance Certificates (EPCs), to help planners and innovators to strategically deploy low carbon technologies. It uses data analytics and machine learning to explore a wide range of data types, such as energy demand, social factors such as fuel poverty, and building type characteristics. The technical demonstrator makes use of LEAR outputs to provide a representation of the current state of a selected local area.

EPN aims to support investigation of local energy decarbonisation pathways, initially focused on decarbonising the delivery of heat in a local area as well as informing long-term policy decisions on the impact of decarbonisation and network choices on the local community. EPN simulates future demand profiles for building archetypes and uses the local characteristics of an area to relate these to the overall energy consumption in that area. It selects technologies to achieve the cost-optimal path to reach Net Zero by a given target date. This optimisation is completed at an archetype level rather than an individual home level to make it computationally tractable. Therefore, the outcomes do not consider the specific circumstances of individual buildings. However, for the purposes of this demonstrator it was decided to attribute the chosen technologies back to individual buildings based on their associated archetypes.

EPO simulates the ways that physical energy assets (consumers, generators and networks), market structures, business models and communications systems interact over operational timescales leading to system-level outcomes. In this demonstrator, outputs from EPO are used to estimate the impact of electrical heating flexibility and different generation mixes on energy usage profiles, energy costs and greenhouse gas emissions.

25 https://es.catapult.org.uk/project/energy-system-digital-twin-demonstrator-project/
26 https://es.catapult.org.uk/tools-and-labs/our-place-based-net-zero-toolkit/local-energy-asset-representation/
27 https://es.catapult.org.uk/tools-and-labs/our-place-based-net-zero-toolkit/local-area-energy-planning/
28 https://es.catapult.org.uk/tools-and-labs/our-place-based-net-zero-toolkit/dynamic-energy-system-simulation/

A more detailed description of the EPN and EPO models is included in a separate document.[29]

Figure 8 below shows the concept reference design for the approach used for integrating these models when implementing the demonstrator. This has been updated from the use case reference design proposed in Phase Two of the project, shown in Figure 16 in Appendix 2, due to the lessons learned from the implementation.

The main updates are as follows:

- The user now directly interacts with the policy selection, although for this demonstrator these are still scenarios pre-selected by an analyst.
- The information flows between the Data Interface, Pathway Modeller, Performance Evaluator and Simulation-Visualisation Interface are different, including a new direct flow from the Data Interface to the Simulation-Visualisation Interface.
- The performance evaluator is based on both EPN and EPO, rather than EPO alone.
- The use of directly consumed data to refine the assumptions has not been included in the scope of the technical demonstrator

29 ESC (2022) 'Model Functional Specification: Summaries of EPN and EPO' (deliverable from Energy System Digital Twin Demonstrator project)

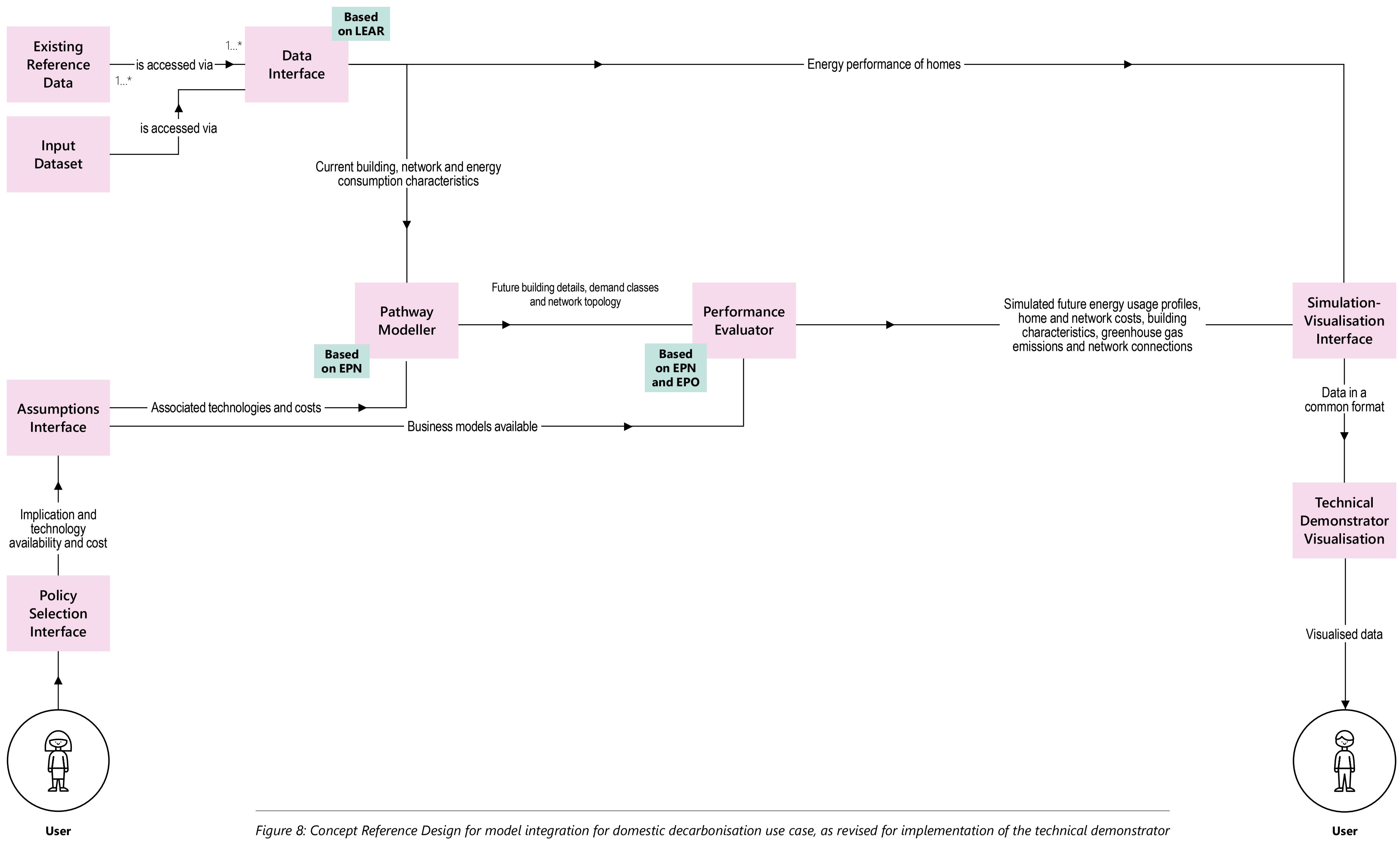

Figure 8: Concept Reference Design for model integration for domestic decarbonisation use case, as revised for implementation of the technical demonstrator

6.2.1. Model Considerations

A key element of the technical demonstrator is data on the present-day condition of domestic properties and the potential transition pathway to Net Zero, as outputs from ESC's LEAR and EPN tools respectively. To enable development of the demonstrator within the time and budget constraints of this project, pre-existing LEAR and EPN outputs were used. Results for the area of Manchester City Council provided the most applicable previous scenarios to include within this demonstrator.

EPN results for Manchester City Council are based on four region-specific scenarios that lead to Net Zero by 2038, the target set by Greater Manchester Combined Authority in their five-year environment plan.[30]

The four scenarios have different assumptions for the cost and availability of technologies:

- **Manchester 2038, Leading the Way –** This scenario focuses on meeting the carbon budget and carbon neutrality target by making use of measures within Manchester's local control where at all possible.
- **Manchester 2038, HyNet 2030 –** A scenario aligned with the local HyNet North West project's Phase 3[31] and the repurposing of the gas grid to hydrogen.
- **Manchester 2038, High Electrification –** A scenario that assumes only electric-based options for buildings' heating and hot water demand.
- **Manchester 2038, High Hydrogen –** A scenario that assumes only hydrogen-based options for buildings' heating and hot water demand.

Different scenarios result in different levels of electrified and hydrogen heating being deployed. More details on these scenarios can be found in Appendix 3, including a comparison against heating decarbonisation scenarios developed by the Department for Business, Energy & Industrial Strategy (BEIS).

An additional aim of the technical demonstrator is to demonstrate the integration of multiple models, with the resulting ability to expand the range of outputs that can be produced. In this case, ESC's EPO model was selected as able to augment the results from LEAR and EPN with additional information. However, EPO results were not available for the Manchester City Council area for the future years and scenarios under consideration. Due to the time available in the project and to reduce risk associated with integrating the full EPO model with EPN and LEAR, a method was developed to estimate the results that would have been obtained from EPO for the area, scenarios and timescales under consideration, using results from EPO in previous projects. This approach has been termed the EPO emulator.

The EPO emulator takes two further inputs, in addition to the LEAR/EPN results already discussed: the national electricity generation mix (aligned to the National Grid ESO Future Energy Scenarios 2021[32]), and the level of uptake of technologies that allow households to flex their heating demand.[33] The output of the emulator is an adjusted time-profile of electricity use that considers the effects of demand flexibility, the greenhouse gas emissions of the home, and home annual energy costs.

The emulator uses results from previous EPO studies which explored the potential result of the Future Energy Scenarios on the wholesale price and greenhouse gas intensity of electricity. These are translated into the annual cost and greenhouse gas emissions associated with a household's energy usage. The effects occur both due to the direct electricity consumption of the house, and indirectly via a house's consumption of hydrogen and heat from heat networks, both of which are assumed to be produced using grid electricity.

30 https://www.greatermanchester-ca.gov.uk/media/1986/5-year-plan-branded_3.pdf

31 https://hynet.co.uk/

32 https://www.nationalgrideso.com/future-energy/future-energy-scenarios

33 Heating flexibility allows households with electrical heating to pre-heat their homes in the afternoon or overnight and thus reduce their peak-time electricity usage, assumed to result in a financial saving.

The emulator changes the energy profile of homes that have been allocated electrical heating depending on the level of uptake of heating flexibility. This results in an overall increase in annual energy use, as the type of heating flexibility modelled pre-heated the home rather than turning off the heating at peak times. This ensured the temperature requested by the occupier was maintained but does result in the home being warmer for longer. The energy use at peak times is reduced, thus the home's annual electricity costs do not increase as the home is taking advantage of cheaper electricity at off-peak times, which actually results in a saving. The resulting greenhouse gas emissions depend on the FES but can reduce, as the greenhouse gas intensities are lower off peak in most cases. In all cases, the effect on greenhouse gas emissions is minimal as you approach 2038 and would be eliminated towards 2050, as the electricity grid is likely to have been completely de-carbonised due to national targets.

Full details of how the emulator works are available in the EPO Emulator Technical Specification.[34] The EPO emulator is a model, but significantly simpler than EPO itself.

Based on learnings from the National Digital Twin Programme's Climate Resilience Demonstrator (CReDo) project,[35] it was recognised that obtaining appropriate data licensing for use of geographic-specific data within this demonstrator could be challenging in future and should be addressed as part of planning and development.

6.2.2. Integrating the Models

LEAR has a long-standing interface with EPN, with LEAR providing information on the current make-up of the housing stock into EPN as the starting point for a transition pathway. Outputs from LEAR and EPN are stored in several Structured Query Language (SQL) databases. For the technical demonstrator, a dedicated series of SQL queries and Python functions manipulate and export the data as Comma Separated Values (CSV) files in the format required for visualisation. Much of the processing is simple conversion or aggregation of the data available in the LEAR and EPN databases. The EPO emulator's more complex manipulations required to produce the outputs described above are performed in both SQL queries and Python code, again producing outputs in CSV form.

The resulting CSV files are visualised using Tableau,[36] a low-code analytics and data visualisation software tool. Tableau suits this kind of project because the development of the demonstrator has involved a significant degree of experimentation with different types of visualisation in order to convey information that supports the objective of the tool. Low-code tools like Tableau enable different visualisations to be rapidly prototyped and tested with users before agreement is reached on the final design. The information is location-centric due to the interest in seeing patterns at the home and geographical area levels, and Tableau has strong geospatial rendering tools to make this easy. Deploying the visualisation tool to users is also simplified by Tableau's fully managed online service such that visualisations can easily be published to a cloud environment so that anyone with an authorised Tableau online licence can access it via a web browser.

Blending and joining multiple data sources is simple in Tableau; however, difficulties did begin to emerge when the size and number of CSV files increased with multiple, layered joins required to enable the user to drill down through the different levels of information. The combined dataset comprising the joined CSV tables exceeded 10 million rows, and the large number of dimensions and measures within the data contributed to a very large dataset. Nevertheless, the tool has performed to an acceptable level with only the LSOA view having a noticeable but not uncomfortable latency in loading.

34 ESC (2022) 'EPO Emulator Technical Specification' (deliverable from Energy System Digital Twin Demonstrator project)

35 https://digitaltwinhub.co.uk/credo/

36 https://www.tableau.com/

6.2.3. Technical Challenges

The key technical challenges encountered related to the data structure of the visualisation interface. Even though the dataset only covered part of Manchester, there were difficulties displaying the data fast enough to be acceptable for an interactive tool. In some cases, the mitigations involved reconfiguring the data: for example, originally the data was provided at the level of individual homes, but to improve responsiveness the data was restructured to provide precalculated aggregations of the per-home data at LSOA and cluster level. This highlights the importance of the simulation-visualisation interface, a function unit that sits between models and visualisation, especially given that the reference designs for the technical demonstrator developed in Phase Two of this project proposed that it would receive data from multiple source models for use by multiple visualisers.

The experiences with responsiveness and processing issues, even within a proof-of-concept with relatively small amounts of data and where many of the values have been precalculated, highlight that it may only be very simple models (or simple parts of models) that could be run on the fly in a digital twin. Thus, having a clear framework for how and when the models will be run will be necessary in any future work. The EPO emulator is one approach for how models could be simplified, although in the current architecture this does not run during usage of the visualisation.

Integration of existing models into a form that meets the use case also proved challenging. For example, EPN is configured to output cost-optimal decarbonisation pathways, while the user may wish to explore other future scenarios that, for example, may be non-cost-optimal but that have benefits for job creation. It should be noted that choices of the EPO emulator inputs may mean that an EPN scenario is no longer cost-optimal within the current work. In future work the models could be reconfigured to allow such exploration, while removing the requirement to optimise the pathway is likely to reduce model complexity. More generally, it highlights the need to match the model to the use case, but undoubtably models will also need some adaptation.

There are also challenges in integration of the multiple models. Within the project the risks were too great to interface EPN and EPO directly, hence the creation of the EPO emulator. Even so, there are still some inconsistencies within the demonstration. For example, the reduction in peak energy use because of heating flexibility modelling in EPO does not result in a change in electricity network costs which are modelled in EPN. This shows there are many, sometimes unexpected, complications when bringing different models with slightly different modelling philosophies together.

6.2.4. Demonstrator Outputs

The technical demonstrator allows the user to select one of the scenarios described in Section 6.2.1., the year they wish to view, and the 'measure' to be shown (the specific model output parameter). The years available are 2021 (present-day), 2025, 2030, 2035 and 2038. Figure 9 shows an example selection of scenarios, year and measure. A description of the measure selected is also shown in Figure 10.

Figure 9: Technical demonstrator control panel, which allows sections of the scenario, year and measure to be displayed

Figure 10: Measure details for the measure currently being displayed, in this case Annual Home Energy Costs

There are three types of measures available within the demonstrator, in terms of the way in which they are derived:

- **Current data –** data about the present-day state of the homes directly translated from current sources, and not available for future years.
- **Home attributes –** data about the physical structure of a home, derived from current sources for the present day and from modelling for future years.
- **Derived values –** values that are constructed by models for all years but are informed by typical values for the present day. This category includes energy usage, greenhouse gas emissions and several estimated costs (including capital and operating costs, both for energy networks and for domestic energy-related appliances and building upgrades).

There are many types of current data that could be provided. Within the demonstrator we have provided:

- current EPC rating
- potential EPC rating
- current EPC efficiency
- potential EPC efficiency.

These are not available for future years, as the models do not attempt to predict how these will change. Homes with no EPC ratings are indicated by a grey colour in the demonstrator.

The home attributes we have chosen to include in the demonstrator are the U-values[37] of the external walls and roof and whether a home is connected to a natural gas network, a hydrogen network or a heat network. The present-day state of the home is based on currently available data. Future states are based on modelling, where homes may have been fitted with installation or the connections to energy networks may have changed.

A selected measure can be viewed at three spatial scales, as illustrated in Figure 11 and Figure 12:

- 'Cluster' level, showing the whole Manchester City Council area divided into 'clusters' (regions bespoke to EPN based on the electrical substations within an area)
- LSOA level, showing a selected cluster divided into LSOAs
- Home level, showing all individual domestic properties within a selected LSOA.

In the demonstrator it is only possible to drill down to lower-level data for cluster 4, as this made its production more tractable. A national view is not available for the technical demonstrator, as data was not available.

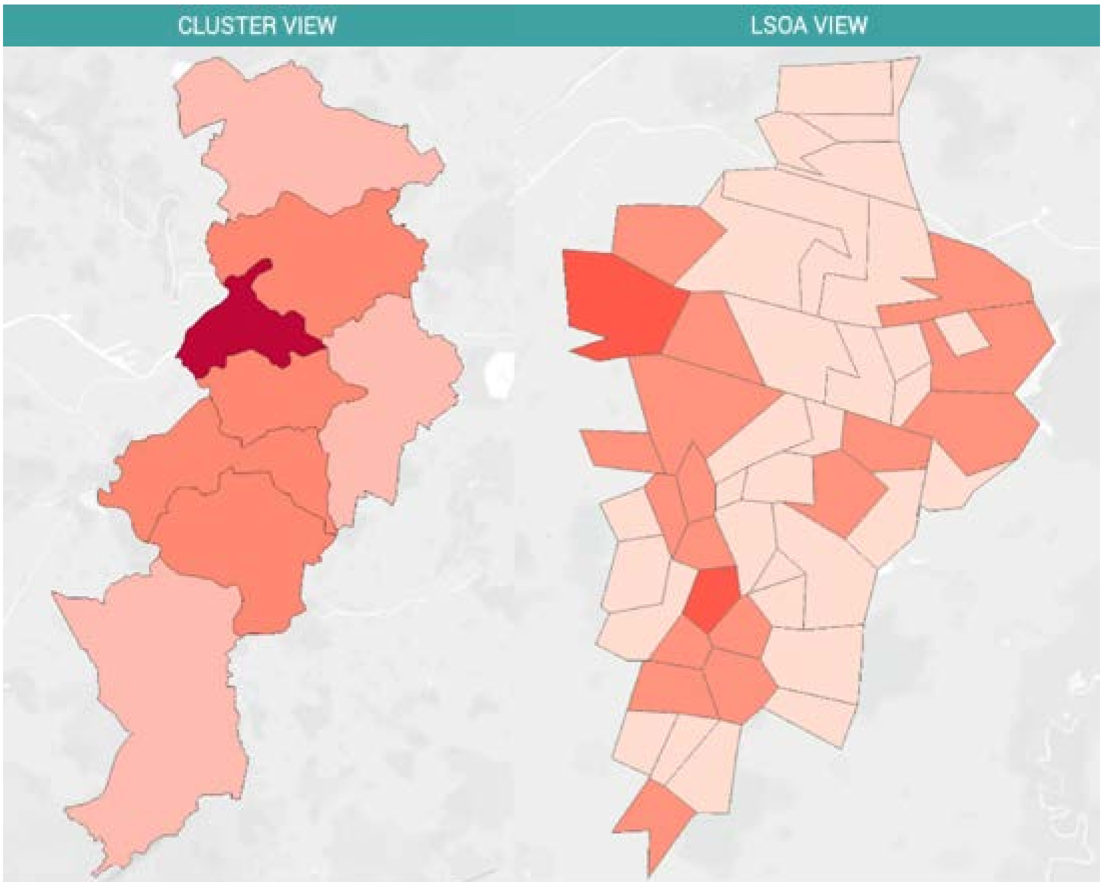

Figure 11: Examples of viewing Annual Home Energy Cost at cluster and LSOA level.
N.B. Values are for demonstration purposes only.

37 U-value provides details of how well insulated a wall or roof is

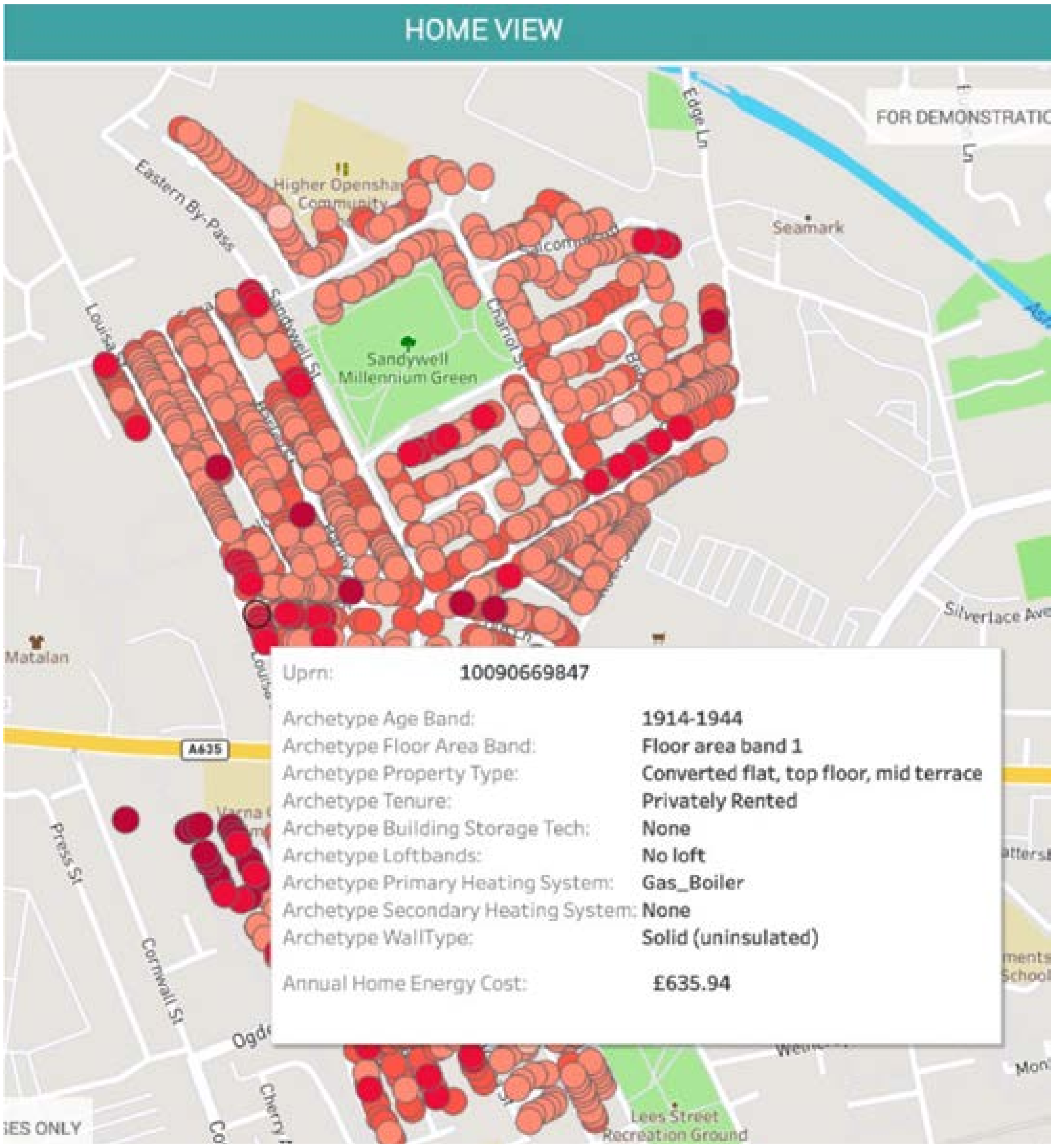

Figure 12: Examples of viewing Annual Home Energy Cost at home level. An example of the additional information provided when hovering over a home is also shown. N.B. Values are for demonstration purposes only.

Daily energy usage values are provided for electricity, oil, natural gas, hydrogen and heat from heat networks. These can also be viewed as a 24-hour profile for a home, LSOA or cluster, as shown in Figure 13.

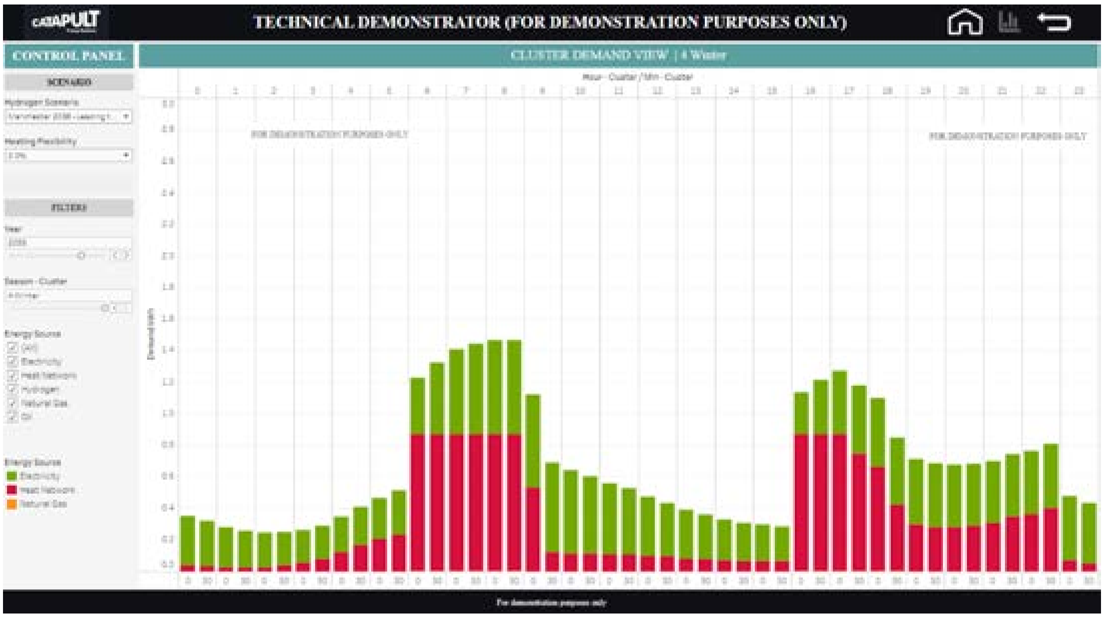

Figure 13: Example energy usage profile over the course of one winter day for cluster 2, across electricity, heat network and natural gas. N.B. Values are for demonstration purposes only.

GHG emissions are calculated on an annual basis, which is based on energy usage and the electricity generation mix from the National Grid FES.

In terms of estimated costs, costs associated with individual homes are broken down into the capital costs associated with upgrades, energy use costs and operational costs other than energy. Costs at the network level are provided for electricity, natural gas/hydrogen and heat networks. (It is assumed that the gas network will be repurposed to carry hydrogen, so a single cost is provided covering both energy vectors.) Capital, operational, and total[38] costs are provided for each energy network type.

Network costs are only provided at cluster level as the costs are not directly attributable to individual homes. Other measures, which can be evaluated at the per-home level of granularity, are aggregated together to provide the cluster and LSOA views. For most measures this is done by taking a mean across all homes within the appropriate larger geographical area to ensure values are comparable between views. For energy network connection measures, the percentage of homes connected to the relevant network in each larger area is given. For categorical values, the most frequently occurring home-level value (i.e. the mode) is presented.

38 TOTEX is used as one method to combine capital and operational costs into a single value. This method has been selected as one example, since it has been used in the RIIO process for determining energy network operators' regulated revenue: https://www.ofgem.gov.uk/sites/default/files/docs/2017/01/guide_to_riioed1.pdf

6.2.5. Analytical Outputs

The benefit of a future digital twin addressing this use case is to enable a much broader range of people to understand and investigate model outputs, thus broadening the range of analytical insight that can be drawn from the underlying models.

The outputs available in the proof-of-concept demonstrator allow the investigation of the implications of implementing policies that affect electric vs hydrogen heating uptake, heating flexibility and generation mix. One way this may be used is to investigate implications of home costs at a local level. Figure 14 and Figure 15 show an example of this: it compares the per-home capital cost and annual energy cost for the Manchester 2038 – Leading the Way and Manchester 2038 – HyNet2030 scenarios. This comparison highlights the additional capital costs of greater electrification of heat in the first scenario, and the higher annual energy costs due to greater hydrogen usage in the second scenario. Moreover, it can indicate geographical areas where, for example, both capital cost and ongoing energy cost are high in the hydrogen-heavy scenario, potentially highlighting the need for additional support in such locations.

The use of a configurable low-code analytics tool for the technical demonstrator (Tableau in the implemented version) also demonstrates that interactive visualisations can be produced relatively rapidly without requiring extensive software engineering skills. The power of such an approach is potentially to unlock additional insights through producing further visualisations during an analysis activity, in addition to the pre-existing visualisations. For example, analysts could produce alternative interactive visualisations bespoke to a particular policy question.

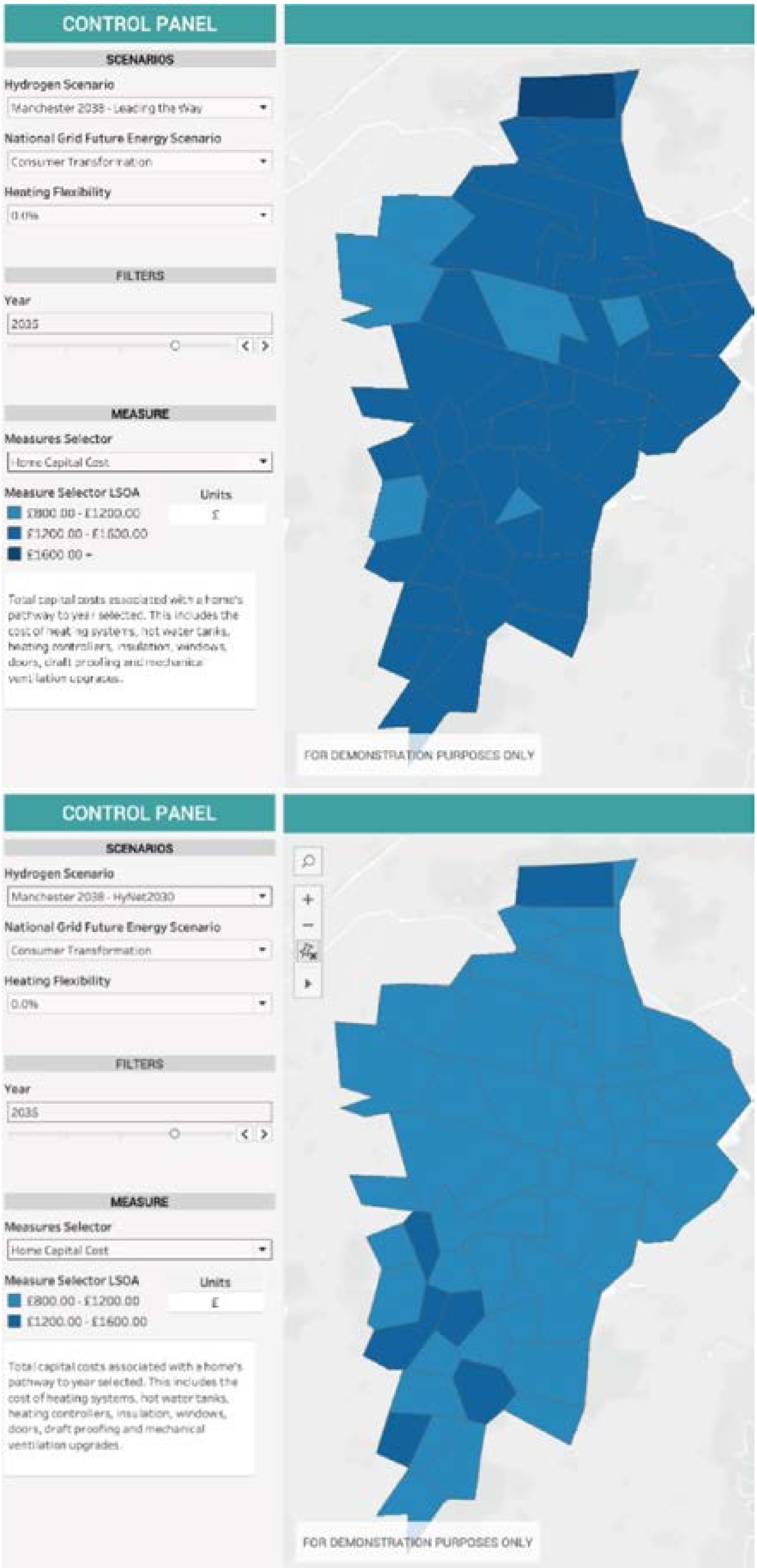

Figure 14: Example comparing Home Capital Cost for Manchester 2038 - Leading the Way (top) and Manchester 2038 - HyNet2030 (bottom) at LSOA level. N.B. Values are for demonstration purposes only.

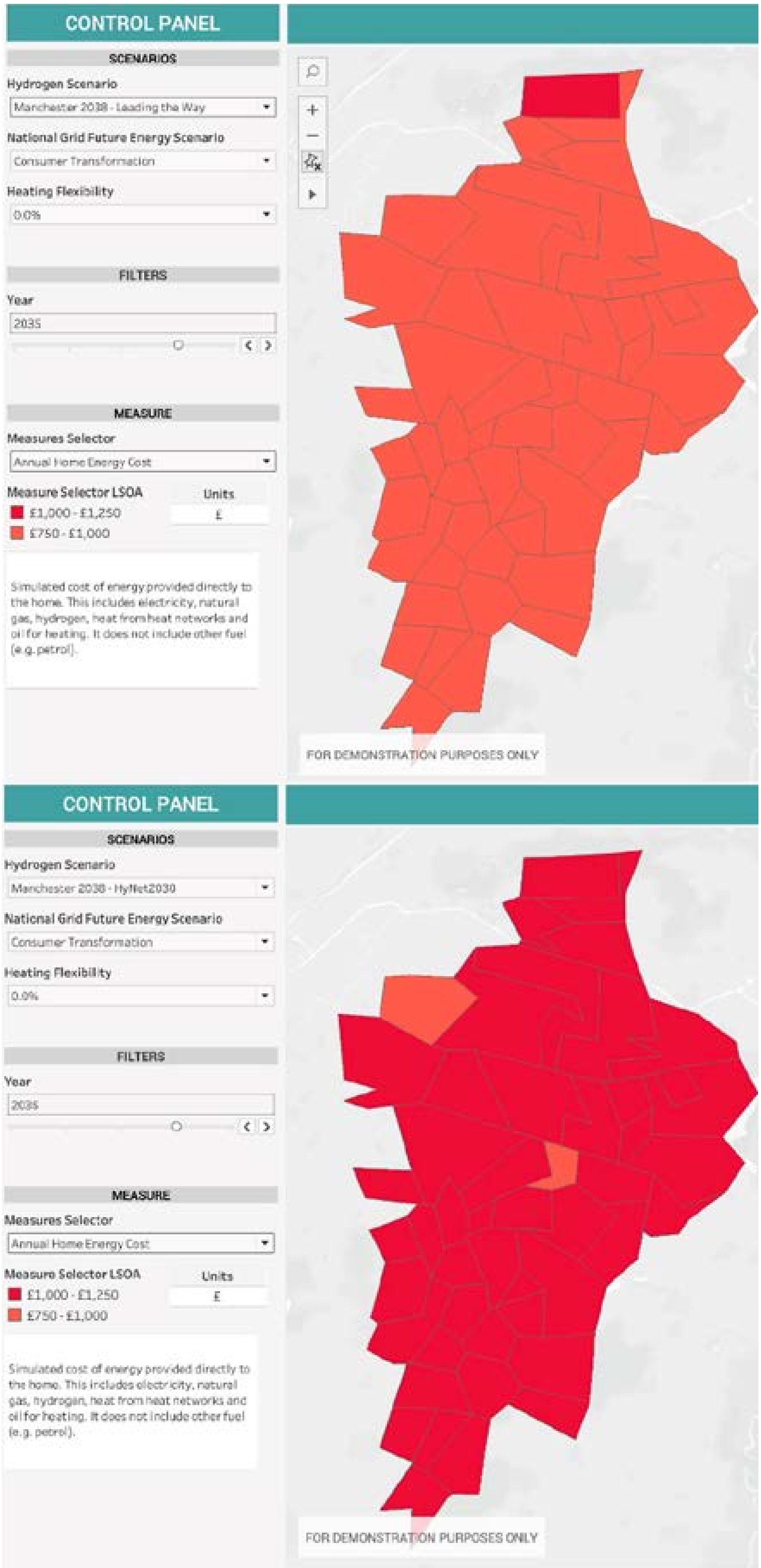

Figure 15: Example comparing Annual Home Energy Costs for Manchester 2038 - Leading the Way (top) and Manchester 2038 - HyNet2030 (bottom) at LSOA level. N.B. Values are for demonstration purposes only.

6.2.6. Demonstrator Implementation and Supporting Material

Supporting material for the technical demonstrator can be found on the ESC Digital Twin project page,[25] which provides links to the technical demonstrator, as well as a video walk-through guide. Technical demonstrator access requires a licence, with five having been made available for demonstration purposes. For access to the actual demonstrator, please contact ESC.

6.3. Alignment Between the Two Demonstrators

Both demonstrators aim to support the same use case, with each showing different maturity for different elements of a digital twin. Both show the ability to view measures at different geographical levels. The visual demonstrator is more mature in terms of the visual impact and the ability to provide a national view (albeit partly filled with non-model data at this stage). The technical demonstrator can however provide more insight into the daily profile of energy use, which is important in investigating the impact of some policies, such as those that might enable heating flexibility.

The technical demonstrator also provides a larger set of measures and policy scenarios produced by a combination of models. It can also display more present-day data (e.g. EPCs, where available), and uses it as a starting point for future projections, unlike the visual demonstrator, whose outputs are grounded in the 2011 census.

Both demonstrators are restricted in that they rely on predefined scenarios for which data is available to be explored through the respective user interfaces, limiting the user's ability to investigate potential policy outcomes more freely. This was viewed as a pragmatic step to enable demonstrator development but is clearly a substantial limitation for the use of this form of tool in practice. The visual demonstrator is more aligned with the ultimate vision of this use case, allowing the user to explore a range of options by choosing investment levels across three policies, leading to outcomes that may or may not reach Net Zero. Ultimately, it is likely to be desirable for a digital twin system's user interface to allow not only for inspection of predefined scenarios, but also for free exploration and automated optimisation of control inputs to identify optimal routes towards a goal, whether Net Zero or otherwise (e.g. maximising green jobs).

6.4. Alignment with BEIS' Requirements

BEIS had two key requirements for the use of digital twins to improve their modelling capabilities, as outlined in section 4.1:

- Work across different levels of spatial and temporal granularity to produce one whole-system output for visualising the impacts of policy changes within the UK
- Demonstrate a way in which these outputs can be communicated to non-technical policy makers in an intuitive way, to empower them with the knowledge needed to make effective policy decisions.

Although the initial challenge was framed as building one integrated demonstrator, the separation of the problem into the creation of complementary visual and technical demonstrators has enabled us to show the potential for improvement in both key requirements:

- The technical demonstrator seeks to demonstrate the power in aligning differing model types, to give both spatial and temporal granularity, and shows the necessity for standardising inputs and outputs within these models.
- One of the largest barriers to interpreting analytics on policy change is presenting the analysis results in an intuitive form. The visual demonstrator enables this immersive exploration of policy effects on a national, local and street level, allowing policy makers to better explore how policy changes may impact individual areas within the UK.

In future work, there is the potential to bring these two outputs together into a single digital twin system, allowing users with all levels of technical expertise to access appropriate interfaces and interact with modelling results in a way that best suits their individual needs.

7. Digital Twin Next Steps and Considerations

Digitalisation is at the forefront of the energy sector's ongoing mission to reach Net Zero. Using common interrelated source datasets across models with more granular spatial and temporal characteristics has the potential to support many of the aspects of a Net Zero energy ecosystem, including:

- Modelling, simulation and what-if scenarios for the roll-out of low carbon technology
- Better understanding of the relationship between national, regional and local models
- Whole-system management – e.g. to accommodate intermittency of generation, dynamic flexibility and consumer behaviours
- Real-time status monitoring, fault detection, service restoration and root-cause analysis.

The analytical framework for calculating carbon budgets uses a suite of related models to assess the feasibility and cost of decarbonisation options. The models have developed over time and have helped provide a rational evidence base; however, the models have some limitations:

- Stand alone with limited interoperability and written in a wide variety of languages
- Primarily nationally focused with limited levels of spatial and temporal granularity
- Offer limited visualisation capabilities
- Only usable by expert modellers.

The long-term vision is that future modelling tools using digital twin techniques could:

- Be highly interoperable, in terms of inputs, assumptions and outputs
- Be capable of being validated and verified with real-time data
- Model in multiple modes: manually specified 'what if', optimisation and/or 'satisficing' modes
- Represent energy system operation at fine spatial and temporal granularity to understand how:
  - the energy system meets service demands at a variety of emissions levels
  - the system could evolve to a zero carbon configuration under a range of external drivers
  - multiple energy vectors and energy network types, including heat networks, contribute to the overall system
  - variation in weather patterns could impact system outcomes
- Have an accessible user interface, for ease of experimentation and to suit a range of expertise levels.

This would bring the models and the real world closer together to:

- Understand and close the gap between expected behaviours and real-world behaviours
- Enable more agile approaches for rapidly re-evaluating long-term modelling and planning
- Enable models and simulations to learn, evolve and adapt to complex, dynamic interactions.

This proof-of-concept project has highlighted some of the potential use cases and the 'art of the possible' in terms of how and where digital twin techniques could be utilised in the energy system modelling arena. The focus was to identify the barriers and limitations that currently hold back the creation of such solutions (e.g. availability of data and interoperability standards), and how the barriers can be mitigated using lessons drawn from other application areas for digital twins.

The insights from this project provide a solid foundation for further research and evolution to focus on some of the specific challenges and opportunities it has highlighted. This is a complex undertaking and requires a collaborative approach to understand whole-system needs and make best use of collective expertise, resources and funding from within and outside the energy sector.

The project has built a strong community of stakeholders and advisers, and the next step is to work collaboratively to develop one or more propositions for the next stages of work and the options to move from proof-of-concept demonstrators to early-stage prototypes to address the practical challenges when transitioning from research to production implementations.

7.1. Fitting Into the Ecosystem

This project begins to demonstrate the power of connecting different models within the energy sector. The energy system is fast becoming more complex, and without increased shared learnings, model connection and data sharing, generating whole-system thinking is going to become harder. Digital twins may provide tools to address this complexity. However, 'connected digital twins' are more powerful systems that are better able to help us tackle the complexities and understand the interdependencies of the changing energy system.

Connected digital twins are defined by the Centre for Digital Built Britain as 'digital twins that are connected across organisational and sectoral boundaries'.[39] Key to this is the standardisation of models and the data used within them. The technical demonstrator offers a first look into what outputs can be gathered when models can work alongside each other; however, as a proof-of-concept demonstrator this was done in a relatively manual way to showcase the benefits. Working towards a full prototype, defined interfaces for different modelling types will be needed, with the ability to align models in a more coherent manner regardless of the code base with which they are built.

One enabler for connected digital twins explored within this demonstrator project was the Data & Analytics Facility for National Infrastructure (DAFNI) platform,[40] which allows users to store both datasets and models in order to combine them into complex workflows. Technically, DAFNI can support, run and integrate models written in any programming language; however, further work would be required to incorporate models currently requiring proprietary licensing arrangements, such as MATLAB (used in ESC's EnergyPath Operations model). The project team decided that, due to such practical issues, usage of DAFNI would not be a good fit for the project timescales and so a more project-specific integration of models was undertaken using ESC computational resources. For longer-term future development of this use case, and more broadly connected digital twin activities, shared facilities such as DAFNI will be essential for increased collaboration.

Another area explored in this project was the requirement for more standardised datasets, described further in section 7.2. A common problem is differing data types and standards used within different models, perpetuating the challenges of interfacing models and interchanging datasets. Interoperable data is key, and for any digital twin architecture proposed, usable data is a priority requirement. Work in standardising data is needed to support future digital twin projects, and ontologies such as the Information Management Framework[41] are taking the steps to do this.

The problem remains twofold and although it is well understood that the need for better data is more prevalent than ever, organisations lack the incentives to convert data into the appropriate formats. The 'buzz' currently surrounding the digital twin conversation has begun to spark the first organisations to participate in movements towards increased data sharing and collaboration, and it is hoped that demonstrations of digital twin's abilities to unlock future use case potentials will fully encourage the majority of the energy sector to get involved. The demonstrators produced here take those first steps, but for future work, more effort will be needed to tackle the data challenge head on, rather than manually editing datasets to meet immediate needs.

39 https://www.cdbb.cam.ac.uk/files/gemini_papers_-_what_are_connected_digital_twins.pdf

40 http://dafni.ac.uk/wp-content/uploads/2021/05/DAFNI-as-a-Digital-Twin-Platform-Final-report.pdf

41 https://www.cdbb.cam.ac.uk/what-we-do/national-digital-twin-programme/explaining-information-management-framework-imf

7.2. Standardisation of Data Formats

Not only do digital twins offer accessible and noteworthy visual forms of analytics, but they can also provide high-quality, visually interactive forms of analytics and models. They also open the door to a wider conversation about the benefits of information sharing. Until recently, the energy system has operated in a traditional 'closed door' system, with organisations reaping benefits by doing tasks in silos; however, the move towards decentralised ways of working with increasing market participants makes this traditional system less appropriate for the future.

With an ever-changing energy system, decision-makers are now tasked with joining together data from more sources than ever and from increasing numbers of assets, while faced with rapid developments in low carbon technologies, changing consumer patterns and expanding communities of organisations participating in the sector. Besides digital twins offering a more immersive information viewing environment, their core infrastructure shifts the focus from previously manual methods of meshing together inputs, to a centralised environment for modelling standardised datasets.

Although standardised data, as a key enabler to providing interoperability between digital twin systems, is consistently communicated within the energy sector, the common data framework to facilitate this transition is less well understood. The BIM community began to introduce common data requirements for projects within the construction industry; this experience has the potential to provide learnings that could be transferred to energy and adjacent sectors. One initial example of this learning is the Information Management Framework[41] being developed by the National Digital Twin programme: a collection of open, technical and non-technical standards to enable the sharing of data within the National Digital Twin.

Although robust standards are crucial in the longer term, it should be recognised that much of the data that currently exists within the energy system is not in a standardised format. Demonstrators such as these should be used to encourage data owners to both share their data more openly, and in a standardised form, and begin to evaluate the current level of quality of their data and take steps to improve it. Digital twins should be used as tools to promote the benefits of increased data sharing and model standardisation in order to help build a culture around interoperability.

7.3. Learnings

This project has demonstrated it is possible to build demonstrators by repurposing models and model data to fit this particular use case. This came with challenges. In general, these have been overcome by adapting the models and/or making simplifying assumptions; although these reduce the 'accuracy' of the overall results, this was viewed as an acceptable compromise for the purposes of this project in order to create functional demonstrators to elicit further learnings regarding the role such systems might play. However, in some cases such simplifying assumptions have resulted in unrealistic values for model outputs that are readily apparent to the user. One example is the assumption of a 60%:40% electricity:gas energy use within the visual demonstrator, which is applied to all years, including up to 2050, despite the expectation of full decarbonisation by that year. Ultimately, there will always be compromises between the original modelling principles and the practical requirements placed on a digital twin, driven by the use case it is attempting to address.

These challenges increased as more models were brought together (e.g. EPN and EPO), each with their own different modelling principles. The addition of more models to show a range of future predictions based on different assumptions in future digital twins will only add to this issue. This includes the challenge of making it possible for a user to understand the derivation of a particular observed result, to trace it back to the relevant input data, assumptions and models; if a modelling pipeline is built up from multiple information-processing stages, there may be many factors contributing to a single output value. Thus, careful management and a clear systematic approach will be required when bringing models together for the power of digital twins to be realised.

The simulation-visualisation interface of the technical demonstrator went through several different forms. We learned that increasing the amount of output processing on the simulation side, for example by pre-aggregating data from per half-hour per home to LSOA and cluster level, simplified and improved the performance of the visualisation. This demonstrator used relatively small amounts of data compared with a digital twin of the whole country, so developing methods for effective processing of the data and only calling on the data that needs visualising will be a key component of a future digital twin.

In this project, two forms of visualisation in the separate demonstrators have been demonstrated: a visually appealing form which is tailored to some specific needs, and an analysis-focused one based on a low-code tool which could be easily adapted to meet changing needs but is not as engaging. Each has a potential place in supporting users to explore the outputs of the underlying models. Although we chose not to demonstrate it in this project, the use of a common simulation-visualisation interface would allow the use of multiple visualisers to view the same data. This would unlock the ability to take both approaches to visualisation, allowing users to interact with the systems in the way that best suits them.

7.4. Cyber Security

The advantage of using digital twin technology for energy systems has been discussed earlier in this report, but the use of this technology increases the number of cyber vulnerabilities for energy systems. To keep the digital twin secure, both digital twin implementation and its instrumentation need to consider security measures and iteratively test against cyber-attacks.

If digital twins are compromised, the infiltrators will be able to identify weaknesses of the system, which can lead to misleading the operator or corrupting the system. While physical security of digital twins should be protected from people and environmental damages by various techniques, such as adding locks to the server rooms and data centres, cyber security of digital twins needs to be preserved against cyber threats and vulnerabilities. The cyber security considerations for a digital twin are twofold. On one hand, the cyber side of the digital twin, including software, PCs, cloud services and the system in which the digital twin is implemented, need to be secured. Additionally, the real-world environment that the digital twin represents and the components in this real environment should be cyber secured. If the cyber security of a digital twin is compromised, this system could suffer from several challenges, including the loss of data and control, loss of intellectual property, loss of access and incorrect output of the system. To reduce the cyber security risks, we need a cyber security strategy to identify the vulnerabilities and challenges of such systems and provide a mitigation strategy.

7.4.1. Cyber Security Challenges

Since digital twin technologies are a close representation of a real system and provide an internal view of such a system, if these technologies are hacked, they can open doors to the real system and disclose data of such system, enable identification of components' interfaces and behaviours, detection of vulnerable attack points, tests of the potential success of the attack, and finally carry out hacking attempts on the real system with a higher success rate. The visualisation facility which is used to present the real system connected to the digital twin software adds another layer of cyber vulnerability. If the visualisation facility is compromised, hackers can redesign the system with faults and manipulate the reality visible to the human operator.

One of the cyber security challenges of digital twins is to preserve the confidentiality, integrity and availability of such systems.

- Confidentiality entails ensuring only authorised users have access to the data and the systems, and it equally applies to the digital model, shadow and twin.
- Integrity means preventing unauthorised modification or destruction of data that are stored, processed and transmitted. It equally applies to the digital model, shadow and twin.
- Availability means ensuring the data and the system are available in a timely manner. Additionally, ensuring non-repudiation and authenticity is critical, such that the validity of these data, communications, commands and actions cannot be denied, and they can be verified and trusted.

The move from digital model to digital shadow and digital twin increases the vulnerability of such systems against cyber-attacks. Digital shadows and twins have a number of additional cyber security challenges, which are caused by pervasive use of IoT systems and remote-control functionalities.

The IoT ecosystem empowers the move from digital model to digital shadow and digital twin, by enabling real-time data collection. However, this transition adds another layer of cyber security challenge to the system. Digital twins harness the power of IoT and the data that IoT devices generate. These data, which feed the digital twin, were previously siloed and private, but now they are becoming more accessible and better at enabling the modelling and real-time monitoring of energy system components and environments to a fine level of granularity. These IoT sensors have known vulnerabilities such as limited power and computing capacity and network throughput, thus can be breached, accessed and manipulated by unauthorised users.

Digital twins use remote-control technologies with several cyber security challenges. But the additional cyber security challenge for remote-control technologies in digital twins lies in the fact that digital twins are being continuously updated and that they implement control both to the digital representation and the real-world environment. Hackers can manipulate this control at digital twin level and at the remote-control signal level. Both manipulations can mislead the human operator by presenting a faulty and manipulated digital environment.

Another cyber security challenge that is caused by two-way information flow between the real environment and the digital twin software is the maintenance of the privacy of the components, data and interactions between systems, and how to set an appropriate balance between protecting the privacy of the system and maintaining the efficiency of the digital twin.

A further challenge for digital twins is the limited understanding of the cyber security gap between the digital twin and the physical system connected to it; for example, hardware and physical devices can benefit from advanced security measures such as secure micro-controllers, which might not be applicable to the digital twin platform itself.[42]

7.4.2. Mitigation Strategies and Recommendations

To keep the digital twin cyber secure, several security techniques are needed. The traditional security techniques such as air gapping and hardware security are not applicable for digital twin platforms. Thus, new security measures need to be considered to preserve the cyber security of digital twins, to continuously ensure the confidentiality, integrity, availability, non-repudiation, authenticity, safety, maintainability and resilience of the system, so that its output is trustworthy, correct, consistent, reliable and accurate.

A digital twin's data, platform, access and the real objects that are connected to the digital twin should be made cyber secure by using approaches such as governance best practices, authentication (two-factor authentication (2FA) or multi-factor authentication (MFA)) of actors and devices, encryption (for data at rest, in use and in transit), using a cyber security control catalogue (e.g. NIST's Cybersecurity Framework[43] and Security and Privacy Controls for Information Systems and Organizations[44]), and identity management, among other mitigation techniques. It is recommended that energy system digital twin providers should implement ground-up security measures, which start with defining a secure software development lifecycle (SDLC) management process. The software design phase needs to meet security requirements, and security should be tested regularly and iteratively through the software lifecycle.[45] Additionally, a set of security techniques such as data and software transformation used for software protection or software hardening should be considered, to make the binary executable hack resistant.[45] Data and copy protection technologies (e.g. whitebox cryptography) and hardened APIs should be used to lock software and data to specific devices. Finally, preventing the propagation of twin implementations between devices can reduce the cyber risks from data or software being copied to another machine.

---

42 Hearn, M. and Rix, S., 2019. 'Cybersecurity considerations for digital twin implementations.' Industrial Internet Consortium Journal of Innovation, pp.107–113.

43 https://www.nist.gov/cyberframework

44 NIST, 'Security and Privacy Controls for Information Systems and Organizations.' 2020. 992 https://csrc.nist.gov/publications/detail/sp/800-53/rev-5/final

45 https://www.nist.gov/privacy-framework

Maintaining the privacy of data collection and data processing is critical for digital twins, and both personally identifiable and non-personally identifiable data need to be kept private in order to protect the privacy and intellectual property of the system. Techniques such as encryption, redaction, noise, delay, aggregation, differential privacy, masking and lifecycle management can help with preservation of data privacy. Furthermore, it is recommended that privacy controls should be implemented based on a comprehensive privacy control catalogue (e.g. using the NIST Privacy Framework[45]). Digital twin providers need to adhere to data protection regulations (e.g. GDPR), information security management standards (e.g. ISO 27001) and SOC 2 when providers store their data in the cloud, which could reduce the level of exposure of information systems to internal and external risks. Additionally, to keep the energy system digital twin secure, providers could improve their security standards to become compliant with IoT and consumer IoT cyber security technical specifications (e.g. ETSI TS 103 645).

Preserving the cyber security of sensor networks connected to digital twins is also of high importance, and standard encryption algorithms such as AES and Triple DES could be used to ensure the security of such networks. Additionally, to reduce the malicious activity and to protect privacy, encryption techniques could be used for sensitive API parameters and role-based access control could be implemented.

Finally, other approaches such as updating security policies and network security controls, and training and educating the digital twin users could be considered to improve the security of digital twins.

To conclude, currently there is no cyber security framework for energy system digital twins, but a number of recommendations provided in this report can be used to improve their cyber security, and digital twin providers are advised to work towards developing a reference architecture for cyber security of digital twins for energy systems.

7.5. Future Work

7.5.1. Approach to Use Digital Twin Technologies to Support Decarbonisation Policy

This project, through producing the visual and technical demonstrators for a digital twin to support the decarbonisation policy described above, has supported the definition of a roadmap for future developments. It is envisaged that the next step should be a 'pilot' system, with initial capabilities and the ability to contribute valuable insights based on robust underpinning data and modelling. This section expands on some of the considerations needed to do this.

7.5.1.1. Areas Of Development

Work to date has identified a number of key technical areas in which further development is needed to align the capabilities of a twin system with the needs of the application area, and some of the key challenges within them for future work:

- **Stakeholder engagement:** The starting point for any future development must be more wide-ranging engagement among the policy community to understand the needs, requirements and use cases for an energy system digital twin. For this purpose, the demonstrators created during this project will provide tools to illustrate potential functionality and help to elicit issues and improvements to be translated into requirements for future work.
- **Data sources:** Expanding the functionality of the digital twin system is likely to require new data as inputs into the models – whether a broader range of types, more recent, or more fine-grained – resulting in a need to identify sources for such data and the corresponding data owners. Aligned to this, as noted in section 7.3, it will become increasingly important for a user of the system to be able to trace back from results to the assumptions and data used to create them, and to manage alternative sets of assumptions and data for different contexts.
- **Data standards:** As discussed in section 7.2, and following on from the previous point, it is important for future development to be informed by data standards where applicable. This may involve identifying data standards, encouraging data owners to implement them, and adapting models to ingest standardised data.

- **Visualisation:** Work to date can be enhanced, not only at the level of the design and functionality of the visualisation, aiming for a single interface to suit a range of audiences (analysts, policy makers, data owners etc.), but also in terms of the technologies and implementation options; it is notable that the technical and visual demonstrators used different technologies to implement their visualisations. Although one focus of work on the visual demonstrator was the creation of a 3D/immersive view, the benefits of this should be explored through user engagement.
- **Representation of policy decisions:** The technical and visual demonstrators explored different mechanisms to reflect impacts of policy choices on the energy system. However, it is envisaged that for a potential pilot, further understanding should be gained into the appropriate framing of inputs into the energy system model that would best support a policy-development application.
- **Modelling consumer choice:** Related to the point above, many energy system models are designed to explore what should happen – i.e. where energy system actors make rational choices in response to 'perfect' market signals or other incentives. However, a key aim of a digital twin system would be to understand what would happen in response to a given national policy. Methods for representing methods for such choice should be investigated and potentially incorporated into the relevant models.
- **Energy network considerations:** Modelling should consider the constraints posed by network infrastructure on energy usage or uptake of new technologies, and the knock-on cost impacts of enhancing network infrastructure to accommodate new demands, building on the initial work in this respect undertaken for the technical demonstrator.
- **Approaches and frameworks for model integration:** Work to date has used computational facilities that are either directly controlled by or procured by the project delivery partners, with bespoke approaches for translating data between models (using middleware, adaptors or direct development of source models). For an integrated twin, more appropriate approaches should be taken for computational infrastructure and data translation, for example the use of shared facilities such as DAFNI as described in section 7.1.
- **Interactive modelling:** As described in section 6.3, the demonstrators were based on data from discrete predefined scenarios to allow for interactivity (since the underpinning models take multiple hours to execute). This restricted the richness of engagement and exploration possible for a user and is a key constraint to be addressed in future work. For example, this might involve model order reduction and/or finer-grained upfront scenario generation; the ability of such techniques to handle the characteristics of the model outputs should be investigated.
- **Cyber security:** As highlighted in section 7.4, cyber security is a key consideration in future digital twin systems. Since a policy application is less likely to involve real-time data flows or control authority over physical assets, the key consideration would be protection of privacy-sensitive data where applicable. This would combine technical aspects such as encryption with operational mechanisms such as consents for specific uses and anonymisation where attribution is not needed.
- **Validation of outputs:** To build confidence in models and demonstrate their explanatory power, data sources and processes are needed that can compare model outputs against historical system outturns, for example in terms of consumer behaviour change in response to new policy introduction. Allied to this is the need to allow for sensitivity analysis to understand confidence in outputs (using e.g. an ensemble of inputs).

- Alignment with external initiatives: Work in this area should consider and collaborate with other relevant initiatives, including for example:
  - **National Grid ESO Virtual Energy System**[46] **–** the selection of VES' use cases will determine the most beneficial collaboration route, but for example it is envisaged that there is likely to be alignment on present-day data sources.
  - **National Digital Twin –** as discussed in section 7.2, the NDT initiative is supporting definition of data standards, data sharing frameworks[41] and an ontology for defining data content, and thus can guide work in these areas.
  - **DAFNI –** as described in section 7.1 and above, DAFNI might form both a computational facility for hosting models and a platform for structuring their data transfer.

7.5.1.2. Stages of Maturity

Taking into account the areas of development described in the previous section, it is recommended that the following works are categorised into stages of maturity, with works leading towards a more sophisticated modelling environment and more clarity for users.

- **Mapping existing models:** The first stages towards a clearer modelling environment would be to gain full visibility of the existing suite of models. Works should be done to investigate where differing models may align internally and also externally with similar modelling types, such as between UKTIMES[47] and ESME.[48] Inputs and outputs of each model should be captured, as well as modelling languages and data formats required for functionality.
- **Updating of data to be more recent:** Digital twin solutions do not necessarily require real-time data streams; however, they would benefit from using more consistent and up-to-date data sources to ensure more accurate outputs. Some examples of these could be aggregated annual consumption patterns, low carbon technology behaviour metrics or consumer behaviour preferences. This mitigates the risk of having out-of-date simulations.
- **Improvement of models:** Currently the suite of models existing within the energy system experiences a range of quirks, such as running on differing granularities or having differing abilities to ingest broader data ranges. Bringing together models into one central integration environment, such as DAFNI as discussed previously, would allow for the more seamless integration of inputs and outputs, while also simplifying the scenario forecasting process.
- **Increased sophistication of modelling suite:** One of the largest problems associated with the current modelling suite is the time taken to output scenarios. To get to a near-real-time output solution, approximate modelling could be used for investigating specific user-defined scenarios. It would also be beneficial to have a greater range for the choices of policies/inputs, as opposed to the predefined scenarios used within this demonstrator.
- **Better visualisation:** Better visualisation for modelling would be beneficial throughout their lifecycle, from increased understanding of inputs and policy metrics to easier interpretation of outputs. Model use should be user-centric and digestible, from non-technical to technical users, and could be generated through more accessible user interfaces, street-level forecasted views or colour coding of changes within systems, for example. These have been demonstrated within both demonstrator types.

---

46 https://www.nationalgrideso.com/virtual-energy-system
47 https://www.ucl.ac.uk/energy-models/models/uk-times
48 https://www.ucl.ac.uk/energy-models/models/esme

7.5.1.3. Practical Considerations

As outlined above, the roadmap towards a sophisticated digital twin solution requires effort in a number of different workstream areas. For this demonstrator project, the development the two demonstrators took a project team of seven individuals four months. Moving into a pilot phase, with a working prototype, it is expected that this would increase by a factor of two to five times. There would be an option to expand the size of the team, but this would incur increased costs, time and effort, as well as effort into the required development of upgraded models.

As discussed above, much of the computational infrastructure to support digital twin solution development does not currently exist, or would need considerable development, and so it is anticipated that the technical knowledge and expertise within the team would also need to be expanded. There is an option to align with wider initiatives to share this workload, but this is dependent on the use cases proposed and the development prioritised.

7.5.2. Steps Towards a Full Digital Twin

The demonstrators created in this project are digital models, rather than 'full' digital twins, since they ingest static data sources and output calculated metrics. Although much of the conversation surrounding digital twins has revolved around their need to ingest real-time data sources and provide a two-way flow of information, in reality it is likely that many of the use cases being prioritised within the energy sector are not going to need this.

The use cases prioritised by BEIS are more likely to be centred on more strategic decision-making and the validation of previous scenario modelling, and so increased data access is required, rather than real-time, and therefore work should be carried out to identify priority datasets.

To continue development of the domestic decarbonisation use case into further phases, it would be beneficial to gain access to more 'real' datasets that can give more accurate insight into consumer behaviours than previously used synthesised datasets. For example, one area that was not focused on in this project is how consumer preferences are incorporated into the models and how this compares to outputs from previous model projections. Sources of data could remain more static, utilising in-depth surveys to obtain consumer preferences on thermal comfort levels, typical occupancy patterns and willingness to accommodate flexibility, in order to generate a consumer-centric, house-by-house level view.

For wider expansion of the domestic decarbonisation use case, moving towards a full bi-directional digital twin, the following should be considered.

7.5.2.1. Digital Shadow

A digital shadow is able to integrate an automated one-way data flow from the physical system, and so for domestic decarbonisation this could be data ingestion from network-level or household data. For a home-by-home basis, this could be from in-home sensors or by smart metering to gather metrics on room temperature preferences, real-time consumption or environmental changes. For a network-level digital shadow, incorporating more dynamic data streams into the model would also be beneficial, providing insights on flexibility and indicating where changes could be made in real-time. This could help, for example, to better understand demand profiles of domestic EV chargers and to develop appropriate flexibility services.

7.5.2.2. Digital Twin

A 'full' digital twin system is able to integrate a two-way data flow between the model and the physical system, allowing modelled changes and optimisation of assets to happen in real-time. In principle, a digital twin system could be granted control authority over the flows of information within a local region of the energy system; however, to realise this for the domestic decarbonisation use case, the following would need to be considered.

- Assuring consumers their information is secure and used transparently for only the proposed use case
- Implementation of appropriate security measures to tackle the security vulnerabilities that digital twins face
- Installing of sensor and monitoring equipment on the network to gather real-time data
- Prioritisation of robust IoT solutions that could enable the optimisation of assets in real-time
- Large-scale storage and computing solutions to ensure large amounts of data can be ingested and modelled, while also supporting established standard requirements.

Much of this requires in-depth consumer participation, and so although digital twins can provide value within the sector for applications such as optimisation of heating within homes, reduced renewable energy curtailment or EV charging optimisation, it is likely that these use cases will only be targeted by organisations offering those specific services, rather than whole-system thinking organisations, such as BEIS.

Given the above requirements, it's important that the focus is shifted from digital twins being the end goal, to investigating how to better leverage their individual components within the roadmap, to ensure that users of the tools are able to achieve maximum benefit at minimal expense.

7.6. Conclusion

Policy makers are now tasked with the challenge of accurately modelling scenarios and making strategic decisions in an ever-changing energy system, and so solutions that empower these users with the knowledge needed to complete this task are crucial. 'Digital twin' as a buzzword has existed within the energy system for decades but working demonstrators that are able to show the power in increased data sharing, alignment of models and better visualisations have been few and far between, and so communicating their benefits has so far been difficult.

This project has produced two proof-of-concept demonstrators: one technical, which is able to demonstrate the power in aligning data streams and models; and one visual, which is able to output immersive, user-driven scenarios for non-technical users. Not only do the demonstrators begin to paint a picture of what these solution types can offer, but they also open up a discussion about how to move the conversation around digital twins away from the flashy visuals to one centred on the importance of the central infrastructure and requirement for robust data sharing standards.

A large amount of time has been spent on this project communicating to the sector that the end goal of these projects should not be focused on reaching a full bi-directional twin system, but instead on dissecting and prioritising differing use case areas within the sector to highlight where the problem areas are and to propose effective solutions to address these. It is likely that for future phases of work, BEIS' use case areas will be heavily reliant on increased sophistication of digital models, and so, as discussed in section 7.5.1.2, effort is needed to both increase the sophistication of the current modelling suite and engage with policy makers to investigate data types required.

Making the move towards these solution types will be no small challenge, and a huge part of the next steps is achieving a full understanding as to how to incentivise more organisations within the energy sector to interact with these solutions and conveying to them how they will gain benefit from providing an increased amount of information. The need for these solution types for the transition to Net Zero is well understood; however, it is the clear demonstration of benefits that will likely encourage the increased participation needed from wider organisations. It is hoped that this demonstrator project acts as the initial steps towards this transition, and that any future phases will continue the momentum gathered in order to move towards a 'full' solution.

Appendix 1 – Data Landscape

Table 2 lists the datasets identified as relevant to the domestic decarbonisation use case during a data landscaping activity. Table 3 provides a glossary for the column headings in Table 2.

Dataset	Data Provider	Spatial Granularity	Coverage	Update Frequency	Proposed use (Technical Demonstrator, Visual Demonstrator or future development)
Energy Performance Certificate (EPC) Data	gov.uk	Per Household	UK	n/a	Technical
Historic Energy Consumption Patterns	gov.uk	Per Middle Layer Super Output Area (MSOA)[49]	UK	Annual	Technical
Historic Weather Data	EnergyPlus[50]	Approx. 50 locations across the UK	UK	Historic	Technical
House Types	ONS	Per Lower Super Output Area (LSOA)37	UK	Historic	Technical
English Housing Survey, Welsh & Scottish House Condition Survey	gov.uk	Regional	GB	Annual	Technical and Visual
Geospatial Data	Open Street Map	Per Street	Per Street	Prior to Baseline Household Evaluation	Visual
Off gas postcodes	Xoserve	Postcode	GB	Historic	Technical
Baseline Energy Performance	Model (Home Energy Dynamics)	Per Household	Per Household	Per Household	Technical
Electricity Networks Assets (substations)	Distribution Networks	Per substations	UK (dependent on availability)	Varying intervals	Technical
Fuel poverty statistics	gov.uk	LSOA	England	Annual	Future
Feed-in Tariff Installation	gov.uk	LSOA	England and Wales	Six monthly	Future
Rural Urban Classification	gov.uk	LSOA	England and Wales	Historic	Future
Social deprivation and economic activity indices	ONS	LSOA	UK	Historic	Future
Publicly available charge points	gov.uk	Per Charger	UK	Real-time (Snapshot, if used in demonstrator)	Future
National data from Renewable Energy Planning Database	gov.uk	Projects over 150kW	UK	Quarterly	Future
		Aggregated to a small geographical area	GB	Real-time	Future
	Smart DCC	National	GB	Real-time	Future
		Aggregated to a small geographical area	GB	Real-time	Future
Historic Energy Consumption Patterns	LSOA register	Per LSOA	Per LSOA	Annual	Future
Current Weather Data	MET office	Approx. 270 locations across the UK	UK	Real-time	Future

Table 2: Dataset details

49 https://www.gov.uk/government/statistics/lower-and-middle-super-output-areas-electricity-consumption
50 Several other sources available.

Field	Description
Data Topic	A concise description of the information contained in the data
Data Source	An example source for the data
Spatial Granularity	The finest spatial granularity of each data topic that can be accessed for the demonstrator
Coverage	The spatial characteristics of the data topic
Update Rate	How often updated datasets are produced
Proposed Use	Where the data topic is anticipated to be used, either in the visual demonstrator, technical demonstrator or a Future Energy System digital twin

Table 3: Data landscape glossary

Appendix 2 – Phase Two Concept Reference Design

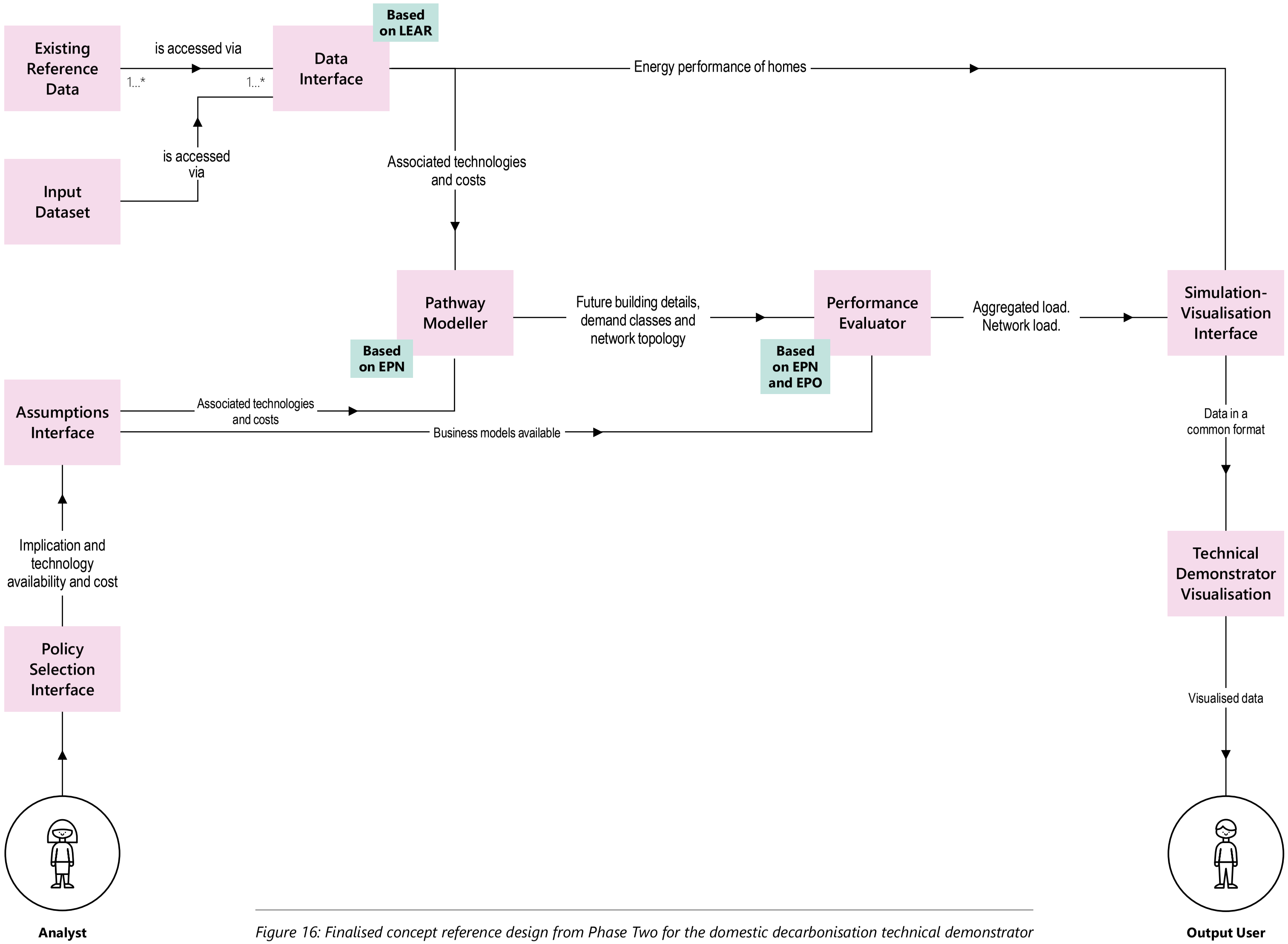

Figure 16: Finalised concept reference design from Phase Two for the domestic decarbonisation technical demonstrator

Appendix 3 – Comparison of ESC Energy Scenarios For Manchester with BEIS Energy Scenarios

The Department for Business, Energy & Industrial Strategy (BEIS) has produced three energy scenarios for decarbonisation of heating of buildings across the UK for the UK Government's 'Net Zero Strategy: Build Back Greener'.[51] This section compares the BEIS scenarios with those created by Energy Systems Catapult (ESC) in its Manchester Local Area Energy Plan,[52] produced by ESC's EnergyPath Networks model.

Although there are similarities between some of the scenarios' names, these scenarios are not identical and are not directly comparable. The table below gives a comparison of the scenarios from ESC for Manchester, and from BEIS for the UK.

ESC Scenario	Most Similar BEIS Scenario	Common Difference	Other Significant Differences
Leading the Way	High Electrification	ESC's scenarios assume a 2038 target date for Net Zero (consistent with the Greater Manchester 5-year Environment Plan[53]) compared with a 2050 Net Zero target date for the BEIS scenarios.	No other significant differences, but not designed to be comparable.
HyNet 2030 (An Alternative Future Local Energy Scenario)	Dual Energy System		No other significant differences, but not designed to be comparable.
High Electrification	High Electrification		ESC assumes the only low carbon heating option is in-home electric heating, while BEIS' scenario allows in-home electric heating, heat networks and limited hydrogen heating.
High Hydrogen	High Hydrogen		ESC assumes the only low carbon heating option is hydrogen, while BEIS' scenario allows hydrogen heating, heat networks and limited heat pumps, as a result of assuming that most of the gas network is converted to hydrogen.

Table 4: Scenario Comparison

51 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1033990/net-zero-strategy-beis.pdf

52 This was the output of a project carried out for Greater Manchester Combined Authority (GMCA) by ESC in 2021. The Local Area Energy Plan is confidential to GMCA, but GMCA have granted permission to use the EPN outputs for this project.

53 https://www.greatermanchester-ca.gov.uk/media/1986/5-year-plan-branded_3.pdf

The BEIS scenarios are as follows:

High Electrification

In this scenario, we assume there is no significant use of hydrogen for heating in buildings. This may be because hydrogen is not proven to be feasible, cost-effective or preferable as a solution for low carbon heating, or because its deployment has been significantly delayed. In this scenario, we would need to continue the rapid growth of the heat pump market beyond 600,000 per year in 2028 to up to 1.9 million per year from 2035, resulting in roughly 13 million homes using low carbon heating systems by 2035 – around 11 million with heat pumps and around 2 million using heat networks.

High Hydrogen

In this scenario, hydrogen has proven feasible and preferable as a solution for heating most UK buildings, and decisions taken in 2026 set the UK on a path to converting most of the national gas grid to hydrogen. We would expect to begin the transition by converting a pilot hydrogen town by the end of the decade and then accelerate roll-out. The conversion would likely start by building out from existing hydrogen production and use in industrial clusters, and roll-out would involve switchover on an area-by-area basis in different locations.

Dual Energy System

In this scenario, both hydrogen and electrification prove feasible and preferable as heating solutions to large numbers of consumers.

This could arise in several forms:

- All or most of the gas grid is converted to low carbon hydrogen, but the costs and benefits of switching to hydrogen versus installing a heat pump are viewed differently by different consumers. This could result in a high switchover to both hydrogen and heat pumps on the gas grid.
- There is partial but still extensive conversion of the gas grid to hydrogen, based on differing geographical or built environment factors. This would require careful consideration of which parts of the grid would be converted and where responsibility for decisions about the costs and benefits of converting different areas should lie.
- There is widespread consumer demand for hybrid systems that utilise a mix of energy sources.

The ESC scenarios are as follows:

Primary Scenario – Leading the Way

This scenario focuses on meeting the carbon budget and carbon neutrality target by making use of measures within Manchester's local control where at all possible.

Secondary Scenario – HyNet 2030 (An Alternative Future Local Energy Scenario)

This scenario assumes hydrogen options for residential heating and non-domestic buildings become available in Manchester from 2030 onwards (aligned to HyNet Northwest Phase 3[26]) and that the repurposing of the gas grid to hydrogen remains an option.

Scenario 3 – High Electrification

This scenario assumes the only low carbon options for space heating and hot water demand are electrical.

Scenario 4 – High Hydrogen

This scenario assumes the only available low carbon options for space heating and hot water demand are hydrogen based from 2031 onwards.

Licence/Disclaimer

Energy Systems Catapult (ESC) Limited Licence for BEIS ENERGY SYSTEM DIGITAL TWIN DEMONSTRATOR FINAL REPORT

ESC is making this report available under the following conditions. This is intended to make the Information contained in this report available on a similar basis as under the Open Government Licence, but it is not Crown Copyright: it is owned by ESC. Under such licence, ESC is able to make the Information available under the terms of this licence. You are encouraged to Use and re-Use the Information that is available under this ESC licence freely and flexibly, with only a few conditions.

Using information under this ESC licence

Use by You of the Information indicates your acceptance of the terms and conditions below. ESC grants You a licence to Use the Information subject to the conditions below.

You are free to:

- copy, publish, distribute and transmit the Information;
- adapt the Information;
- exploit the Information commercially and non-commercially, for example, by combining it with other information, or by including it in your own product or application.

You must, where You do any of the above:

- acknowledge the source of the Information by including the following acknowledgement:
- "Information taken from 'BEIS ENERGY SYSTEM DIGITAL TWIN DEMONSTRATOR FINAL REPORT, by Energy Systems Catapult";
- provide a copy of or a link to this licence;
- state that the Information contains copyright information licensed under this ESC Licence.
- acquire and maintain all necessary licences from any third party needed to Use the Information.

These are important conditions of this licence and if You fail to comply with them the rights granted to You under this licence, or any similar licence granted by ESC, will end automatically.

Exemptions

This licence only covers the Information and does not cover:

- personal data in the Information;
- trademarks of ESC; and
- any other intellectual property rights, including patents, trademarks and design rights.

Non-endorsement

This licence does not grant You any right to Use the Information in a way that suggests any official status or that ESC endorses You or your Use of the Information.

Our Mission – To unleash innovation and open new markets to capture the clean growth opportunity.

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

es.catapult.org.uk
@energysyscat