Virtual Energy System

Workstream 2 - Developing the underpinning frameworks

Benchmarking Report

February 2022

Contents

Executive summary

Background

National Grid ESO have launched the Virtual Energy System (VirtualES) programme. Its objective is to enable the creation of an ecosystem of connected digital twins of the entire energy system of Great Britain, which will operate in synchronisation to the physical system.

This ecosystem of connected digital twins will facilitate the secure and resilient sharing of energy data across organisational and sector boundaries, enabling scenario modelling and whole-system decision making - resulting in better outcomes for society, the economy, and environment. Creating the VirtualES is a socio-technical challenge that requires a collaborative and principled approach, aligned with the National Digital Twin programme.

Arup, supported by the Energy Systems Catapult and Icebreaker One, have been commissioned to deliver workstream 2 of the programme. The objective of the workstream is to determine the socio-technical framework that form the foundation of the VirtualES.

This report is an external benchmarking of the objectives and requirements of the VirtualES against emerging cross-sector and international best practice for connecting assets, systems, and digital twins.

Approach

The methodology consists of two sequential and iterative activities: research and benchmarking.

In the research activity, the outline dominant high-level use cases for a connected energy system were determined through reviewing existing literature and assessing the current needs and challenges of the sector. These were confirmed through interviews with energy sector experts.

Cross-sector and international case studies were then identified that demonstrated, or had the characteristics of, assets and systems being connected together into an ecosystem.

This characterisation was used because the label ‘digital twin’ is not ubiquitously or consistently applied across industry or globally.

The identified digital twin case studies were then compared against the energy sector use cases, and analysed and synthesised to understand the lessons and key socio-technical factors that could be considered when developing the VirtualES.

Recommendations

The research, expert interviews, and benchmarking assessment has highlighted the socio-technical nature of connecting digital twins, assets, and systems at scale.

Whilst the creation of an ecosystem of connected digital twins is considered possible from a technology perspective, there are greater challenges from a people, process, and data perspective. For example, legal challenges with data sharing agreements, commercial sensitivities with models and data, interoperability difficulties through the lack of metadata standards or common ontologies and taxonomies, and the need to focus on skills, education, and change management.

The domain of connected digital twins and whole-system integration is a developing market. There are tangible lessons to be learnt from the in-sector and cross-sector programmes underway across the world, which highlight the need for a collaborative and principled approach.

It is also considered that external benchmarking is an iterative activity. It should be revisited periodically as the VirtualES progresses and more case studies and use cases become apparent.

Nomenclature

AEMO Australian Energy Market Operator
AESC Australian Energy Simulation Centre
ARENA Australian Renewable Energy Agency
AI/ML Artificial Intelligence/Machine Learning
AIDM Airline Industry Data Model
AIS Automatic Identification System
API Application Programming Interface
APICA Antwerp Port Information & Control Assistant
BBA British Bankers Association
CAISO California Independent System Operator
CDBB Centre for Digital Built Britain
CDR Consumer Data Right
CM Condition Monitoring
CMA Competition and Markets Authority
CSIRO Commonwealth Scientific and Industrial Research Organisation
CST Connection Simulation Tool
CSTIWG Connection Simulation Tool Industry Working Group
DER Distributed Energy Resources
DNSP Distribution Network Service Providers
DNO Distribution Networks Operators
EDiT Energy Digitalisation Task Force
EDTF Energy Data Task Force
EMT Electromagnet Transient
ERCOT Electric Reliability Council of Texas
ESC Energy Systems Catapult
ESO Electricity System Operator
EV Electric Vehicle
FCA Financial Conduct Authority
FES Future Energy Scenarios
FinTechs Financial Technology Companies
GDPR General Data Protection Regulation
G-PST Global Power System Transformation Consortium
IAPH International Association of Ports and Harbours
IASR Inputs, Assumptions and Scenarios Report
IB1 Icebreaker One
IC Integrated Circuit
IMO International Maritime Organization
IHPC Institute of High Performance Computing
IoT Internet of Things
IRENA International Renewable Energy Agency
ISP Integrated System Plan
ITPCO International Taskforce Port Call Optimization
LTC Low Carbon Technology
MEDA Modernising Energy Data Access
MESMO Multi Energy System Modelling & Optimisation
NEM National Electricity Market
NG National Grid
NTU Nanyang Technological University
PD Partial Discharge
PV Photovoltaics
SITEM Singapore Integrated Transport Energy Model
SLES Smart Local Energy Systems
TCC Traffic Control Centre
TUM Technical University of Munich
VirtualES Virtual Energy System
WEM Wholesale Electricity Market

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Approach

Context

The Virtual Energy System

In response to the need for achieving net-zero, and the changing landscape of generating, managing and consuming energy, National Grid ESO launched the Virtual Energy System (VirtualES) programme.

The objective of the VirtualES is to enable the creation of an ecosystem of connected digital twins of the entire energy system of Great Britain, that will operate in synchronisation to the physical system.

This ecosystem of connected digital twins will enable energy data sharing across organisational and sector boundaries, facilitating scenario modelling and whole-system decision making - resulting in better outcomes for society, the economy, and environment.

Creating the VirtualES is a socio-technical challenge that requires a collaborative and principled approach, that is aligned with the National Digital Twin programme. To start development of the VirtualES, National Grid ESO have commissioned three workstreams. This report forms part of workstream 2.

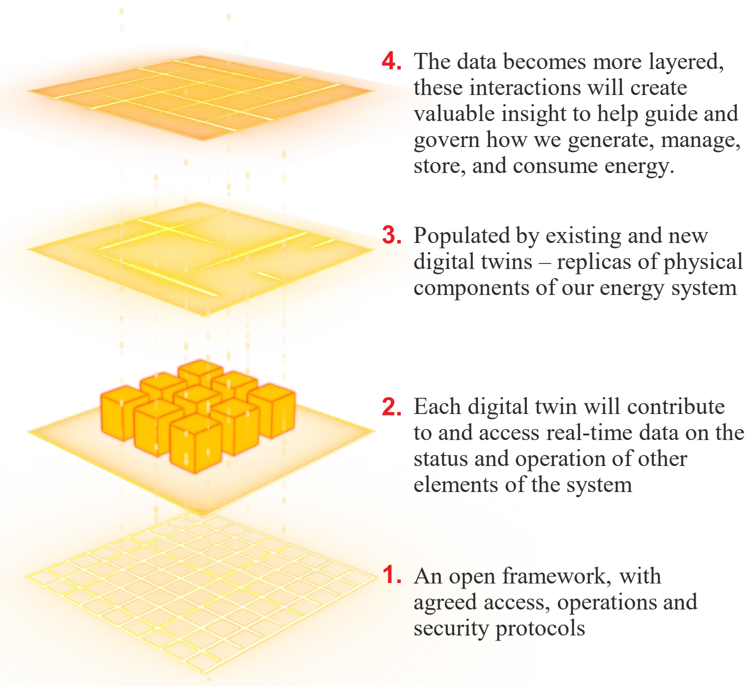
- Workstream 1 - Stakeholder engagement
- Workstream 2 - Common framework & principles
- Workstream 3 - Use cases

Workstream 2 - Common Framework & Principles

The objective of this workstream is to determine the socio-technical framework that will form the foundation of the VirtualES – enabling the creation of this ecosystem of connected digital twins.

This framework will consider factors such as, for example, common elements of taxonomy; metadata standards; interoperability approaches; and security and access protocol. This framework will be developed through three interconnected work packages:

1. **External benchmarking (this report):** Understanding the cross-sector and global best practice for connecting assets, systems, and digital twins.
2. **Defining the key elements:** Determining the key socio-technical factors that need to be considered for the VirtualES to succeed.
3. **Developing agreed standards with partners:** Collaboratively developing, with industry, the agreed standards and approaches for the key elements.



Virtual Energy System

Indicative components of the Virtual Energy System

Delivery team

Workstream 2 (common framework & principles), is led and delivered by Arup, supported by the Energy Systems Catapult and Icebreaker One.

- **Arup:** An employee owned, multinational organisation with more than 15,000 specialists, working across 90+ disciplines, with projects in over 140 countries and the mission to 'shape a better world'. Arup have extensive energy and cross-sector digital twin expertise, and actively contribute to the National Digital Twin programme.
- **Energy Systems Catapult (ESC):** An independent, not-for-profit centre of excellence that bridges the gap between industry, government, academia, and research. Set up to accelerate the transformation of the UK's energy system and ensure businesses and consumers capture the opportunities of clean growth. The ESC were responsible for the Energy Data Task Force (EDTF) and are delivering the Energy Digitalisation Task Force (EDiT).
- **Icebreaker One (IB1):** An independent, non-partisan, non-profit organisation with a mission to 'make data work harder to deliver Net Zero' by creating Open Standards for data sharing across agriculture, energy, transport, water, and the built world.

Together the three organisations assembled a delivery team to effectively collaborate and deliver the objectives of this workstream.

This external benchmarking work package was delivered over 6 weeks, and followed an agile delivery methodology – with the delivery team working in 3 sprints, each 2 weeks in duration – in close collaboration with National Grid ESO throughout.

The external benchmarking methodology and approach is detailed in the following pages.

Benchmarking methodology

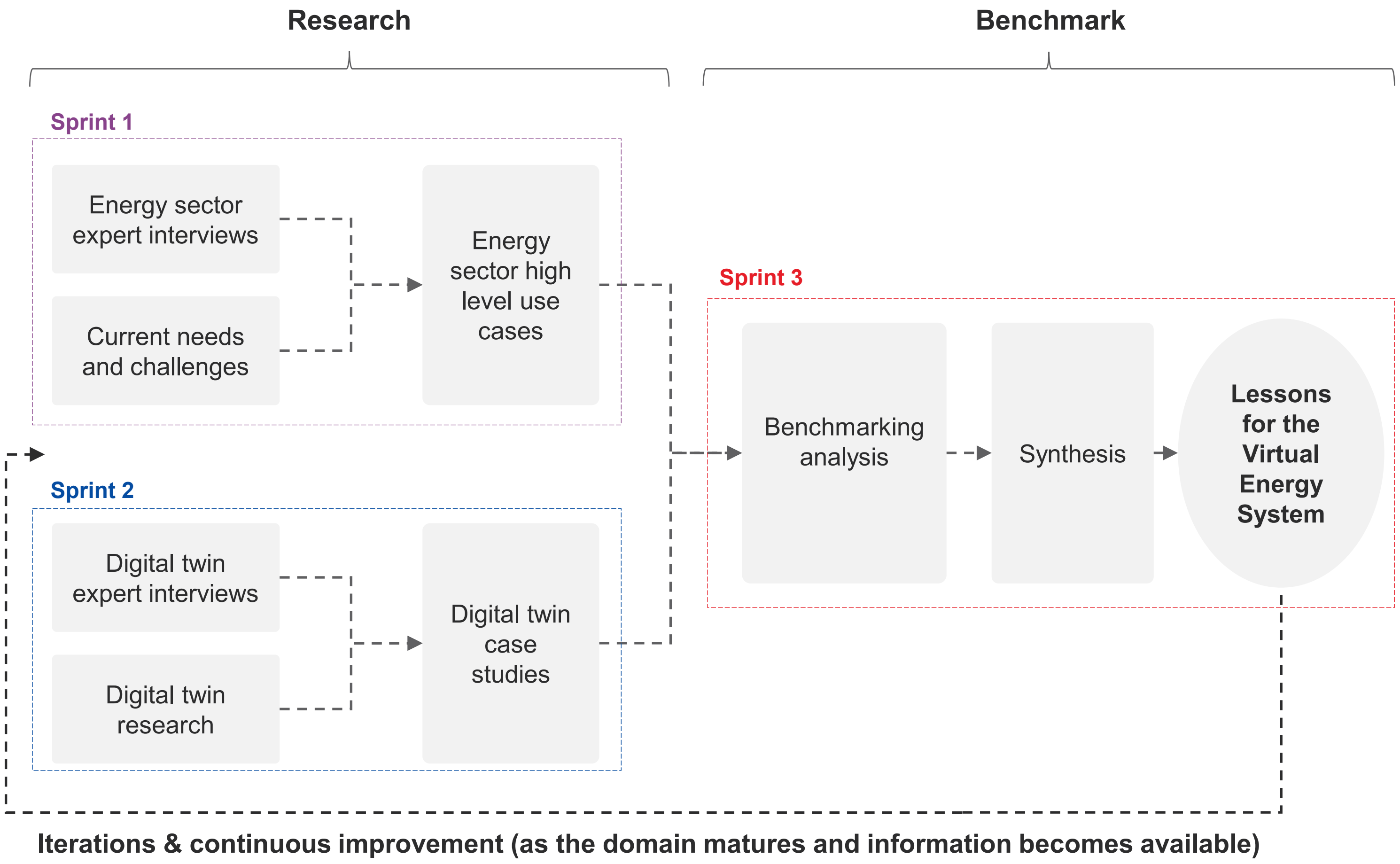
Approach overview

The methodology consists of two sequential and iterative activities: research and benchmarking.

In the research activity, the outline dominant high-level use cases for a connected energy system were determined through reviewing existing literature and assessing the current needs and challenges of the sector, and were confirmed through interviews with energy sector experts. Cross-sector and international case studies were identified that demonstrated, or had the characteristics of, assets and systems being connected together into an ecosystem. This characterisation was used as the label ‘digital twin’ is not ubiquitously or consistently applied across industry or globally.

The digital twin case studies were compared against the energy sector use cases, and analysed and synthesised to understand the lessons and key socio-technical factors that could be considered when developing the Virtual Energy System.

It is important to recognise that this is an iterative methodology. The domain of connected digital twins is not a mature market, and obtaining detailed information on case studies is limited by commercial sensitivities.



Benchmarking methodology

Energy system components / segments

Whilst the Virtual Energy System will ultimately impact the whole energy system, for the purposes of this benchmarking report only the electricity system was considered.

The electricity system was divided into five components or segments that represented the five main functions and actors of the system – all of whom would be users or benefiters of the Virtual Energy System. These delineations allowed for the use cases to be more easily determined and categorised.

- **Generation:** Generators produce electricity. This is sold on the wholesale energy market, where it is then used in UK industry and homes.
- **Transmission:** Generated electricity flows through high voltage wires along the transmission network.
- **Distribution:** Distribution network operators (DNOs) carry the energy from the transmission system to UK homes and businesses. There are 14 DNOs responsible for different distribution areas.
- **Retail:** Suppliers buy electricity from the wholesale energy market. They pay the DNOs for transporting it along their distribution network to consumers.
- **Consumption:** Home and businesses buy electricity from the energy suppliers.

Use cases

For each energy system segment, the dominant use cases for a connected energy system were determined by reviewing existing literature and industry programmes (such as the Energy Data Task Force, Modernising Energy Data, and Open Energy) to understand the current needs and challenges of the sector.

The use cases were iterated and tested through interviews with energy sector experts, from across industry, to produce those detailed on pages 14 to 18.

Certain use cases were found to be applicable across multiple segments. The use cases were also categorised using the digital twin use case framework published by CDBB.

The use cases are for benchmarking purposes only, and have therefore only been developed at a high-level (i.e. detailed personas and problem statements were not produced). They are complementary to the work being completed in workstream 3 (use cases).

Role of National Grid ESO and the regulator

Regulation, and the role of National Grid ESO and the regulator, are considered applicable across all segments and use cases, and is discussed separately in Section 4.

Digital twin use case framework
Part of the Digital Twin Toolkit, published by CDBB

Benchmarking methodology

Case studies

Given the broad definition and usage of the term 'digital twin', case studies were identified based on whether they demonstrated, or had the characteristics of, assets and systems being connected together into an ecosystem – ideally at scale (such as city-scale or nationally).

The case studies were identified through desk-based research, interviews with digital twin experts, and through the delivery team's collective digital twin experience. The case studies are explicitly in-sector and cross-sector, taken from the UK and internationally, to ensure the greatest learnings and knowledge transfer.

Limitations on available case studies

The domain of connected digital twins, and whole-system integration is not a mature market in any sector, in any region. Therefore, there are a limited number of directly comparable case studies that match the objectives and aspirations of the VirtualES. It is also difficult to obtain detailed socio-technical information about the case studies, primarily due to commercial sensitivities.

To address this, a broader definition of 'connected assets and systems' was taken. The identified case studies were then evaluated using their obtainable information against each of the identified use cases. The evaluation is therefore only as detailed as the available information allows.

It is considered that the external benchmarking activity is iterative, and will be periodically revisited as and when more case studies or use cases become apparent.

Sectors considered

In the first iteration of this external benchmarking report the following sectors were identified and considered. Each has demonstrable examples of assets and systems being connected together into an ecosystem.

- Aviation
- Banking
- Climate resilience demonstrator (CReDo)
- Energy
- Rail
- Maritime and shipping
- Telecoms (through CReDo)
- Water

In future iterations of the benchmarking activity it is considered that further sectors will be evaluated.

Evaluation criteria

The case studies were evaluated against each of the identified use cases to understand to what extent each case study addressed the needs of the use case.

Given the limitations discussed above, a three-point qualitative scale was used for the evaluation:

- **Fully met or will fully meet** – meets all of the use case needs, or as part of the scope
- **Partially met or will partially meet** – meets some of the use case needs now, or as part of the scope
- **Not met / will never meet** – meets none of the use case needs

For the purposes of the evaluation the entire scope of the case study was considered, even if components of the scope were yet to be implemented or go-live.

The results of the evaluation were then aggregated and presented at the energy segment level (i.e. generation. transmission, distribution, retail, consumption) per case study for the benchmarking comparison. By presenting the results at this level it is possible to draw comparisons against the objectives of the VirtualES.

The full benchmarking results are detailed in Section 3, with the case study and use case evaluation data given in Appendix A.3.

2

Research

Research overview & summary

Use cases

The benchmarking methodology is detailed in Section 1.

The research identified 24 high level use cases for a connected energy system, which could be addressed by the Virtual Energy System. Each use case has associated socio-technical principles that will be considered when developing the common framework (see page 6). Many of the use cases are applicable across one or more of the energy system segments (i.e. transition to net zero).

It is considered that further use cases will exist, and will become apparent or dominant over time. These will be considered as part of future iterations of the external benchmarking activity.

The identified use cases are summarised in the box below, with full descriptions given on pages 15 to 18.

Regulation, and the role of National Grid ESO and the regulator, is considered applicable across all segments and use cases, and is discussed separately in Section 4.

Use cases (see pages 15 to 18)

1. Transition to net zero
2. Asset monitoring & predictive maintenance
3. Optimisation of energy production
4. Linking electricity & gas networks
5. Real time balancing and forecasting
6. Flexibility modelling for increase renewables
7. Model energy storage needs
8. Dynamic power modelling
9. Planning the future transmission network
10. Optimise connectivity capacity
11. Model stability of network
12. Visibility of transmission & distribution interface
13. Hazard event & threat impact simulation
14. Multi-pathway resilience modelling
15. Asset monitoring for improved modelling
16. Predict localised energy production
17. Real time distribution network optimisations
18. Optimise energy storage usage
19. Planning future distribution network
20. Improve demand forecasting
21. Better services to customers
22. Smart demand response
23. Prosumers
24. Planning of local LCT implementation

Case studies

10 case studies were identified based on whether they demonstrated, or had the characteristics of, assets and systems being connected together into an ecosystem.

The case studies are described in detail on pages 20 to 47. They are both in-sector and cross-sector, taken from the UK and internationally.

Energy sector (country-scale)

- Australia
- Estonia
- Singapore

Other sectors

- Aviation
- Banking
- Climate resilience demonstrator (CReDo)
- Rail
- Maritime and Shipping
- Telecoms (through CReDo)
- Water

For each case study, information was obtained through desk-based research and stakeholder interviews.

2.1

Use cases

Energy system use cases summary

As detailed in Section 1, the energy system has been divided into five segments with dominant use cases identified for each segment that be addressed by the Virtual Energy System. These use cases are for the benchmarking purposes only, with their summaries given on the subsequent pages.

Generation

Generation

Generators, such as power stations and wind turbines, produce electricity. This is sold on the wholesale energy market, where it is then used in UK industry and homes.

Generators are facing a series of new challenges driven by changing energy demand, pricing and shift toward non-carbon intensive production systems.

They are under pressure to optimise their production while safeguarding returns, account for price volatility, assess long-term investments and diversifying into renewable energy generation.

Transmission

Transmission

The generated electricity flows through the high voltage wires along the transmission network.

Transmission networks face major challenges around security, balancing, and reliability of the electricity grid. The increase in renewable energy and new decentralised energy production technologies is disrupting energy supply patterns, which become increasingly intermittent and variable.

This demands new ways to adapt to changing scenarios and raises new challenges around the impact on existing assets, the need for future connectivity, and the pricing of services.

Distribution

Distribution

Distribution network operators (DNOs) carry the energy from the transmission system to UK homes and businesses. There are 14 DNOs responsible for different distribution areas.

With more distributed production (electricity generated by small-scale plant and injected into the local distribution grid) and local trade, distribution networks will have to take on responsibility for balancing supply and demand locally, as well as providing security and reliability to the overall system.

DNOs will have to provide increasingly localised trade of energy and grid services and interact with the numerous new and emerging actors, such as Smart Local Energy Systems and prosumers.

Retail

Retail

Suppliers buy electricity from the wholesale energy market. They pay the DNOs for transporting it along their distribution network to consumers.

Energy retail is characterised by an increasing volatility of its players. Energy retail profitability is at its lowest in years, while customer-churn levels and new-entrant numbers are at their highest.

New players, such as energy service companies and aggregators, and new forms of energy generation are changing the traditional linear energy value chain.

Additionally, the convergence of industries such as mobility, smart devices, telecom services, and even financial and construction services is re-shaping retailers positioning in the in the energy ecosystem.

Consumption

Consumption

Home and businesses buy electricity from the energy suppliers.

Greater automation, the diffusion of IoT devices in the residential and commercial sector (e.g. smart thermostats directly connected to the power market and to weather forecast providers), localised energy production and higher deployment of EV and smart charging systems will all allow further integration across demand and supply. This will unlock greater cost savings for individual consumers and the system overall.

The distinction between traditional suppliers and consumers will blur further, allowing for a more interconnected and localised energy system to emerge.

Identified dominant use cases

These use cases are for benchmarking purposes only, and have therefore only been developed at a high-level.

1. Transition to net zero

In response to the need for achieving net-zero, and the changing landscape of generating, managing and consuming energy, it will be necessary to simulate real world scenarios, develop decarbonisation strategies to build long term strategic pathways, and guide diversification into non-carbon intensive areas – whilst accounting for policy and regulatory processes.

Generation Transmission Distribution Retail Consumption

2. Asset monitoring & predictive maintenance

Understanding the performance of their assets and where maintenance would be needed. This will reduce the producer's risk of downtime and inefficiencies of production, extend the operational lifetime of assets, and reduce costs.

Whilst monitoring and maintenance is already conducted, this use case considers greater digitally enabled asset management.

Generation Transmission Distribution

3. Optimisation of energy production

Better planning, monitoring and control of the energy system assets to improve power plant efficiency.

A representation of the current state of a system combined with external sources such as forecast models (e.g. weather, demand, pricing) will allow energy producers to more accurately estimate and optimise energy production and reduce the risk of energy being curtailed or not monetised.

Generation

4. Linking electricity & gas networks

Understanding the dependencies and growing synergies between electric and gas production and transmission, such as heat pumps or hydrogen conversion.

A connected virtual representation of both systems, from generation to transmission and distribution, will help coordination and will optimise the operation of the gas and electricity networks.

Generation Transmission

5. Real time balancing and forecasting

Balancing real-time & predictive supply and demand within constraints of the overall system to inform network reinforcement decisions. This can help with network understanding and anticipating where there are capacity constraints, greater intermittent generation, etc.

This is based on integration across energy systems and producers, distributors networks, and retail and demand.

Transmission Distribution

6. Flexibility modelling for increased renewables

Monitoring of generation plants, storage and demand can help to improve the predictability of the systems and increase the rate in which renewable generation is added onto the network.

Flexibility in the power system becomes crucial for maintaining reliability and cost-effectiveness, impacting how infrastructure is planned and operated long term.

Transmission

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Identified dominant use cases

These use cases are for benchmarking purposes only, and have therefore only been developed at a high-level.

7. Model energy storage needs

Ensuring reserves are sufficient and the system delivers the power to meet needs.

Energy storage can give the ability to rapidly respond to large fluctuations in demand and can make the grid more responsive. However, there needs to be methods in place to determine when best to store energy, and at what scale to store it in.

Transmission Distribution

8. Dynamic power modelling

Power system operators must be equipped with the knowledge that the grid is going to be able to continue to run seamlessly, and fluctuations in generation are modelled and accounted for.

Power systems modelling should be able to account for a variety of new generation techniques, network storage and consumption equipment, as well as all market, customer and regulatory issues in a whole system context to create a far more responsive, predictable and dynamic power system.

Transmission Distribution

9. Planning the future transmission network

Improve the creation of future energy scenarios (FES), Electricity Ten Year Statements (ETYS), and Network Options Assessment (NOA) by better accounting for players across the entire energy system and other external factors. For example, FES currently only models large renewable energy produced.

This will help to better model how to best run the network, while minimising cost to the consumer, selecting investments needed and helping the rest of the industry align.

Transmission

10. Optimise connectivity capacity

Both transmission and distribution operators are seeing an increased set of assets connecting to their network. Bringing together accurate information around current performances with the ability to model several impact scenarios for new connections on the system will help determine the best path forward. This can also assess the use and impact of multi-purpose interconnections to allow several assets to connect to the grid (e.g. an interconnectors cable from another country together with an offshore wind farm connection).

Transmission Distribution

11. Model stability of network

With the increase of renewable energy sources, there is an increased risk that disturbances due to a change in demand or generation (e.g. loss of a circuit or generator) propagate more rapidly through the network. Bringing together data on the typology of the network, electric characteristics, power system generation models, network conditions, and variance of energy production from renewable will allow for better understanding of the stability of the network and how to mitigate potential system instability.

Transmission Distribution

12. Visibility of transmission & distribution interface

Both transmission and distribution networks have increasing numbers of commercial arrangements with different market players providing power and balancing services, within the market rules and service definitions. Service providers can enter into agreements with both transmission and distribution networks. Making visible those commercial layers and agreements, and monitoring when services are called upon, will reduce the risk of conflicts created by contrasting instructions being given to service providers.

Transmission Distribution

Identified dominant use cases

These use cases are for benchmarking purposes only, and have therefore only been developed at a high-level.

13. Hazard event & threat impact simulation

The energy system can be characterised by unprecedented levels of uncertainty and new emerging risk. For example, climate change, equipment failure, cybersecurity, outages, and security of supply.

Simulating the propagation of hazardous events across the energy system will help evaluate the sequential impact these events have across the industry, and assess the system vulnerabilities.

Generation Transmission Distribution

14. Multi-pathway resilience modelling

Given the limited amount of data around the impact on the energy system created by extreme events (e.g. climate change), multi-pathway modelling of the resilience of the energy system and its components will help build understanding on what the best potential resolutions should be.

Generation Transmission Distribution

15. Asset monitoring for improved modelling

Several energy asset models are run on a static set of assumptions (e.g. generation profile based on a summer and winter parameter, transmission modelling and maintenance budgets based on static values, performances factor fixed on a static rate with assets running at optimal state at all time, etc.). Accessing more granular and timely information about the performance and condition of assets would help improve energy network modelling and allow for more accurate optimisation of the network.

Generation Transmission Distribution

16. Predict localised energy production

Visibility of interconnection across distributed energy generation systems, local aggregators and Smart Local Energy Systems (SLES) and prosumers together with advance forecast modelling of energy production will be key to enable DNOs gaining a correct picture of the load on their networks. Better modelling of localised and decentralised energy production can enable DNOs in balancing supply and demand locally securely and reliably.

Distribution

17. Real time distribution network optimisations

By collecting continuous and real-time data on the state of transmission and distribution lines at various points (e.g. temperature, voltage, or current) as well as other complementary datasets through digital sensors, efficiency gains can be achieved by lowering the rate of losses in the delivery of power to consumers. Remote monitoring allows equipment to be operated more efficiently and closer to its optimal conditions, and flows and bottlenecks to be better managed by grid operators.

Distribution

18. Optimise energy storage usage

Optimise the usage of energy storage to better manage distribution networks and defer the need to reinforce networks as demand grows.

This will be key to help balance the increasingly localised supply of energy.

Distribution

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Identified dominant use cases

These use cases are for benchmarking purposes only, and have therefore only been developed at a high-level.

19. Planning future distribution network

By bringing together data around demand forecast (e.g. travel, heating), network models, any assets connected (including those behind the meter), upcoming connections, network components, usage conditions, performance data, and more, DNOs can better simulate future networks needs and more accurately plan their medium and low voltage networks.

Distribution

20. Improve demand forecasting

By collecting and aggregating in real time energy consumption information, retailers will be able to understand actual consumption patterns. This will enable better services to be delivered to their customers, and if shared would benefit the overall balancing of the grid.

More granular consumption data can then drive sophisticated analysis and modelling to predict and forecast demand more accurately.

Retail

21. Better services to customers

By utilising aggregated open data on electricity consumption, production by source, trade, CO_2 emissions, transmission line capacity, and price the on wholesale market, new consumer products and services can be developed.

This will enable retailers to lower consumer turn-over and provide more holistic solutions.

Retail

22. Smart demand response

Digitalisation will allow for a greater number of electricity consumers to respond flexibly to signals from the system. Digital connectivity allows appliances and equipment to be monitored continuously and connected to the grid. This connection could be used to shape demand profiles to respond to specific supply scenarios – with consumers and/or their assets receiving and acting upon specific signals and instructions from the network.

Consumption

23. Prosumers

Matching demand to the needs of the overall system in real time opens up the opportunity for millions of consumers and producers to sell electricity or provide valuable services to the grid. With sufficient connectivity it allows the linking, monitoring, aggregation and control of large numbers of individual energy-producing units and consuming equipment - so these can be used to best match demand. These assets could be, for example, a rooftop solar PV system on a home, or a boiler on an industrial site, or an EV.

Consumption

24. Planning of local LCT implementation

Bringing together data from several parties around local distribution networks, demand forecasting, power generation forecasting, and emissions monitoring will enable local actors such as Local Authorities and Smart Local Energy Systems (SLES) to model and understand the best mix of Low Carbon Technology to achieve 2030 net zero goals. A specific Local Authority use case is currently being delivered through Modernising Energy Data Access (MEDA) via Open Energy. MEDA is also exploring EV set up in housing developments.

Consumption

2.2

Case studies

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Case study - Australia: energy system

Context

Australia's energy system is undergoing major disruption driven by the rapidly changing bulk-generation mix, consumer energy resources, and growing interdependence between energy systems. This makes it more dynamic, complex and significantly more challenging to plan and operate safely and reliably. Existing data, models and analysis tools are no longer able to deal with this context.

Established in 2009, Australian Energy Market Operator (AEMO) is Australia's independent energy markets and power systems operator, and system planner.

AEMO, in collaboration with the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and with funding from Australian Renewable Energy Agency (ARENA) Advancing Renewables Program and International Renewable Energy Agency (IRENA) undertook a feasibility study between May 2021 and August 2021. The study looked at developing a cross-domain, and detailed simulation system of Australia's energy systems with digital twins that mirror the National Electricity Market (NEM) and Western Australia's Wholesale Electricity Market (WEM) in real time, and can be used to model proposed changes to every aspect of the grids.

The work has been supported by some key initiatives developed since 2019, including, for example:

- The Integrated System Plan (ISP) is a whole-of-system plan that provides an integrated roadmap for the efficient development of the National Electricity Market (NEM) over the next 20 years and beyond.
- The Engineering Framework – this is a toolkit to define the full range of operational, technical and engineering requirements needed to deliver the futures envisaged by the ISP. The Engineering framework seeks to facilitate an orderly transition to a secure and efficient future NEM system.
- AEMO has published its 2021 Inputs, Assumptions and Scenarios Report (IASR) incorporating five future energy scenarios, ranging from 'slow change' to 'hydrogen superpower', which will inform AEMO's 2022 Integrated System Plan (ISP). The IASR, developed over 10 months of collaboration with industry participants, governments and consumer representatives, reflects stakeholder feedback and significant refinement of inputs and assumptions from workshops, webinars, public forums, other engagements and more than 40 submissions.

Compared to the 2020 ISP scenarios, these scenarios have been refined with respect to the economic and technological change expected over the coming decades. Specifically, the pace of economy-wide decarbonisation, the ongoing consumer investment in distributed energy resources, and the growth of transport and industry electrification.

The five scenarios are Slow Change, Steady Progress, Net Zero 2050, Step Change, and Hydrogen Superpower.

The IASR aims to help investors and policy makers decide on prudent investments in generation, transmission and storage, which can minimise the cost of developing, operating and consuming energy.

AEMO will use these inputs in its future work to identify system improvements in the long-term interests of consumers. Future work includes the 2021 Electricity Statement of Opportunities in August, along with the Draft ISP in December, and the next final ISP due in June 2022.

AEMO engage and communicate with industry including webinars, existing forums, websites and newsletters. They seek support from industry bodies to gain visibility of Connection Tool to increase adoption.

Case study - Australia: energy system

Australia’s energy networks

Australia’s energy network comprises of the transmission towers, substations, poles, wires and pipes which supply gas and electricity to almost every household and business in the country. The infrastructure is owned and managed by a mix of private and government-owned organisations which are responsible for the security and reliability of Australia’s energy supplies.

The networks of Western Australia and the Northern Territory are isolated from the rest of the country, but even so, the electricity grid on the east coast (which forms the National Electricity Market) is one of the largest interconnected electricity networks in the world.

The National Electricity Market (NEM) was created following the formal adoption by the Council of Australian Governments of a national competition policy in 1995. Full operation started December 1998. The previously vertically integrated generation, transmission, distribution and retail functions were separated. The generation and retail sectors transitioned to competitive markets and the transmission and distribution businesses became regulated *natural monopolies.

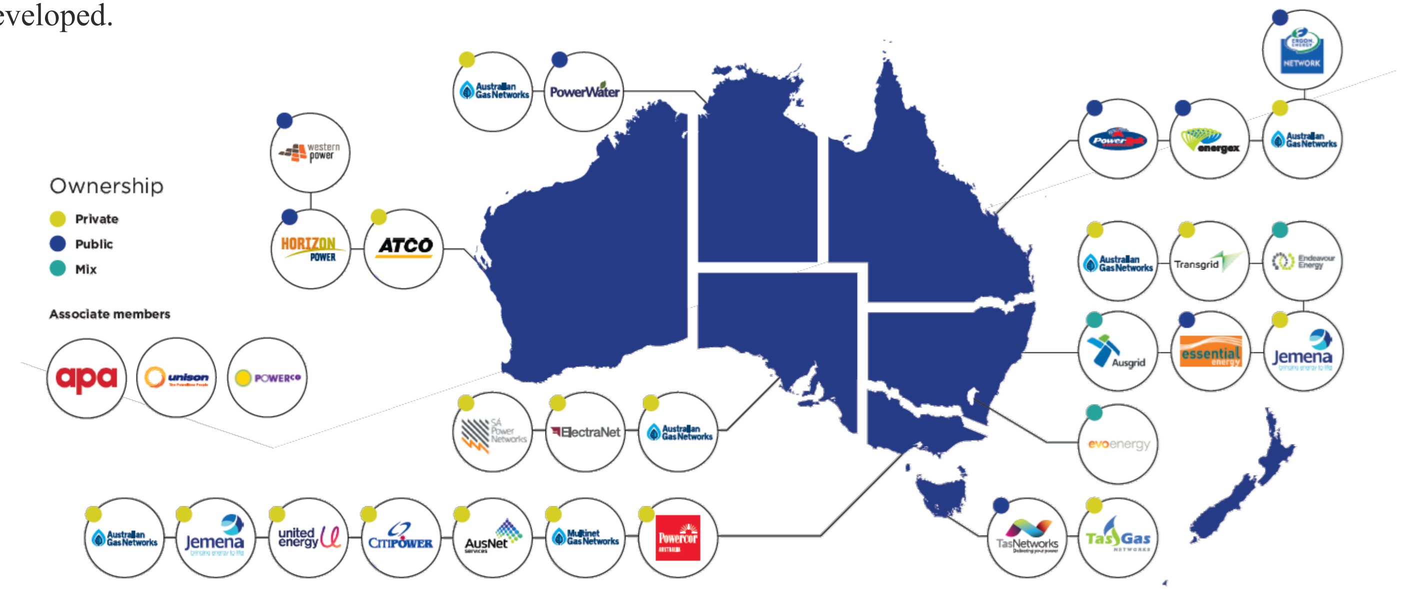
The first electricity privatisations were in Victoria between 1995 and 1997, then South Australia in 1999 and then NSW from 2008. Western Australia and the NT remain separate from the interconnected NEM.

Australia’s gas distribution networks in South Australia, Victoria, Western Australia and Queensland were privatised by their respective state governments in 1993, 1997, 2000 and 2006. The main gas networks across NSW, Tasmania and the ACT were all privately developed.

Electricity transmission

The interstate transmission network is Australia’s electricity superhighway. It is an essential link between power generators and customers, transporting high voltage electricity over long distances.

This system has evolved to connect networks between states. Australia’s east coast now has the longest interconnected electricity system in the world.



Case study - Australia: energy system

Australian Energy Simulation Centre

The Australian Energy Simulation Centre (AESC) is a AUD$12.95million programme to be delivered through a staged approach. When fully implemented, the AESC will encompass data and models of electricity and gas transmission, distribution and fuel dependencies. The AESC will provide an integrated real-world view of the energy system with 'what if?' analytical capability, built and maintained with actual operating data.

In November 2019 the National Energy Simulator Feasibility Study concluded, identified a suite of seven tools that AMEO should develop to ensure the optimal management and operation of distributed generation resources that are connected to the National Electricity Market (NEM).

Two priority simulation tools were identified, and are being developed to support the progress of connected systems. One is the **Connection Simulation Tool** (CST) a cloud-based resource available for developers to test and tune power system models for new generation projects planning to connect to Australia's National Electricity Market (NEM). Which aims to reduce risks, costs and time to approve the connection of new generation projects.

The other is an in-house, **Operations Simulator**, a 'digital twin' of Australia's energy systems which is being developed to further deliver on responsibilities to operate the power system and navigate the energy future. The first of its kind in Australia, the data-informed replica of the NEM will allow highly detailed analysis of the grid's behaviour and help inform future planning, system design and policy scenarios.

Connection Simulation Tool

One of AEMO's principal responsibilities is settlement of the $16 billion-plus NEM which connects the grids of eastern and southern Australia states and territories to create a wholesale energy market. Retailers and wholesale consumers pay AEMO for the electricity they use, and AEMO then pays the generators.

Large volumes of weather-dependent, inverter-based renewable projects are concentrated in areas with plentiful wind and solar resources. However, these projects are often located in electrically weak parts of the grid, prone to poor system strength and thermal and capacity limits. This is presenting unique technical complexities, when combined with regulatory and project-specific issues, contributing to delayed connections.

The tool is being developed to help increase the pace at which Australia is integrating distributed resources with the grid in order for the country to achieve its energy security and decarbonisation goals.

Operations Simulator

Australia's power system is transitioning from conventional synchronous generation, such as coal-fired power stations, to inverter-based generation, such as wind and solar farms, at a pace and penetration level not seen in any other major interconnected system in the world. Due to the difference in how inverter-based plants operate compared to synchronous plants, there has been a shift to electromagnetic transient (EMT) models that more accurately capture and predict power system behaviour. As the NEM power system continues to rapidly evolve, being able to model new operating conditions will be critical to maintaining a reliable and minimally constrained supply of electricity.

A feasibility study was undertaken in 2019, initiated by AEMO and the CSIRO, which prioritised the need for a 'real-time' simulator for an AESC. AEMO is investing in a simulator with the initial capability to better integrate renewable generation and manage threats to the power system, such as bushfire and storms.

Case study - Australia: energy system

Operations Simulator (cont.)

Microsoft have partnered with AEMO to develop the Operations Simulator. AEMO has been working with Microsoft and partner Tata Consultancy Services to transition from a legacy settlement system to its big data Metering Data Management solution built on Microsoft Azure cloud.

Cosmos DB is the main data store, leveraging Azure Kubernetes Services for the application and runtime layers. The simulator will be built in a hybrid platform, using cloud-based access to allow industry, researchers and developers to simulate the grid, which has never been done before. It will also reduce the time taken to run a one-minute simulation from two hours to approximately three minutes without loss of fidelity.

Distribution Network Service Providers

There are a multitude of other initiatives in Australia; some are being run by AEMO to feed in to the overarching AESC objectives, others are being run by research organisations, Distribution Network Service Providers (DNSP).

They support elements of the AESC from community level battery storage pilots; increasing visibility of Distribution Networks; projects and studies to further integrate distributed energy resources (DER) into the electricity system; open data initiatives and regulatory adjustments to support the transitions.

Roles taken by participants

Overseeing the programme AEMO appointed a Chief Digital and Technology officer in 2017. This role leads the technology department, and is charged with working with the rest of the business to develop the systems architecture necessary to manage an integrated, two-way power and gas system.

Best practices used

- **Moving towards open data:** In August 2019, Australia started the move towards an open data economy as the Consumer Data Right (CDR) legislation was passed.

  Consumers have the right to share their energy data with third-party providers. Companies who make use of this, can meet the needs of consumers, capitalise on technology-enabled innovation, and leverage the opportunities that shared data creates.

- **Global collaboration:** AEMO Participate in the Global Power System Transformation Consortium (G-PST). This consortium engages key power system operators, applied research and educational institutions, governments, businesses, and stakeholders from developed and developing countries to accelerate clean energy transitions at the ambitious scope and scale that is required.

  CEOs of six of the world's leading system operators, Australia Energy Market Operator (AEMO), National Grid Electricity System Operator UK, California Independent System Operator (CAISO), Electric Reliability Council of Texas (ERCOT), Ireland's System Operator (EirGrid), and Denmark's System Operator (Energinet) are leading this consortium.

Case study - Australia: energy system

Interoperability

November 2021 the Australia government announced energy providers will be required to share product information via application programming interfaces – software that allows different IT systems to talk to each other – from October 2022, pushing out the deadline by six months.

From November 2022, energy companies will need to provide consumers with access to their usage and connection data, mirroring the requirements by financial institutions for the "open banking" regime.

Benefits & impacts

The benefits and impacts are yet to be observed. It is also expected to encourage data sharing amongst energy stakeholders, including original equipment manufacturers, consultants, network service providers and AEMO project planning, deployment and operations.

- **Operations Simulation Tool:** current modelling tools used to run EMT studies on a power system level can take hours to complete. This tool will allow AEMO to perform these studies in minutes, enabling operational management and power system security.
- **Connections Simulation Tool:** It is anticipated that the CST will provide critical solutions to assist project developers in more efficiently preparing their applications for projects, such as new solar or wind farms, and reduce the time to connect them to the NEM. This will reduce both risk and costs and reduce the iterations/time to complete connections approvals - including AEMO's time to assess and finalise new asynchronous plant connections.

The digital twins of the NEM and the wholesale energy market of Western Australia, will allow all parties to determine where new transmission and distribution infrastructure needs to be planned. Being able to rapidly model outcomes of design changes to the grid in a digital replica that integrates gas distribution and financial settlement markets will serve as decision support tool, and enable acceleration in investment in the right places.

The fast-changing relationships and ratios between penetration of rooftop solar and storage, and development of large-scale solar, wind and storage, and retirement of thermal capacity can't currently be taken into account quickly enough to ensure confidence that supply throughout the grid will stay in balance with demand.

Costs

AEMO is accessing funding from ARENA to implement an AUS$12.95 million project that includes the development of a new cloud-based connections simulation tool to ensure more distributed energy generation resources are connected to the grid for reliability.

The initial Feasibility study May 2019-Nov 2021 was AUS$1.71m. The Connections Simulation Tool is estimated to be a AUS$2.23 million programme.

For the Connection Simulation Tool they anticipate the following cost considerations which are discussed in greater detail in the next Connection Simulation Tool Industry Working Group CSTIWG sessions:

- CAPEX will be funded by ARENA
- The CST will be optional for all users
- The tool usage fees will be charged on a cost recovery basis - price model under investigation
- There will be no impact to industry fees

There is no detailed information on the cost model for the Operations Simulation Tool

Case study - Singapore: digital twin for national power grid

Context

Currently, Singapore national power grid comprises over 18,000 transformers, with more than 27,000 km of underground cables interconnecting over 11,000 substations. Singapore is looking to greener, more diverse sources of energy.

It is acknowledged that power grid operations will become more complex with increasing electrification and deployment of more distributed energy resources (DERs). The National Power Grid digital twin aims to future-proof the power grid within Singapore, to ensure that it is well-equipped to manage such complexities while maintaining reliability of grid operations.

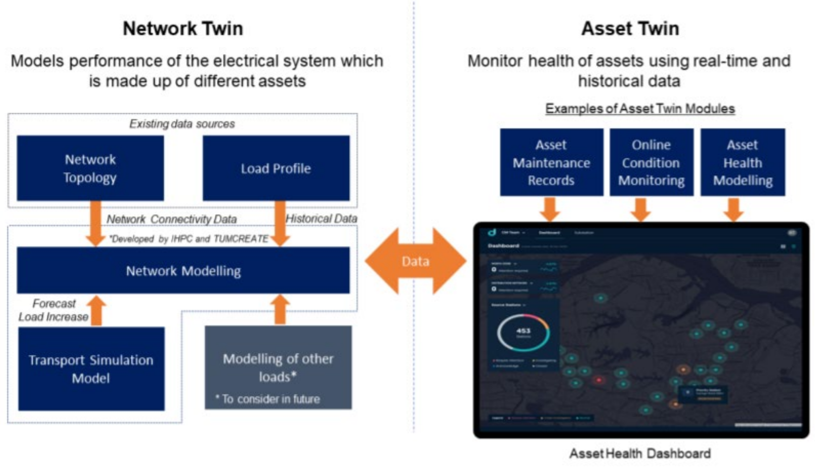
Singapore National Power Grid digital twin is currently in a prototype stage and is expected to be fully developed over the next few years. When fully deployed, it will enable SP Group (SP, the transmission and distribution operator for Singapore) to better plan, operate and maintain the national power grid through modelling and simulations so that the actual works can be carried out in a more effective and efficient way.

Roles and approach taken

The National Power Grid digital twin project brings together key government agencies (the Science and Technology Policy and Plans Office), the energy regulator (Energy Market Authority), the transmission and distribution operator (SP Group) and several research centres of excellence.

The digital twin of Singapore's power grid will comprise two key models that both enable better decisions to be made faster:

- The Asset Twin to optimise the planning, operations and maintenance of SP's grid assets (such as substations, transformers, switchgears and cables). The Asset Twin will remotely monitor and analyse the condition and performance of assets and identify potential risks in grid operations early..
- The Network Twin for impact assessment. This will use modelling and simulation to determine the impact of additional loads (such as new electric vehicle charging points) and distributed energy resources (such as solar photovoltaics and energy storage systems) on the grid. The Network Twin aims to provide a high-level assessment of the impact of demands on the grid and any upgrades required for different scenarios.



Singapore National Power Grid digital twin comprising the Asset and Network Twin. Image Source: Energy Market Authority

Case study - Singapore: digital twin for national power grid

Technology landscape of the asset twin

Research is currently ongoing **across 4 streams** which will leverages available technologies, integration of data and a science based approach.

- **Enhanced System planning** – creation of a risk-based decision-making methodology on a single platform that includes asset heath condition and network criticality to optimize asset planning in a cost and operationally effective manner.
- **Component Design** – delivering a material degradation software model of key components and a digital twin of the switchgear key components to represent the actual degradation characteristics (including at a material level) and determination of the lifespan
- **Failure mode analysis** – developing software solutions which take into consideration the current operations practices, failure statistics, local operating environment and maintenance information to analyse the root causes of failures, to predict future failure probability or lifespan, and to put in mitigation measures to minimise future distribution equipment failure rates.
- **Enhanced Condition monitoring** – developing a novel, cost-effective and advanced online Condition Monitoring (CM) solution to monitor distribution switchgears in real-time and includes trending analysis to advance the utility asset management strategy. The future solution will leverage sensing technology to develop cost-effective Partial Discharge (PD) sensors, Integrated Circuit (IC) technology, AI and ML technologies for PD Detection/PD identification to facilitate switchgear health diagnostics.

Technology landscape of the network twin

The Network twin uses Multi Energy System Modelling & Optimisation (MESMO) an advanced software framework that combines simulation of electrical grids and optimisation techniques to mitigate the grid impact of distributed energy resources (such as photovoltaics) and new types of loads (such as EV charging).

MESMO is a free open source software developed by TUMCREATE as a simulation tool which integrates active distribution grid operation with classic power flow studies (a repository can be found on Github and implemented in Python 3.8). As part of the Grid digital twin project MESMO is being further developed.

MEMSO is equipped with power flow solvers and optimal scheduling algorithms suitable for modelling of unbalanced multi-phase distribution grids and a range of distributed energy resources. It currently supports:

- **Traditional simulation** - non-linear models for electric and thermal grids, DERs and power flow.
- **Optimisation** - convexified models for electric and thermal grids / DERs and solution interfaces for convex optimisation.
- **Market simulation** - bidding strategies of flexible DERs and transactive energy market clearing mechanisms. (under development)

MESMO system architecture comprises various modules for model definitions, problem definitions, plotting, etc.

The mathematical models include solution algorithms. The database interface is for definition of access methods for internal model and scenario data, while the Application Programming Interface (API) is used to define user-exposed functions and orchestration of interaction between subsystems.

It targets different kinds of users – from researchers using MESMO's low-level interfaces to other users such as decision using makers using MESMO's high-level interfaces.

Case study - Singapore: digital twin for national power grid

Best practice

Start from core players: The initiative brings together the core players responsible for energy provision in Singapore across transmission and distribution such as EMA, and SP group. As SP Group is the sole electrical grid and gas grid operator in the country, the Grid digital twin is set from the start to be a nationally adopted initiative and is likely to be able to promote change across the wider energy system having already locked in the support of existing key stakeholders.

Partnership with academia and research institutions: The Asset Twin is led by the SP Group - NTU Joint Laboratory while the Network Twin involves A*STAR's Institute of High Performance Computing (IHPC), Singapore's lead public sector R&D agency, TUMCREATE Ltd (TUMCREATE), research group from Technical University of Munich (TUM) and Nanyang Technological University (NTU) supported by Singapore National Research Foundation.

The collaboration between the research teams and relevant government agencies allows for integration of cutting edge approaches with a new set of national level challenges. This will help create a set of approaches and standards that will best define the technology, modelling, data, methodology to be followed.

Open source technology: The Network component of the digital twin initiative has adopted the use of an open source software framework MESMO. On top of the traditional advantages of Open Source Software (such as simpler licencing management etc..), open software can create wider engagement and help grow the number of practitioners that contribute to further enhance the development. This is particularly critical with solutions that are cutting edge and deal with new complex questions and modelling requirements.

Cross sector data sharing: The choice to utilise MESMO as framework for the Network Twin is allowing Singapore energy grid modelling to be connected into other systems/sectors, in this case transport. MESMO is feeding into Singapore Integrated Transport Energy Model (SITEM) initiative employing advanced capabilities including large scale complex systems modelling and optimisation, high performance and distributed computing, and empirically grounded agent-based modelling of human behaviour to conduct a comprehensive analysis of projected EV charging patterns and energy demand. This has enabled collaborating government agencies and industry partners to validate and refine their planning assumptions on, for example, grid capacity and consumer uptake.

Benefits and impact

The benefits of the Grid digital twin are vast. They include but are not limited to:

- **Improving network planning** analysis and remote monitoring of asset conditions to **save resources** in carrying out extensive physical inspections
- Providing a **more holistic model of the grid** to facilitate planning of infrastructure for different needs (such as installation of electric vehicle chargers, and connection of solar photovoltaic systems and energy storage systems).
- Lowering **carbon emissions**, and providing greater energy **security** and **supply resilience**.
- **Enhanced condition monitoring of assets** and **prioritisation of asset renewal**, by having a decision tool that can identify risks and prioritise grid assets renewal plans.
- Improvement in carrying out network planning analysis by having a **better network utilisation when balancing new or peak electricity loads**.
- **Optimisation of asset investment**, by identifying potential synergies between asset renewal and upgrades for load growth without compromising grid resilience.

Case study - Estonia: Consumer driven energy market through digital innovation

Context

Estonia has a single public gas and electricity transmission system operator (TSO) called Elering. They manage a network of 5,420 km of high voltage transmission lines and 997 km of gas pipelines. The electricity system is connected across borders to Finland, Latvia and Russia, and the gas network to Latvia and Russia.

Elering's transmission networks supplies 60 electricity and gas distribution system operators (DSO). Elering also develops the energy sector's IT infrastructure, which enables solution developments to support the smart grid. This allows energy producers and consumers to analyse the data generated in order to increase the efficiency in energy production and consumption.

The Estonian government decreed in 2010 that all homes and business should have smart meters installed by the DSOs, and that Elering should host a central data hub (called EstFeed) with data supplied by the DSOs. This datahub would be provided as a network service, and was the core pillar for digitization in the Estonian electricity sector. By 2017, 100% of power consumers had smart meters, with 750,000 meters installed and the data hub accepted and audited for security.

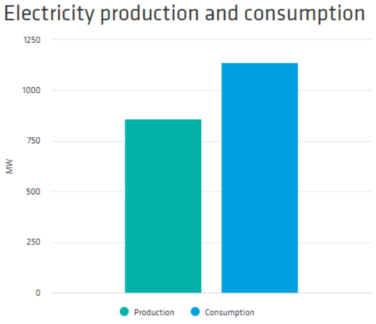
Roles and approach taken

The central datahub (Estfeed) is hosted independently of the DSOs, and provides a single database and structure of hourly information that integrates the retail market. For example, in Germany there are 400 DSO information systems, which is a barrier to selling electricity across the country in an open market.

Estfeed enables energy companies, demand response aggregators, and other service providers to access data from one place in a secure and GDPR compliant way - enabling the retail market integration.

Elering Live is a dashboard of flows across borders for both electricity and gas (see figure), and provides near real time data and historical data, available via API as well as their website.

Elering are also the issuing body of renewable electricity and gas 'guarantees of origin', which provides confidence in the source of energy to the market. They provide subsidies of renewable energy, and are the operator of the transport sector certificates offsetting platform. Currently under development is a renewable energy portal for consumers, so they can see the origin and properties of the consumed energy and CO_2 emissions on an hourly basis.



Estonia's Elering Live website provides electricity and gas near real time data dashboards and feeds and cross border flows . Image Source: Elering

Case study - Estonia: Consumer driven energy market through digital innovation

Technology and innovations

The Estonian Data Hub (Estfeed), with a centralised database and common data standard, has enabled suppliers to provide customers with access to their hourly energy consumption data through apps and websites since 2016. Consumers are warned of price increases, and where their consumption has dramatically risen. The data feeds have also helped DSOs reduce losses through improved fault detection - dropping from 5.7% in 2012 to 4.1% in 2019. Overall the customer satisfaction rating has also increased significantly as a result of the improved information and better service.

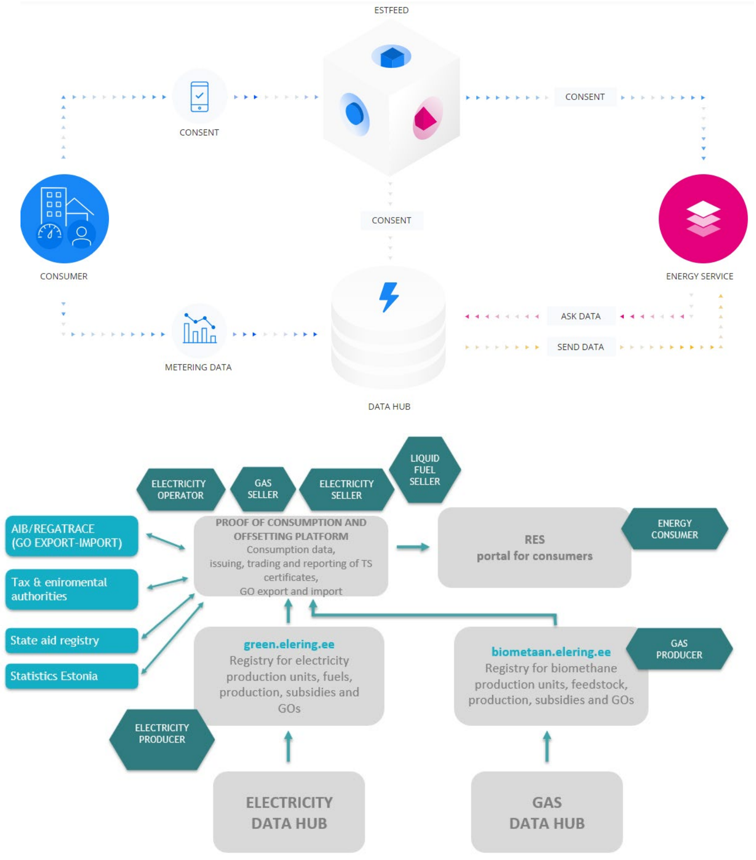
The data sharing platform has a highly secure architecture with consent management built on top of the data exchange platform (see figure). This enables the data owners (end users / businesses) to give permission to different energy service providers to use their data. Elering are also developing a Renewable Energy portal which provides consumers information about the origin and CO2 emissions of the power they are consuming hourly, enabling better informed choices. Other initiatives which have been developed by Elering include an e-Grid map, where the capacity of substation connections is presented within a webmap with the costs associated, allowing businesses and organisations to plan developments accordingly.

Benefits and challenges

With the choice and transparency which this system established within the Estonian energy sector, consumers have far more information, control and therefore choice about their energy consumption. They have access to hourly historical consumption information, and data about their power costs and emissions.

The network operators also benefit from having far more information about outages and performance due to the meter data they can access, therefore improving their service, the ability to inform customers of outages, and ultimately customer satisfaction. It also facilitates preventative maintenance and improved system reliability by analysing node electrical test information.

The certification of renewable energy origin also provides a transparency and improved consumer choice about where their energy comes from, and when it is best to consume it from an emissions perspective. However with all the benefits outlined above only a small percentage of consumers (15%) download the apps, and 5% use them regularly. Nearly 50% of consumers are on fixed price contracts, so are not taking advantage of the flexibility this system can offer. The flexibility and constant price changes have also led to a certain amount of market fatigue.



Estonia's data hub Estfeed provides a secure system with consent to metered data for energy services. There is also central data management for subsidies and certification of energy origin, which is also provided to the consumer.

ARUP

Case study - Estonia: Consumer driven energy market through digital

Best practices

Centralised Smart meter data platform: Estonia are demonstrating best practice in maximising the benefits of having a central data hub for hourly smart energy meter readings with a single data standard. There is a secure consent mechanism to access the smart meter data, which provides mutual benefit to both consumers and suppliers. Consumers receive offers resulting from their pattern of use and preferences, and suppliers can better manage their network and assets, and offer consumers information more quickly should outages occur and reduce costs. Industrial customers can change their production timing based on energy prices or emissions.

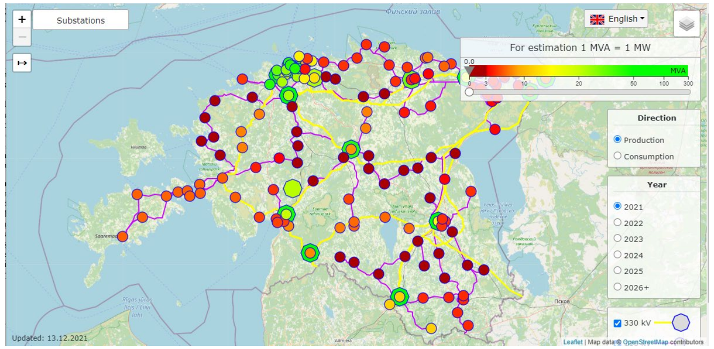
Visualisation of energy data: Elering are maximising the benefit of a consistent data standard and the centralised data management of energy use, certification of origin, and network control, to provide apps, dashboards, webmaps (e-gridmap – see figure) and APIs to the wider sector. This provides consumers (residential and commercial) with the information they require to make decisions about connection (capacity and cost), the energy supplier they use, which time is best to consume energy, the emissions of a fuel mix, and future predicted pricing at increasing frequency.

Predictive Asset maintenance and outage management: DSOs, as a result of having a smart grid, are able to assess the network for resonances. This enables predictive maintenance regimes and improved reliability of the network.

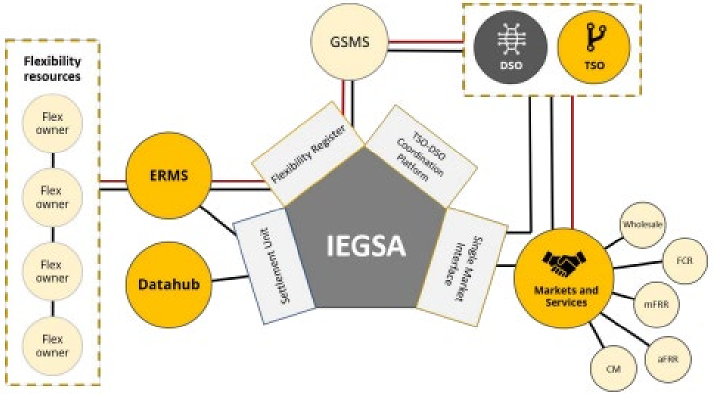
Providing consumers, through applications and SMS, information about outages and expected repair times has vastly reduced the number of enquiries and improved consumer satisfaction. This has all been enabled through improved data analysis and availability of smart meter data.

Promotion of open and flexible markets: Elering have been proactive in the EU to encourage the sharing of smart meter data into one hub by 2025, and have been actively promoting the benefits of their own system.

They have been central to demonstration projects such as the EC funded Horizon 2020 INTERRFACE project, which is piloting a Finnish – Estonian – Latvian common flexible market framework for TSOs and DSOs. They aim to demonstrate how congestion management of distributed energy resources across borders is possible (see figure);



Source: E-Gridmap hosted by Elering provides information about the available capacity of connections to substations https://vla.elering.ee.



Source: INTERRFACE Project figure of the flexible market framework developed to reduce congestion in energy balancing through cross border supply demonstrated in Finland, Estonia and Latvia.

Case study - Aviation industry

Context

Aviation demonstrates excellence in Open Data standards and sharing. The aviation sector, due to the global cooperation and interoperability required to run scheduled international flights, have instigated data sharing initiatives in several areas of its operation. Some of these datasets and standards are open, and others shared as commercial datasets.

There are a significant number of developments throughout the Aviation sector, many of which involved the development of consistent data standards which enable this data sharing. In some areas (such as airport operation) the combination of data can be considered a connected digital twin, but others are confined to the specific asset such as the aircraft or flight traffic control system in isolation.

Approach taken

The following data standards many are based on the Airline Industry Data Model (AIDM) are in place covering aspects of the aviation business:

- **Aircraft monitoring –** Aircraft Monitoring Systems are widely used to ensure efficient, safe operation of aircraft;
- **Air traffic control -** SWIM (System Wide Information Management) and its associated reference system and framework hosted by EuroControl, is to put in place an interoperable air traffic management system;
- **Airport management** - An open data standard developed for smooth passage of passengers and aircraft is called ACRIS (ACI Aviation Community Recommended Information Services) – see next page;
- **Flight status** – Shared using the AMSOpen protocol and API available to developers via SITA;
- **Baggage monitoring** – Several systems use BaggageXML which is an open standard used to transfer baggage information;
- **Passenger traffic and sales -** datasets established by IATA and ARC are available commercially which enables innovation in the industry for analysis of commercial opportunities;
- **Airline schedules -** companies such as OAG provide aircraft and passenger information;
- **Ticketing -** many websites are available to consumers to be able to compare flight costs, CO_2, schedules etc, to make their flight purchase options. This is enabled through the common data standards and sharing of airline schedule / ticketing data.

Roles taken by participants

The roles are varied depending on the application, whether it is commercially available or as an open data standard. Roles will include:

- Standards committees to collaboratively agree on data standards
- Airlines / Airport Data providers (in accordance with standards)
- Aggregators of data for operational use
- Analysts who process the data for market and operational performance / opportunities.

Case study - Aviation industry

Challenges

The Aviation industry is highly competitive and so there is significant value in certain datasets, and hence why some data offerings are commercial and not always from one company or open access.

Lessons should be learnt on sensors and software, as there are grave consequences when they malfunction – for example the Boeing's 737 MAX tragic incidents. Risk assessments in the use of digital twins in critical applications are therefore essential.

Interoperability

The IATA Airline Industry Data Model ensures messaging standards has an industry agreed vocabulary and data definitions, together with a repository of data exchange standards.

ACRIS also represents a series of open data standard and a semantic model structure for sharing of information between systems such as passenger information.

Best practices used

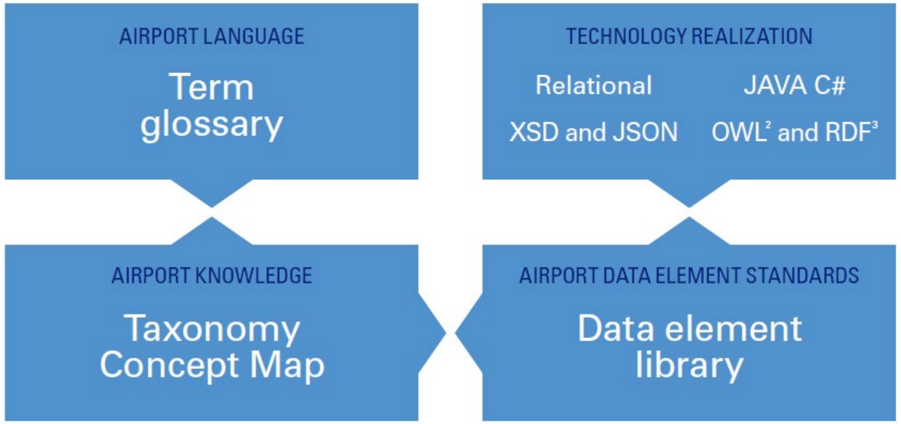
This global industry by its nature must share data in order to operate and remain safe, and therefore has adopted open standards in many areas, to ensure update and interoperability.

Benefits and impact

Each area of the aviation sector described will benefit from the adoption and use of the data standards and systems described. A few have outlined these in their documentation.

ACRIS specifically lists the following benefits for airports:

- Improved economic and environmental sustainability – reduced energy consumption
- Improve situational awareness through access to timely, relevant and reliable information
- Improve operational performance e.g. aircraft turnaround times.
- Improved planning process
- Reduced cost and time in developing applications and systems
- Support provided for initiatives such as APIS Digital twins, condition based monitoring, etc.



Technology realisation layer of the ACRIS semantic model. Image Source: ACRIS

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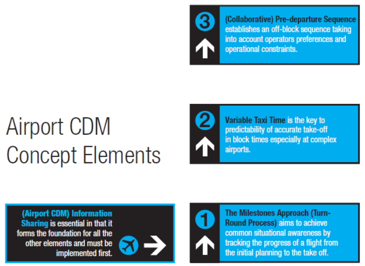
Case study - Aviation industry

Airport Connectivity – ACRIS

The best example of multiple aspects of the Aviation sector coming together is in the airport environment, where you have both passengers, baggage, freight and aircraft schedules which required coordination to operate in a time constrained and pressured environment. A number of use cases demonstrate how having a consistent and connected semantic data model(s) such as this, which is adopted voluntarily, can provide the following applications and benefits:

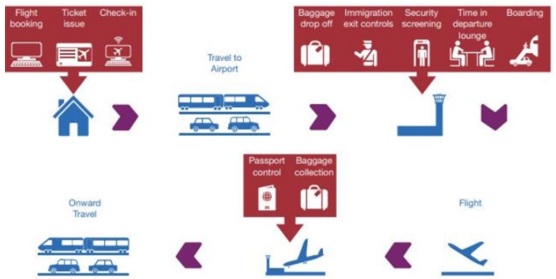
ACRIS
ONE COMMON LANGUAGE FOR DATA EXCHANGE



Airport Collaborative Decision Making

In order to improve the operational efficiency of airport partners, shared data such as flight progress, taxi time calculation, turnaround process etc can reduce delays whilst aircraft is on the ground through a common operational platform. Linked with Airport Operational Control centres this is very powerful.

Image source: Airport Collaborative Decision making (A-CDM) Implementation Manual - EuroControl



Passenger Data Model

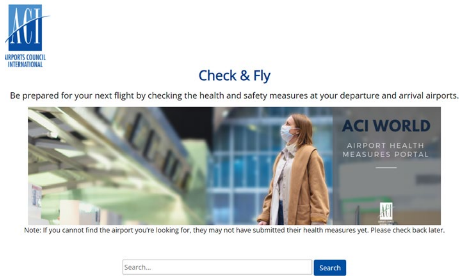
Passenger data is required as a shared resourced between systems within the Airport and with external systems such as Border force systems. Integration of systems can save significant cost if there are standards for the definition and exchange of information throughout the lifecycle of a passenger in the airport.

Image source: UK Government

Baggage Information Exchange (BIX)

The adoption of this data exchange format called BaggageXML can improve the quality of baggage information exchanged between multiple parties, which enables handling of bags more efficiently and reduce baggage costs. This includes movement, storage, sorting, authentication, and security.

Image source: IATA



Airport Health Measures

This data model is available via an API and provides a model for all airports to report their health measures in a consistent way in light of the pandemic. ACI (and potentially others) have set up a Check & Fly portal using this data model to search for contributing airport measures for passengers.

Image source: ACI

Case study - Banking: the Open Banking Initiative

Context

Open banking is a financial services term that refers to the use of open APIs that enable third-party developers to build applications and services around the financial institution.

Open Banking was initiated to make finance more competitive - ending the dominance of banks and allowing new innovators the chance to improve services for the customer. After the 2013 European Commission's revised Payment Service Directive, the UK Treasury announced its commitment to delivering an open standard for APIs in UK banking, to help customers have more control over their data and to make it easier for financial technology companies (FinTech's) or other businesses to make use of bank data on behalf of customers in a variety of helpful and innovative ways.

Today at least 87% of countries have some form of Open API with different countries at different stages. The UK is one of the countries leading the way in open banking innovation and consumer uptake. As of January 2021, more than 2.5 million UK consumers have used open banking-enabled products.

Approach taken

In 2014 HM Treasury commissioned the Open Data Institute, which engaged Fingleton Associates, to investigate the opportunities for data sharing and open data for banks which led to a call of evidence. Following suggestion from the British Bankers Association (BBA), the Open Banking Working Group was created.

The task force was divided in 6 subgroups, each with a different focus. The working group brought together around 150 stakeholders across the banking industry with the aim to produce a framework by the end of 2015.

Following the Open Banking Framework, in August 2016 the United Kingdom Competition and Markets Authority (CMA) issued a ruling that required the nine-biggest UK banks to allow licensed start-ups direct access to their data down to the level of transaction-account transactions. In October 2016, the Open Banking Implementation Entity came into existence to deliver the operational outcome of Open Banking. The entity was also built upon subgroups, each looking at aspects such as the consumer, technology standards and, regulatory and legal requirements. It then took several years for this to be implemented.

Roles

Treasury acted as instigator. Using its' regulator power to bring the conversation to the table was very powerful. Treasury nevertheless retained quite a soft approach throughout the definition of the Open Banking Framework, but it was however present at any working discussions as an observer.

The Open Banking Working Group included representation from across the industry and was led by a co-chairing system which provided strong leadership, and accountability enabling others to take action. Co-chairs were able to provide direction and members were empowered to act on direction and voice course for correction.

Banks and other financial stakeholders were given a very active role in shaping the framework working through topics such as reuse, flexibility, security, customer consents, liability transfer and speed of resolution. After the framework mandate, Banks became core executors and financial sponsors.

OPEN BANKING

Case study - Banking: the Open Banking Initiative

Best practices

Regulatory input: Involvement of the regulator was key. While the Treasury retain a soft mandate and acted as an observer during the formulation of the framework its presence actively encouraged participation from stakeholders.

Governance: In the Open Banking Working Groups Co-chairs have the ability to mandate work to be done. Strong leadership and having processes in place that enforce a decision to be taken enabled momentum to be maintained across advisory and steering groups.

Good data maturity: The good data maturity of the industry is high, which avoided any misconception and time spent building awareness leading to easier reach of consensus (e.g. what is open data).

Open standards: Open standards are key to facilitating data sharing across the industry. These need to become common accepted standards to address legal, intellectual property and, integration considerations that data sharing brings. Utilising open standards also reduces cost to individual organisations since the organisation needs to follow the shared standards as opposed to creating, maintaining and cross-referencing their own methodology.

Clarity around open data: Clarity around what constitutes open data and to whom data belongs is essential to determine how it can be shared and made interoperable. E.g. General Data Protection Regulation (GDPR) changed the understanding of who data belongs to. Previously accounts information was seen as the property of the bank, this is now viewed as the customer's data.

Challenges

Resistance to change: The top led approach created some friction across the industry as banks had to absorb the costs of upgrading their IT systems to comply with the open banking mandate. Upgrades were nevertheless something already needed by the industry due to other regulatory developments (e.g. GDPR) and advancement of technology.

Reaching consensus: Getting stakeholders to reach a consensus when building something new can prove difficult as the enabling context is not in place (e.g. legal frameworks). It is therefore key to have the right stakeholders aligned to the initiative to help facilitate those changes needed (e.g. a change to existing legislation).

High level assessment of likely costs

The Open Banking Implementation Entity was funded by the banks on mandate from government and through the year it saw investments of over £30 million.

Benefits and impact

Open banking demonstrates that creation of cross sector data sharing and digital twins are not solely technological problems. The open banking initiative has enabled sector wide data sharing without developing new technology of its own and in its place creating the framework and standards which enable others to develop their own interoperable sharing protocols.

Open Banking has been a major success in securing positive outcomes for consumers and small businesses. The UK Government reports how it is estimated that by September 2023, 60% of the UK population will be using Open Banking. The ecosystem now extends to more than 330 regulated firms made up of over 230 third party providers of services and more than 90 payment account service providers who together account for over 95% of current accounts.

Case study - Climate Resilience Demonstrator (CReDo)

Context

CReDo is a UK project to develop a digital twin across key services networks to provide a practical example of how connected data and greater access to the right information can improve climate adaptation and resilience. It will develop a digital twin across energy, water and telecoms networks, and look specifically at the impact of extreme weather, in particular flooding.

It will provide a demonstration of how interoperability between digital twins can unlock further value, and how those who operate them can use secure, resilient information sharing to mitigate the effect of flooding on network performance.

CReDo will also therefore demonstrate how a logical framework can be developed for climate resilience investment decisions, based on consideration of a finite number of scenarios that can feasibly be analysed.

Approach taken

CReDo is being delivered through the UK government funded National Digital Twin programme (NDTp), who have partnered with three major UK utility providers (Anglian Water, BT and UK Power Networks).

Using a selected geographical area, the digital twin will incorporate the infrastructure system comprising of Anglian Water's water and sewerage network, BT's communication network and UKPN's power network.

The Digital twin structure consists of a series of layers in which the minimum viable product (MVP) is as follows:

- Mapping of flood depth (or other weather hazard) to an individual assets availability status based on available data and the consequence of the conditions presented with mitigation strategies
- Mapping from individual assets up to system-level outcomes
- A network model, based on dependence relationships derived from the networks' structures (i.e. A requires B, A required B and C, A requires B or C, etc.), including dependence both within and between the three networks

This MVP will help to look at the impact of extreme weather, in particular flooding, on energy, water and telecoms networks and will demonstrate how the Information Management Framework (IMF) of the NDTp supports interoperability of data between organisations.

The MVP is due for delivery in March 2022 where the product will be published however, there are plans for a project extension looking into network restoration and resilience alongside more detailed engineering models of the networks.

Roles taken by participants

CreDo is being delivered through a collaboration with Connected Places Catapult, industry partners and research centres such as:

- Centre for Digital Built Britain (CDBB), a partnership between the Department for Business, Energy & Industrial Strategy (BEIS) and the University of Cambridge which is home to the NDTp and funds the CReDo work.
- Anglian Water, BT and UK Power Networks are key project partners who are providing their asset data on a secure, shared basis to enable a digital twin to be produced for the infrastructure system linking energy, water and telecoms.
- Further industry partners and research centres were used across the programme to consider technical visualization of proposals. Security of data throughout the digital twin, and weather and climate inputs and data.

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Case study - Climate Resilience Demonstrator (CReDo)

Challenges

- Participation – Ensuring partners participate in the programme, and are willing to provide the required information and data.
- Security - any incremental risk associated with sharing of national infrastructure data needs to be assessed.
- Visibility – Ensuring asset owners could see the benefit in sharing data, alongside ensuring the correct legal and governance agreements were in place to enable data sharing.
- Technology – Simulations of large scale flood events is demanding and time consuming.

Interoperability

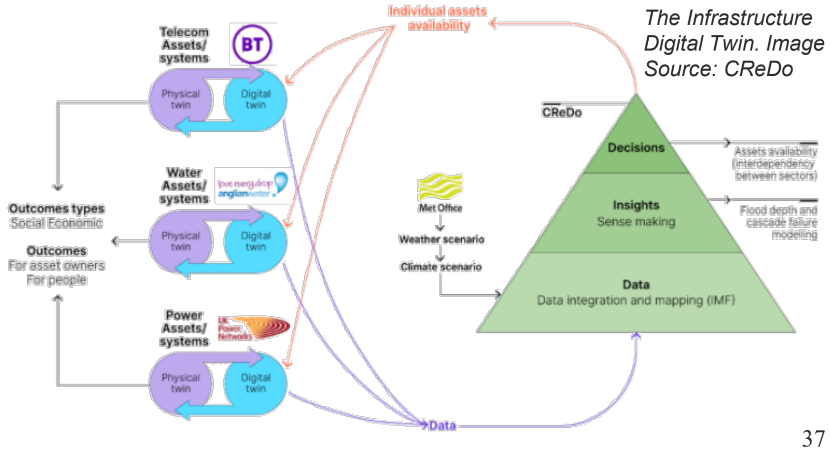
CReDo is looking at how data across multiple industries can be connected and accessed through digital twins to improve climate adaptation and resilience. Alongside this, the alignment of the project with IMF, which is being developed alongside CReDo, and the Gemini Principles, which outlines the values to guide the IMF and the National digital Twin strategy, ensures quality, security and a data sharing framework that can account for all the critical interdependencies.

Best practices used

- Contribution to the development of the Information Framework Management (IMF) which is looking to enable data sharing across connected digital twins in a scalable way.
- Plan to release a public synthetic dataset so others can see the benefit. This can potentially increase participation and interest moving forward.
- Working with Data & Analytics Facility for National Infrastructure (DAFNI) to ensure secure storage of infrastructure data.

Benefits and impact

- CReDo has the opportunity to be utilised for strategic long-term investment in infrastructure alongside emergency management /business continuity planning
- The model can demonstrate how digital twins can help tackle climate change with a large scale understanding of impacts between infrastructure systems in extreme weather events.
- Production of a scalable proof-of-concept digital twin incorporating asset information from key utility providers which can deliver improved climate resilience and service to customers across the participating asset owners.



The Infrastructure Digital Twin. Image Source: CReDo

Case study - Rail industry

Context

Rail demonstrates excellence in monitoring and analysis.

The rail sector has invested heavily in recent years in the greater use of data and systems to improve the performance, reliability and safety of its operation. This has included train borne and in-situ sensors which regularly monitor the network infrastructure and rolling stock, but also the software, data and technology which is required to benefit from the terabytes of data captured. Remote sensing technologies such as imagery, LiDAR, video and IR have also benefited the asset managers such as the UK's Network Rail and metro operators such as Transport for London.

The main focus on digital twins within rail is how best to link the various siloed systems into a decision support and analysis tool. Rail is a complex system of systems each of which interrelate and can have knock on effects on the operation. Its large geographical extent is highly impacted by external factors such as weather, flooding (coastal, fluvial and pluvial) and geology. However the complexity of predictive modelling to determine the appropriate interventions in maintenance is an area where technology can potentially assist.

Approach taken

Network Rail have a number of initiatives to improve the interoperability of information between systems. The Digital Railway initiative has been researching the feasibility of a digital twin approach, especially with the opportunity of ETCS (European Train Control Systems) being trialled and implemented within the UK rail network. ETCS will replace signalling infrastructure, and therefore it will impact many aspects of the rail system.

The most common approach documented is to have both an operational twin and a maintenance twin, joined via a topological network model. Both twins will have their own synthetic planning environment for the testing of future scenarios whether this is a future timetable, or planned maintenance interventions or renewals.

This proposed approach reflects the situation whereby there are existing systems and data standards, which differ quite significantly between the operational and maintenance aspects of the sector. Both can be potentially unified through location using the network model, though not without challenge, due to the way each system references location on the network.

Roles taken by participants

The rail infrastructure manager is usually the predominant driver behind the move to implement a digital twin. A programme of work to focus on the elements which need to be established is funded by that organisation. This is on the premise of achieving a benefits case to reduce cost and run a more reliable and safer rail infrastructure.

The regulator (the Office for Rail and Road in the UK) is also a major driving force behind the progress towards increasing digitalisation through a focus on improving reliability and reducing costs/subsidies.

Other stakeholders are those organisations which run the trains, who will benefit from improved infrastructure and potentially can be part of the solution through provision of data and adding sensors to their rolling stock to aid the process.

Digital Railway

INTELLIGENT INFRASTRUCTURE
DELIVERING THE DATA-DRIVEN RAILWAY

ORR
OFFICE OF RAIL AND ROAD

NetworkRail

Case study - Rail industry

Challenges

- **Siloed systems** – Many of the discipline asset registers and decision support tools in place are siloed to only that specific discipline. They share a referencing system, but rarely is data shared between systems even though they are interrelated. This is a result of the organisation of rail asset managers and their individual asset management planning processes which lead to siloed systems.
- **Lack of automation between systems** – information is still generally exchanged by human interaction through meetings, unstructured documents. Decisions adhere to long-standing rules of thumb or through human to human negotiation. The human operator is the core integrator of vast and complex information sources, relying on tacit knowledge and gut instinct.
- **Different reference systems** – Operational models typically use a logical model using an operational geography of timing points, signal berths and interlockings. Asset system models traditionally use a linear referencing system along the length of track sections. The common language is an asset's location, but this is difficult to accurately define with operational geography to the tolerances required for the combined implementation of a digital twin.
- **Minimal data standardisation** – Whilst Network Rail may have a consistent asset information standard within its different devolved regions and routes, there may be significant differences with other rail infrastructure where there is a need to share data e.g. Transport for London and continental European rail operators. This prevents the sharing of data between wider transport networks. There have been some initiatives such as RailML which provides a standard rail exchange predominantly for the network model and ERTMS a European Rail Traffic Management System standard.

Best practices used

- **Business change:** There is a focus on business change as a key component of system implementation. This is considered essential for the success of the programme by involvement and interaction with end-users within the devolved Routes and other key departments.
- **Adoption of international standards:** the use of international standards such as ISO55000 (Asset management), ISO19650 (BIM), ISO8000 (data quality) and internationally recognised standards like ERTMS are becoming commonplace in the rail sector, in order to align its data management processes and procedures.

Benefits and impact

- Improved business case for schemes, and a greater breadth of options considered.
- Efficient analysis of business investment cases by reduced time to establish simulation models.
- Reduced disruption to services through improved construction planning of schemes.
- Improved data and visualisation to stakeholders, providing a more effective review and decision making.
- Increased efficiency of handover to live operations through data exchange.
- Integrated decision making across network, including rolling stock and crew improving overall performance.
- Continuous improvement approach to timetable planning, benefiting from integrated feedback loop from live operations.
- Better integration of maintenance with operations drives further increase in asset and train service performance.
- Right time condition monitoring and asset degradation history enables preventative and predictive maintenance regimes.

Case study - Rail industry

Rail Monitoring – Intelligent Infrastructure

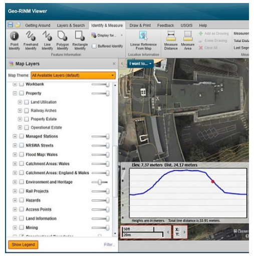
How train borne monitoring information can be combined with asset information to improve the operation and maintenance of Network Rail's infrastructure was central to Network Rail Intelligent Infrastructure Programme. This is achieved by:

1. Rail infrastructure monitoring

A fleet of 'yellow measurement trains' covers the Network Rail network on a designated schedule to capture a variety of condition and geometry information about track, overhead catenary and other aspects.

This data capture exercise generates information available for analysis and assessment of existing condition and its change over time.

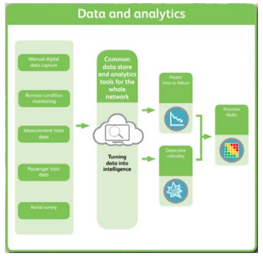
Image source: Network Rail



2. Asset Registers / Visualisation

As with all asset owners, Network rail has a significant investment in its databases of asset information. Significant amount of work to improve and align this data has occurred during and subsequently to the ORBIS programme which commenced in 2011. This has included aerial / LiDAR surveys of the network accessible via a web GIS tool called GeoRINM Viewer the geolocated asset information.

Image source: Network Rail



3. Data & Analytics

The alignment of data from the measurement fleet, imagery and infrastructure asset information is essential to analyse trends over time. This alignment was complex due to a variety of reasons during capture, and so algorithms have been developed to improve the data alignment and therefore the ability to infer trends and root cause analysis.

Image source: NR, II Report June 2021

4. Connected Systems

Intelligent Infrastructure are now piloting the cross discipline decision support tool to provide a more predict and prevent maintenance approach. A big picture view of the railway and its condition support frontline workers by providing evidence for intervention actions. The first version incorporates track and signalling with power and civils to follow.

Image source: NR, II Report June 2021

Case study - Maritime and Shipping industry

Context

Seaports are critical infrastructures to keep supply chains moving and economies across the world functioning. Roughly 80% of goods are transported by sea. A multitude of business and government actors interact in port communities to ensure multimodal flows of vital supplies (medical, food , critical agricultural products, energy streams) and other goods and services reach destinations in time. Port interactions comprise of:

- Physical interactions - such as cargo handling operations, vessel-related services and supplies and, multimodal transfers
- Exchange of data - facilitating clearance of cargo between jurisdictions.

Some port communities are seizing the opportunities of digitalisation and developed into fully fledged ‘smart’ ports. While globally efforts have been initiated to promote wider integration and global coordination, championed both by businesses, regulators and global players.

Approach taken

While many of the biggest port and trades hub are pushing digitalisation in their own contexts, in the global / international arena there are several digitalisation initiatives which look to facilitate a global interconnected maritime supply system:

- **Automatic Identification System (AIS)** - Most cargo and all passenger ships irrespective of size are mandated by the International Maritime Organization (IMO) to carry AIS equipment. AIS transponders automatically broadcast information at regular intervals providing coastal visibility and ship to ship visibility outside coastal areas.
- **FAL Convention** – An international treaty called the FAL Convention enables international shipping to thrive. Since April 2019, the FAL Convention makes it mandatory for ships and ports to exchange data electronically and encourages the use of the so-called “single window” concept, in which the many agencies and authorities involved exchange data via a single portal to facilitate arrival, stay and departure of ships, persons and cargo including notifications and declarations for customs, immigration, port and security authorities.
- **Industry Roadmap for Digitalisation** - The International Association of Ports and Harbours (IAPH) carried out a global survey to assess the current conformity level with the FAL requirement and to highlight any respective challenges that ports are facing. At the end of 2020, this work fed into the IAPH and World Bank joint effort to develop a set of guidance on concrete steps ports can take to accelerate digitalisation.

Other notable initiatives are led by consortiums of different private and public stakeholders such as:

- The International Taskforce Port Call Optimization (ITPCO) which brings together stakeholders from public and private sectors with the aim of mapping out the process of a port call and establishing common shared initiatives to standardize the approach to synchronizing nautical and end-to-end supply chains for cargo and passengers.
- World Ports Sustainability Program which looks to empower port community actors worldwide to engage with business, governmental and societal stakeholders in creating sustainable added value for the local communities and wider regions in which their ports are embedded. One of the key topic of focus is digitalisation .

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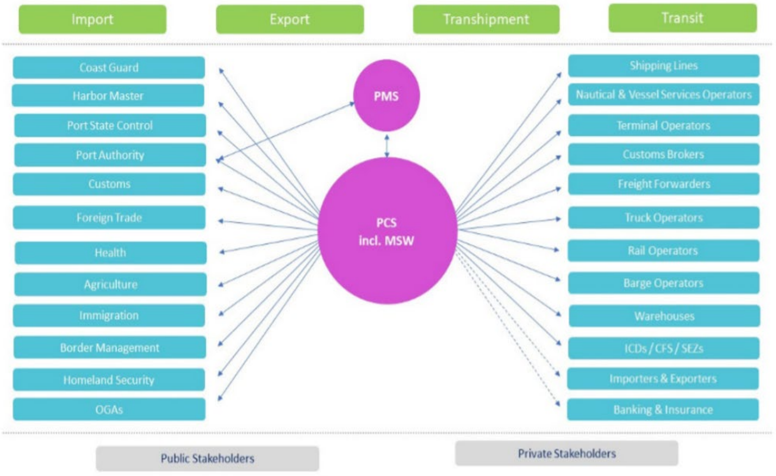
Case study - Maritime and Shipping industry

Roles taken by participants

The roles are varied depending on the nature of the initiative (commercial, regulatory or industry wide). Roles involves a multitude of stakeholders both form the public and private sector.

Apart from regulatory bodies issuing updates to international treaty, most of the initiatives undergoing are either supported by strong national political commitment or by private groups.



Port Community System: Optimal Architecture. Image Source: World Bank "Accelerating digitalisation Across the Maritime Supply Chain"

Challenges

- **Low digitalisation -** Digitalisation of the sector is low with only 49 of the 174 Member States of the International Maritime Organization have functioning Port Community Systems to date, systems which are considered the cornerstone of any port in the current digitalised business landscape. Many ports continue to struggle with larger reliance on human interaction and paper-based transactions as the norms for shipboard, ship-port interface and port-hinterland based exchanges. This is due to the old and fragmented nature of the industry with no big players able to push.
- **Low standardisation -** Uptake of standards and integration with the wider ecosystem is also low. This is also due to a lack of big enough international player to push for change and an historic limited collaboration between shipping, ports, supply chain and trading sectors.
- **Legal** - The legal framework is also a barrier to wider interconnection, as it can frequently depend on competing and/or overlapping public administrations and governmental agencies at municipal, state, or national level.
- **Complex stakeholder ecosystem -** Multi-stakeholder interests in port communities, separate established practices, roles, needs and cultures has created challenges to sharing and reuse of data for efficient electronic reporting and clearance of vessels, cargo, crew and passengers .
- **Cyber Security** - Cyber attacks against port communities have continued to increase in frequency and sophistication. The Port of Los Angeles Cyber Security Operations Centre block millions of unauthorized intrusion attempts at the perimeter of the network every month. Port community members make attractive targets also because so many stakeholders and networks operate within this environment—many with technologies poorly configured against cyberthreats or with unsupported legacy systems. With the push toward further digitalisation, deployments of new technology (such IoT) and wider integration the risk increases even further.

Case study - Maritime and Shipping industry

Best practices

Use of international regulatory bodies to set, maintain and grow industry wide data standards. Since July 2019, the IMO Expert Group on Data Harmonization (EGDH) is responsible for the technical maintenance of the IMO Compendium and for further expanding its data set and data model to areas beyond the FAL Convention, including exchange of logistics and operational port and shipping data.

Recognition that digitalisation is not solely a technological issue, but also as human capital and institutional issues led to the World Bank and IAPH to work on the creation of governance framework to facilitate the necessary political commitment and the appropriate legal, regulatory, and policy oversight across the different disciplines of the maritime, transport and logistics sector. The framework clearly sets role, responsibility stakeholders to help its adoption across the maritime industry.

Ensuring the support and endorsement of the digitalisation of the maritime sector by those players that can provide financing such as the World Bank Group is key when the scale of change required is systemic.

Interoperability

The IMO Compendium on Facilitation and Electronic Business was created in 2019 to harmonized maritime-related data and common agreed standards, to produce guidance for interested parties to automatically map the IMO data set to any of the leading standards and to enable companies involved in maritime trade or transport to create software that can communicate no matter the standard on which they are based.

The IMO Compendium is a tool for software developers who design the systems needed to support transmission, receipt, and response via electronic exchange, of information required for arrival, stay and departure of ships, persons, and cargo to or from a port.

It consists of an IMO data set and IMO reference data model agreed by the main organizations linked to the FAL Convention such as World Customs Organization (WCO) and International Organization for Standardization (ISO).

Benefits and impact

- **Resilience** – As maritime transport carries 90 percent of global merchandise trade, issues have far reaching repercussions. In the short term, these drive shortages and higher prices; in the medium to longer term, they result in slower economic growth, lower employment, and higher trade costs. Being part of larger transport and logistics supply chains and representing clusters of companies and businesses in themselves, ports digitalisation and integration enabling physical and data interactions to occur in a safe, secure, efficient and overall sustainable manner will have a wider spread impact on the resilience many other interconnected sectors.
- **Cost Reduction** – The World Bank recognises how digitalisation of maritime ports and their operation will not only improve their competitiveness, but also reduce the cost of international trade for their respective hosts and hinterland.

Case study - Maritime and Shipping industry

Smart ports

Albeit not a majority, several of the big international port and trade hubs have been digitizing their operation and links to the supply chain and local regions to become more effective and competitive.

As identified by Pagano, Antonelli e Tardo's paper "*A proposal for a comprehensive standardization and implementation plan of digital services offered by the Port of the Future*", digitization initiatives could be categorised by the following outcomes:

- Vessel & Marine Navigation,
- e-Freight & (Intermodal) Logistics
- Passenger Transport
- Environmental Sustainability

Opposite is a brief overview of the vast range of technologies involved in achieving the outcomes listed above.

Vessel & Marine Navigation

- 5G for High-Rate/Real-Time Vessel-Port bi-directional communication;
- IoT for Accurate Bathymetric Data,
- Real-Time meteo-marine monitoring,
- Smart cameras /HD video sources on vessel/port;
- Block chain for retrieving reliable information about cargo;
- AI/ML to aid autonomous navigation, vessel performance (e.g. fuel consumption optimisation).

Passenger Transport

- 5G network for mobility information and journey monitoring, Just-In-Time information delivery and port-vehicles-pedestrians real-time communication
- Integration with Traffic Control Centre of the C-Roads and Railways and Port-to-road full-fledged data Exchange
- In-port Smart and Autonomous Mobility.

e-Freight & (Intermodal) Logistics

- 5G for implementing real-time communication
- IoT for implementing a distributed monitoring network, pervasive monitoring and control of freight in port areas (docks, warehouses, stores), automatic identification of users, vehicles and goods;
- Block chain for retrieving data from port to other inland actors;
- Advance analysis and simulations to aid planning
- Autonomous vehicles
- Smart cameras and drones

Environmental Sustainability

- IoT and other hardware for implementing a distributed monitoring network (e.g. Pollution Control (including CO_2 and noise), Road Traffic Level Control, energy consumption)
- Block chain for storing and securing certified data
- Smart cameras and drones
- AI/ML and simulations for maritime network planning and voyage optimisation to reduce emission
- Dynamic pricing (of all services) to Line and Terminal Operators.

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Case study - Maritime and Shipping industry

Example - Antwerp Digital Twin

The port of Antwerp's digital twin launched in 2018 with the aim to fully control and manage the port remotely. The efforts in Antwerp continues to mature thanks to the gradual influx of data and the piloting and new technology such as a high-performance 5G network, autonomous drones and smart cameras for inspection.

At the core of the digital twin is Antwerp Port Information & Control Assistant (APICA) which provides port authority staff with full situational awareness as it brings together approximately 12 different databases integrated via a data lake enabled by API.

APICA includes real time data gathered from geographic and weather sources, ships, traffic cameras, windmills, drone air pathways, wireless devices and sensors on cranes and other assets, and automated aerial systems that detect oil spills and emergency situations involving people. The intention is to add historical data to run simulations.

Top left: APICA. Image Source: Port of Antwerp

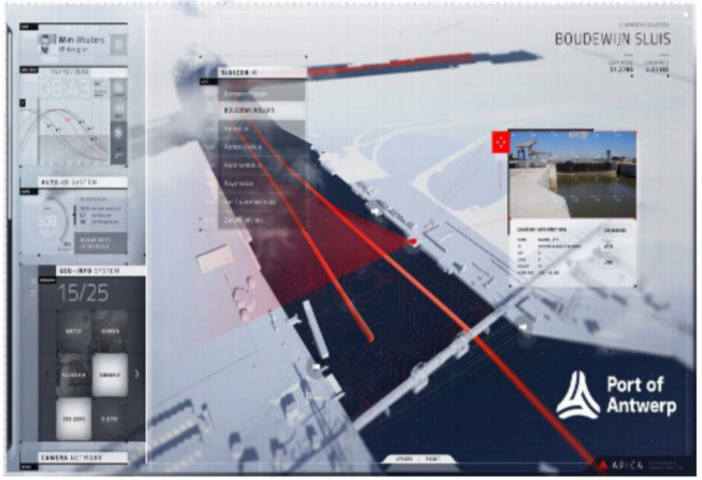
Example - Shanghai Port Community system

Shanghai Port's smart port development comprises four components: terminal operation management, cross-terminal operation management, logistics service, and financing and other auxiliary services.

The smart port links wider into the region thanks to an integrated service platform for the Yangtze River container IWT-Sea intermodal transport service. The platform, as illustrated in figure xx, serves individual ports along the Yangtze River—along with feeder line operators, shipping agencies, freight forwarders, and other service providers to better share information and resources, and improve business.

The Shanghai International Trade Single Window aims to achieve "one declaration, global customs clearance" connects with 22 government agencies and serves 280,000 companies and has reduced the time needed for cargo declaration from one day to 0.5 hours, and ship declaration from two days to two hours.

Bottom left : Yangtze River Container IWT–Sea Intermodal Transport Service Platform. Image Source: World Bank "Accelerating digitalisation Across the Maritime Supply Chain"



Case study - Water industry

Context

The water industry currently faces a number of challenges, such as increased urbanisation, flooding, drought, climate change and the need for a stable water supply.

Digitalisation can help the sector address these challenges by providing real-time information to monitor systems performance and ensure greater confidence in decision-making. The need to handle increasing amounts of data while improving capital and operational efficiencies has directed the attention of the water sector towards advanced digital tools such as operational digital twins.

Digitalisation effort seemed to be most advanced in the UK compared with the rest of the world. It serves over 50 million household and non-household consumers delivering water, sanitation and drainage services through by 32 privately-owned companies. Nevertheless, the water sector remains less advanced than other industries.

Approach taken

The sector has achieved a high level of fluency in digital modelling application as illustrated by the use of:

- Hydraulic models, some extremely detailed and sophisticated support, and planning decisions tools which include other advanced analysis (e.g. what-if analysis and forecasting);
- System-level models, representing bulk water grids, major floodplains or water resource basins, used to vet operational or development decisions;
- Monte Carlo analysis applied in hydrological assessments to take advantage of now readily accessible massive computing power;
- Use of machine learning to identify risks, predict failures and estimate future performance.

In the UK there have also been a few early application of digital twins and wider adoption is underway. These efforts however mostly look at one aspect of the water lifecycle with a confined geographic/catchment scope. An example is Wessex Water smart sewer trial in the city of Bath wastewater catchment.

More holistic application of digital twins are still under research and experimentation across many of the most digital mature water companies (such as in CReDo).

Roles taken by participants

Most digital twin initiatives across the water sector are driven by individual water companies which either under direct procurement or through a partnership approach commission the delivery of the digital twins to third parties provides (specialised companies and consultancies).

Once built, the twin aims to be of use across the entire water management lifecycle by:

- The operator, responsible for the process performance of the plant.
- The maintenance engineer, responsible for optimising technical maintenance.
- The maintenance technician, performing technical maintenance.
- The process engineer, responsible for troubleshooting and optimisation.
- The policy advisor, responsible for long-term thinking in a broader context.
- Management, responsible for framework setting and accountability.

Case study - Water industry

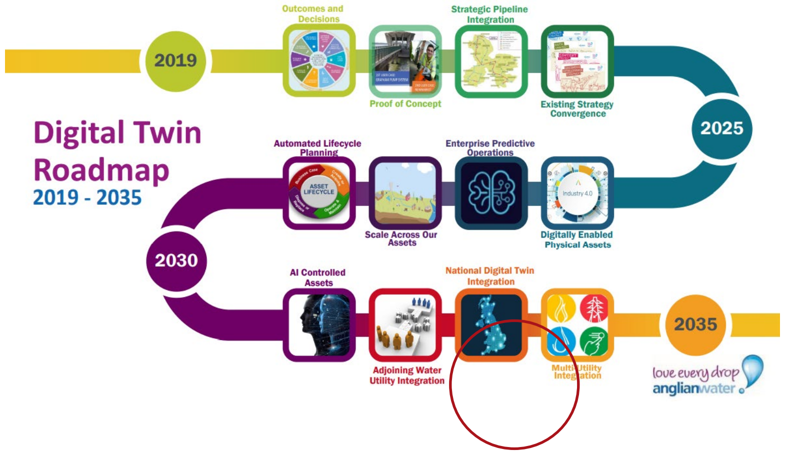
Challenges

- Water and wastewater systems are expansive and complex. This means that the number of sensors needed to represent these networks in real-time would be extreme making the digitalisation of such networks a real challenge.
- There is minimal data standardisation across water asset owners and there are no open data sharing agreement in place. A factor potentially stifling industry wide synergies and innovation.
- Securing sufficient funds, sourcing and installing instrumentation reliably on considerably old assets stock is difficult.
- The historic nature of the asset stock contributes to disruption due to aging equipment and infrastructure which would be capitalising investment over digitalisation or data related initiatives.
- Urbanization and population increase creates pressure on current infrastructure. Similarly natural disasters — floods, drought, cyclones have an impact on the reliability of the water system. Demand might not be met at the agreed standard of service if at all.

Interoperability

In October 2021, the UK water regulator Ofwat launched the “H2Open – Open data in the water industry” publication. The document is designed to ignite conversations across the water industry about open data and its potential to drive efficiencies, catalyse innovation and build trust and transparency.

Certain water utility operators have and advanced awareness of digital twin initiatives. For example, Anglian Water explicitly put “*National Digital Twin integration*” on their digital twin roadmap.



Benefits and impact

Digital twins are intended to be leveraged to manage and operate all types of water-related infrastructure and provide a holistic understanding of a water system. Specifically, digital twins are helpful for the following water utility operations:

- Virtually test new equipment/control sequences, without risk to real-world operations;
- Improve safety by quickly determining workable solutions before going to the site physically;
- Collaborate across engineering, planning, and operations for better and faster decisions;
- Lead to better and faster data-driven decisions making to optimise operation;
- Predict and proactively respond to the future events by combining real time data, data analytics and computer model simulations for planning, incident respond (e.g. pipe breaks) and resilience issues;
- Support operator training;

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3

Benchmarking

Benchmarking overview

Overview

The benchmarking methodology is detailed in Section 1.

Each of the case studies was evaluated against the identified use cases to understand to what extent each case study addressed the needs of the use case. The evaluation used a qualitative scale of **fully met**, **partially met**, **not met** and **will fully meet, will partially meet** and **will not meet**. Quantitative scoring was not possible (see the limitation on page 10).

For the benchmarking comparison the results were aggregated at the energy segment level (i.e. generation. transmission, distribution, retail, consumption). To allow direct comparison between the VirtualES and other energy system case studies, the results were grouped by '**energy sector (country-scale)**' and '**other sectors**'.

For the purposes of the evaluation the entire scope of the case studies were considered, even if components of the scope were yet to be implemented or go-live. For the 'energy sector' results, there is a delineation between implemented and planned. This was not possible for the 'other sectors' due to the information available.

The results are displayed on the subsequent pages, with the full evaluation data given in Appendix A.3.

Interpretating the results

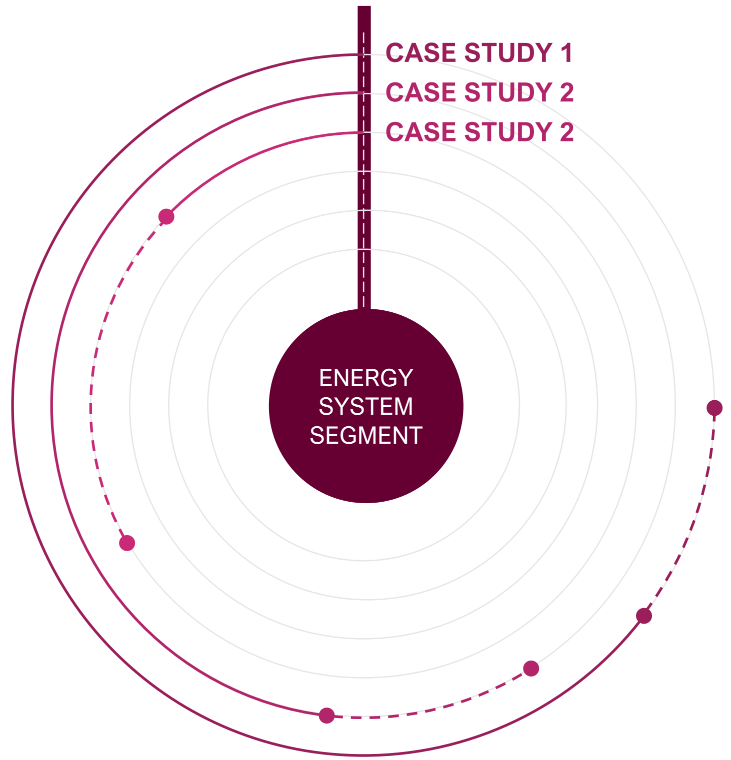
An example of the benchmarking diagram is shown to the right. There are two diagrams per energy segment level, for 'energy sector' and 'other sectors' case studies.

A quantitative score of 1.0, 0.5, and 0.0 was applied to the qualitative scale of fully met/will fully meet, partially met/will partially meet, and not met/will not meet respectively for each use case.

On the diagrams the case studies are represented by the radial rings. The completeness of the ring represents the proportion of use cases that are addressed by the case study. A proportionate scale is used as many of the use cases are applicable across one or more of the energy system segments. The case studies are also sorted by this completeness, i.e. the outer (larger) ring met the most use cases and the inner (smaller) ring met the least.

For the energy sector results, the dashed line delineates the planned scope that has not yet been implemented, i.e. 'will fully meet' or 'will partially meet'.

It is considered that the external benchmarking activity is iterative, and will be periodically revisited as and when more case studies or use cases become apparent.



Example benchmarking diagram

For the energy sector results, the dashed line delineates the planned scope that has not yet been implemented

Benchmarking overview

Comparison of non-energy sectors

Sector comparisons were not always directly obvious when considering the use cases outlined for energy. However there are some relative aspects which have been interpreted in the following way when considering the various use cases in these sectors.

Energy Segment	Aviation	Banking	Rail	Shipping & Maritime	Water
Generation	Manufacture / design of aircraft	N/A	Manufacture / design of rolling stock and traffic management systems	Port energy use and vessel manufacture	Rainfall accumulation and its storage or flow into drainage networks
Transmission	Air traffic control	N/A	The Rail network infrastructure development and maintenance	Port operations and shipping lane navigation	Rivers, pipes and drainage network
Distribution	Airport management including aircraft, passengers and baggage	N/A	Rail network operation and timetable and station operations.	Distribution and management of shipping	Catchment based sharing of water / effluent between treatment works
Retail	Airline ticket offers and purchase	Retail banks customer account information	Passenger information services	Cargo distribution and use of ports.	Water users in homes and businesses
Consumption	Passenger decisions about which airline/route to use based on GHG emissions.	N/A	Passenger decisions on transport options	Consumption of energy by ports	Water conservation measures.

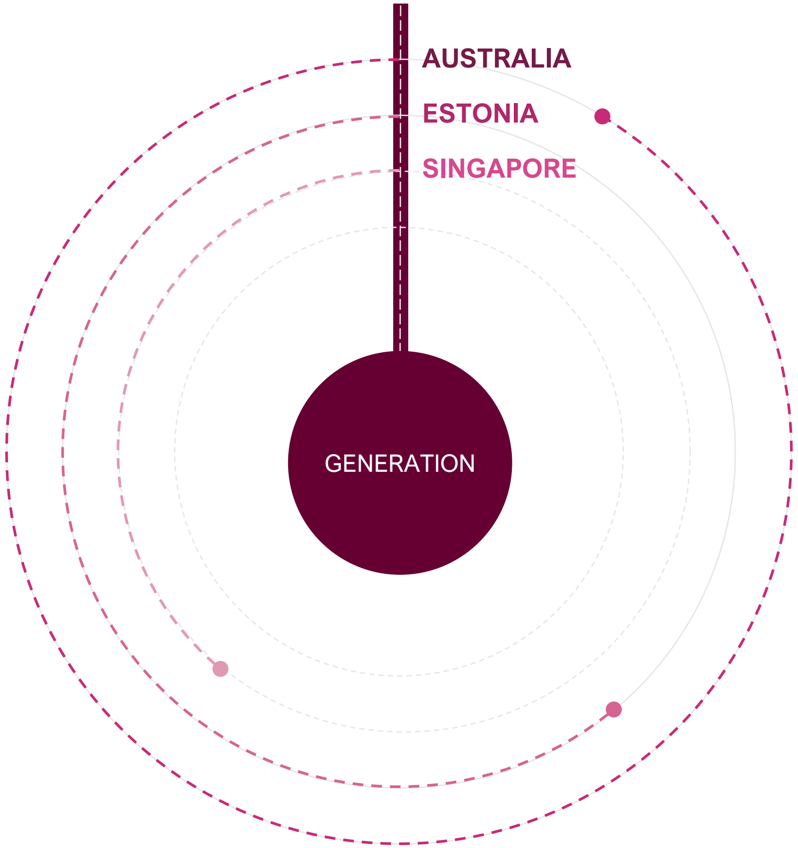
ARUP

Generation - energy sector benchmarking (country-scale)

Generation

Generators are facing a series of new challenges driven by changing energy demand, pricing and shift toward non-carbon intensive production systems.

They are under pressure to optimise their production while safeguarding returns, account for price volatility, assess long-term investments and diversifying into renewable energy generation.



Summary observations

- **Australia:** If fully implemented, the Australian Energy Simulation Centre (AESC) will encompass data and models of electricity and gas transmission, distribution and fuel dependencies. The AESC will provide an integrated real-world view of the energy system with 'what if?' analytical capability, built and maintained with actual operating data.
- **Singapore:** The digital twin for Singapore National Power Grid is looking to use modelling and simulations to determine the impact of future demand and distributed energy resource on the grid to help transition toward net zero and future resilience.
- **Estonia:** Research in progress

The dashed line delineates planned scope that has yet to been implemented

ARUP

Generation - other sectors benchmarking

Generation

Generators are facing a series of new challenges driven by changing energy demand, pricing and shift toward non-carbon intensive production systems.

They are under pressure to optimise their production while safeguarding returns, account for price volatility, assess long-term investments and diversifying into renewable energy generation.

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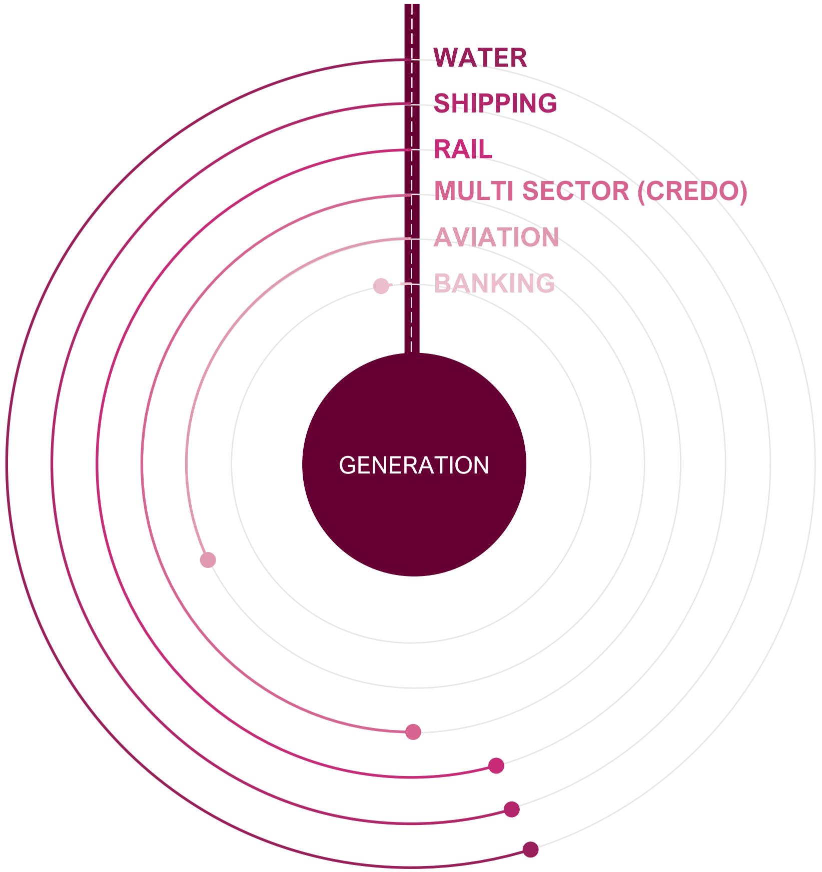


Summary observations

- **Water:** Use of hydrological modelling enables the prediction of water available within reservoirs, aquifers and also what may arrive within the drainage network for management of combined sewer overflows and treatment.
- **Maritime and Shipping:** Several ports across the industry are evaluating the use or better management of sustainable local energy production to decrease their emissions.
- **Rail:** Virtual testing services of rolling stock is used to test and simulate operation during design, and in operation for retrofitting upgrades (e.g. ETCS)
- **CReDo:** Climate Resilience Demonstrator, CReDo, is a climate change adaptation digital twin demonstrator project to improve resilience across infrastructure networks. It is in development, and yet to report findings.
- **Aviation:** Aircraft production makes significant use of digital twins in design and operation to model and simulate aircraft safe operation and efficient use of fuel.
- **Banking:** It was not possible to draw a comparison with the use cases identified under the Generation category. The research undertaken focused on the Open Banking Initiative.

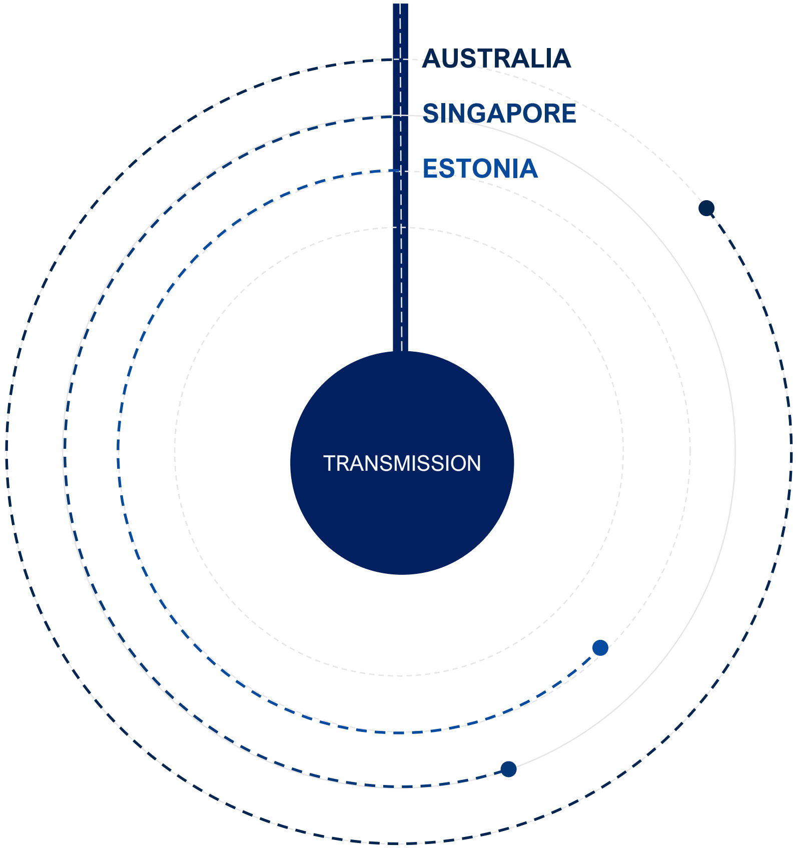
ARUP

Transmission - energy sector benchmarking (country-scale)

Transmission

Transmission networks face major challenges around security, balancing, and reliability of the electricity grid. The increase in renewable energy and new decentralised energy production technologies is disrupting energy supply patterns, which become increasingly intermittent and variable.

This demands new ways to adapt to changing scenarios and raises new challenges around the impact on existing assets, the need for future connectivity, and the pricing of services.



Summary observations

- **Australia:** The Australian Energy Market Operator (AEMO) has commenced the proof-of-concept phase for the implementation of a high-performance simulator for the National Electricity Market (NEM). The initial capability in development is to better integrate renewable generation and manage threats to the power system, such as bushfire and storms. Two tools are being developed; the new generation Connection Simulation Tool to enable faster and more efficient approval of connections applications for new generation plant, and the Operations Simulator, real-time simulation platform which will support effective operation of the energy system.
- **Singapore:** The digital twin for Singapore National Power Grid aims to improve network planning, network utilisation and resilience as well as optimise the planning, investment, operations and maintenance of Singapore's grid assets. This includes both transmission and distribution systems as these are maintained and operated by a sole operator, SP Group.
- **Estonia:** Research in progress

The dashed line delineates planned scope that has yet to been implemented

ARUP

Transmission - other sectors benchmarking

Transmission

Transmission networks face major challenges around security, balancing, and reliability of the electricity grid. The increase in renewable energy and new decentralised energy production technologies is disrupting energy supply patterns, which become increasingly intermittent and variable.

This demands new ways to adapt to changing scenarios and raises new challenges around the impact on existing assets, the need for future connectivity, and the pricing of services.

Summary observations

- **Maritime and Shipping:** There are several example of where single ports are using or in the process of deploying real time asset monitoring (form ships, cargo to doc cranes) & predictive maintenance capability to better optimise port operations.
- **Water:** Increasingly the water network is extensively monitored to manage extreme weather events and also changing demand within the system, so treatment works and the networks can cope.
- **Rail:** The rail network is extensively monitored, and data analysed to move towards predictive maintenance, safe and efficient operations.
- **CReDo:** The impact of a severe event to transmission is being considered. In development, and yet to report findings
- **Aviation:** There is extensive use of data standards and common systems in air traffic control, in order for safe operation and efficient schedules. On board aircraft systems are monitoring aspects during flight also for efficient fuel use etc.
- **Banking:** It was not possible to draw a comparison with the use cases identified under the Transmission category. The research undertaken focused on the Open Banking Initiative itself

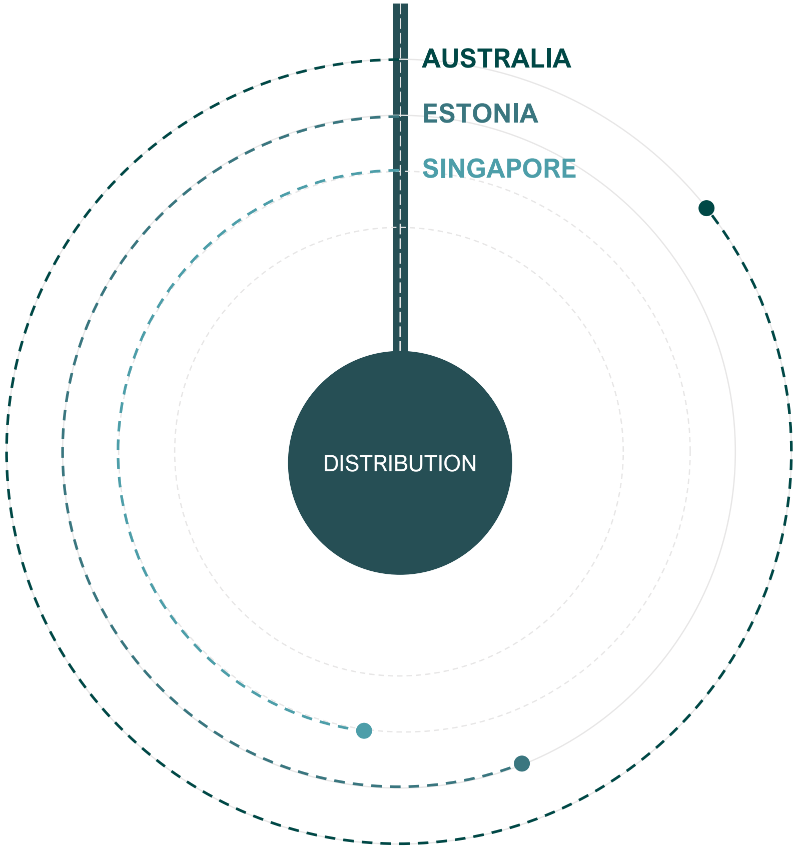
ARUP

Distribution - energy sector benchmarking (country-scale)

Distribution

With more distributed production (electricity generated by small-scale plant and injected into the local distribution grid) and local trade, distribution networks will have to take on responsibility for balancing supply and demand locally, as well as providing security and reliability to the overall system.

DNOs will have to provide increasingly localised trade of energy and grid services and interact with the numerous new and emerging actors, such as Smart Local Energy Systems and prosumers.



Summary observations

- **Australia:** The Connections Tool will help connections applicants, their original equipment manufacturers (OEMs) and consultants, Network Service Providers (NSPs), and AEMO collaborate using common data sets to rapidly verify that prospective generators can be safely connected to the electricity network. The Connections Tool will be developed and rolled out in three phases to progressively larger numbers of users. The Connections Tool Project, combined with the development of an in-house operations simulator, is the first step of a staged approach for delivery of AEMO's Australian Energy Simulation Centre (AESC).
- **Singapore:** The digital twin for Singapore National Power Grid aims to improve network planning, network utilisation and resilience well as optimise the planning, investment, operations and maintenance of Singapore's grid assets. This includes both transmission and distribution systems as these are maintained and operated by a sole operator, SP Group.
- **Estonia:** Research in progress

The dashed line delineates planned scope that has yet to been implemented

Distribution - other sectors benchmarking

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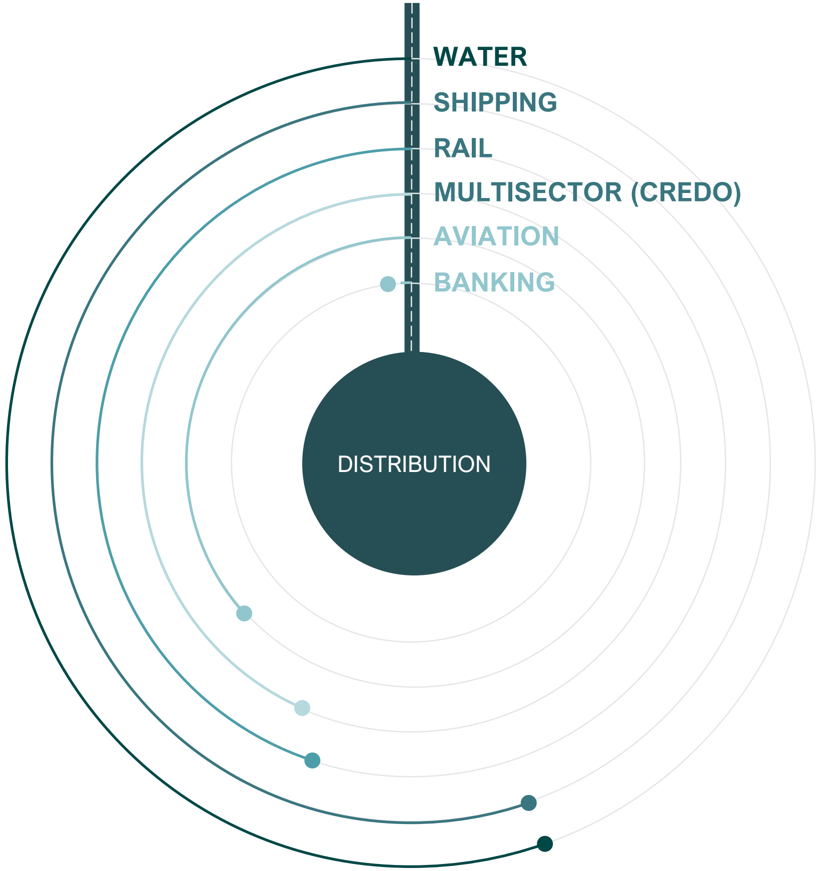


Summary observations

- **Water:** Networks have several monitoring systems in place such as meters and SCADA to monitor performance and plans for shared distribution of effluent treatment are being considered but are still catchment based.
- **Maritime and Shipping:** Several industry actors, particularly port operators, plan for future demands as part of their ongoing management practices. Some ports, such as Antwerp, are deploying digital twins to aid the real time optimisation of port operation. There are also single port initiatives looking to improve the rate and reliability of distribution of onshore and off-shore power supply.
- **Rail:** Signalling systems are being developed to ETRMS radio control rather than physical signals, which are modelled before implemented on track and trains.
- **CReDo:** The impact of a severe weather events was considered in this initiative and how that may affect multiple sector's operations and distribution.
- **Aviation:** In aviation this refers to the routes and airport management. There are several data standards and sharing of key information to allow efficient airport operation and planning for future routes based on passenger demand.
- **Banking:** It was not possible to draw a comparison with the use cases identified under the Distribution category. The research focused on the Open Banking Initiative.

ARUP

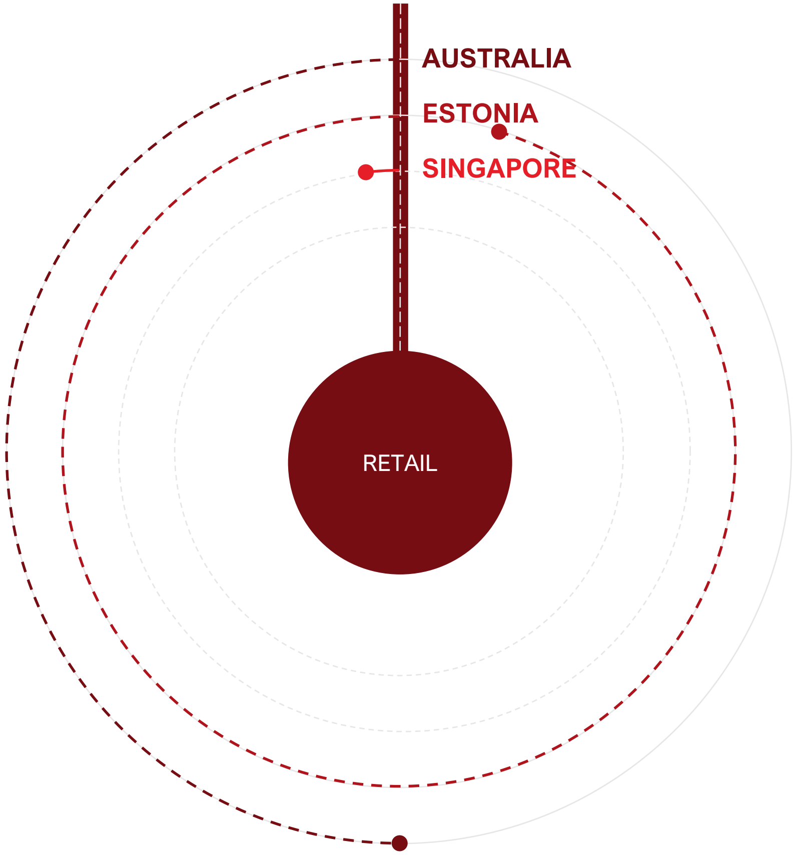
Retail - energy sector benchmarking (country-scale)

Retail

Energy retail is characterised by an increasing volatility of its players. Energy retail profitability is at its lowest in years, while customer-churn levels and new-entrant numbers are at their highest.

New players, such as energy service companies and aggregators, and new forms of energy generation are changing the traditional linear energy value chain.

Additionally, the convergence of industries such as mobility, smart devices, telecom services, and even financial and construction services is re-shaping retailers positioning in the energy ecosystem.



Summary observations

- **Australia:** AEMO's ambitions for the Australian Energy Simulation Centre plan include a partnership with Microsoft developing a big data Metering Data Management solution, and taking advantage of the move to five-minute settlement periods. The landscape is complex, and it's not clear how the tools within the AESC will manage the required changes in energy retail.
- **Singapore:** The scope of the project is currently focused on producing a national twin of the power grid only. Consumption is currently not in scope, so no comparison is possible.
- **Estonia:** Research in progress

The dashed line delineates planned scope that has yet to been implemented

Retail - other sectors benchmarking

Retail

Energy retail is characterised by an increasing volatility of its players. Energy retail profitability is at its lowest in years, while customer-churn levels and new-entrant numbers are at their highest.

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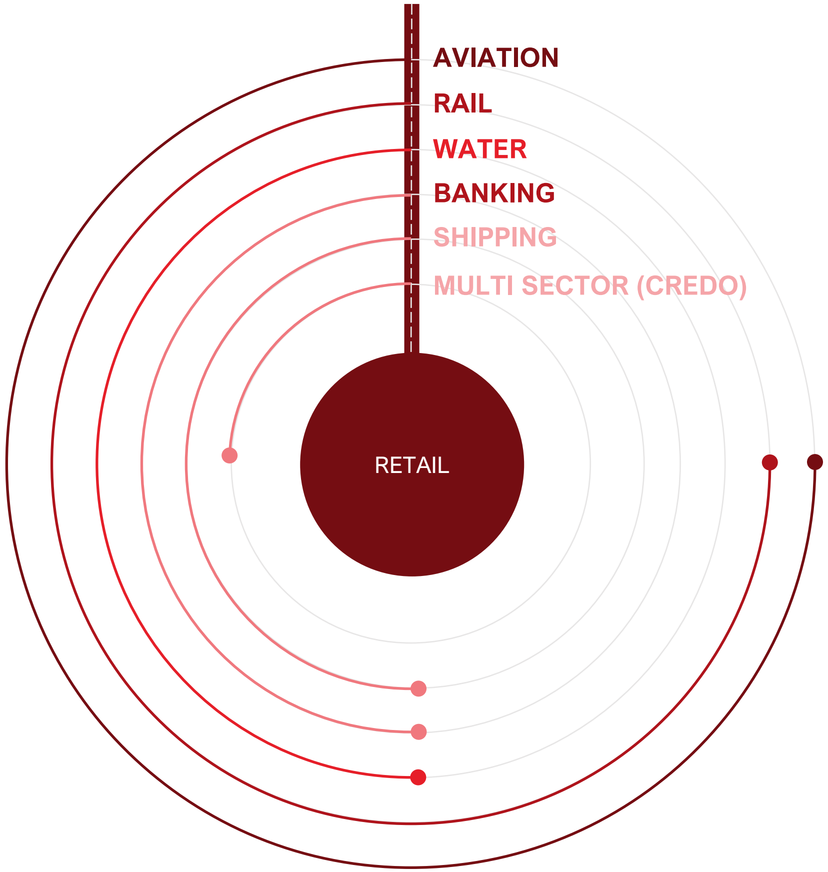


Summary observations

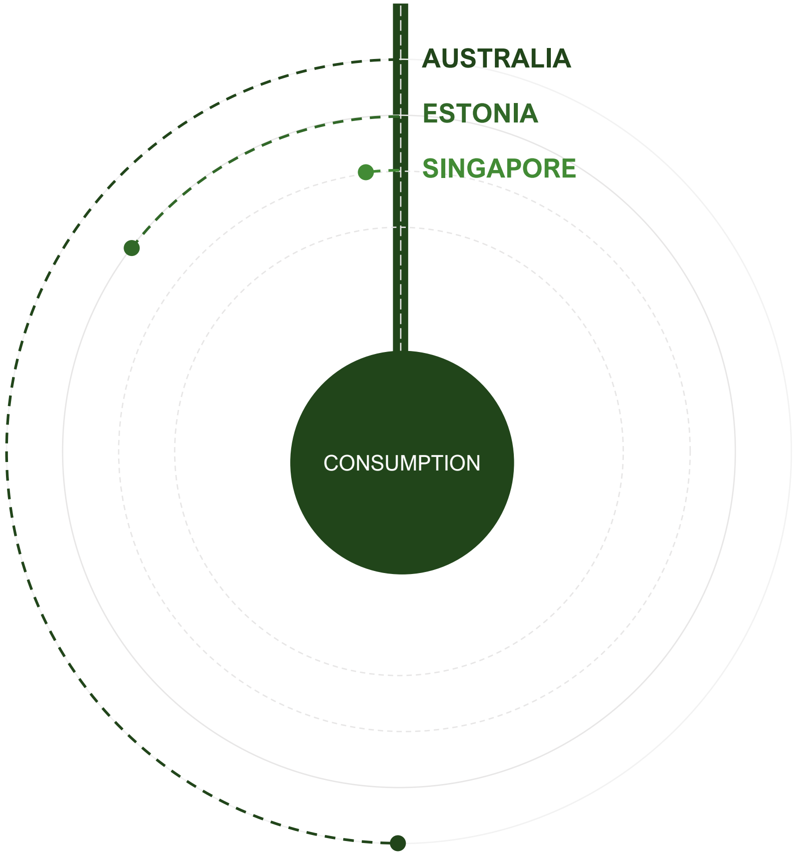
- **Aviation:** Through data standards in ticketing systems it is possible for passengers to access flight information and ticketing from a large number of websites / apps.
- **Rail:** Operations and timing is available to the public through open APIs allowing, for example, decisions on which services to take via apps.
- **Water:** Demand forecasts include factors such as weather, population changes, and industrial / agricultural use and can be modelled and demand planned accordingly. The convergence of alternative water sources is not possible through geographical constraints and service provisions.
- **Banking:** The Open Banking initiatives reframed data ownership around customer account information and introduced an open API across the UK banking industry. This helped customers have more control over their data, and facilitated a marketplace of innovative services.
- **Maritime and Shipping:** Ports capacity, cargo handling, and demand information are key input to the shipping, logistics, and trade industry. There are several initiatives led and supported by international industry bodies aiming to standardise and facilitate data exchange to create a global interconnected maritime supply system.
- **CReDo:** Impact of essential services on the community as a result of a severe weather event is being modelled.

Consumption - energy sector benchmarking (country-scale)

Consumption

Greater automation, the diffusion of Internet of Things (IoT) devices in the residential and commercial sector (e.g. smart thermostats directly connected to the power market and to weather forecast providers), localised energy production and higher deployment of Electric Vehicles (EV) and smart charging systems will all allow further integration across demand and supply. This will unlock greater cost savings for individual consumers and the system overall.

The distinction between traditional suppliers and consumers will blur further, allowing for a more interconnected and localised energy system to emerge.



Summary observations

- **Australia:** There are consultations and pilot projects and in South Australia, New South Wales and Victoria. These are focusing initially on demand response initiatives with air conditioners, electric vehicle chargers, pool pump controllers, and electric resistive storage water heaters.

  The Distributed Energy Integration Program (DEIP) is a collaboration of government agencies, market authorities, industry and consumer associations aimed at maximising the value of customers' distributed energy resources (DER) for all energy users.

  The Connection Simulation Tool (CST) aims to reduce risks, costs and time to approve the connection of new generation projects.
- **Singapore:** The scope of the project is currently focused on producing a national twin of the power grid only. Consumption is currently not in scope, so no comparison is possible.
- **Estonia:** Research in progress

The dashed line delineates planned scope that has yet to been implemented

Consumption - other sectors benchmarking

Consumption

Greater automation, the diffusion of Internet of Things (IoT) devices in the residential and commercial sector (e.g. smart thermostats directly connected to the power market and to weather forecast providers), localised energy production and higher deployment of Electric Vehicles (EV) and smart charging systems will all allow further integration across demand and supply. This will unlock greater cost savings for individual consumers and the system overall.

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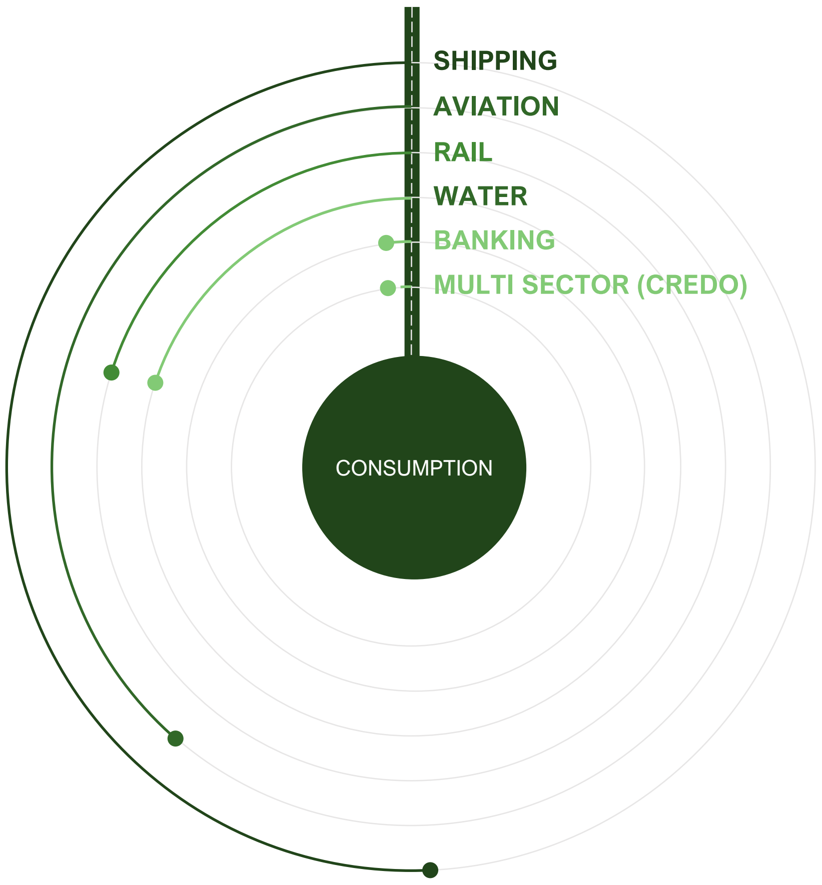

Summary observations

- **Maritime and Shipping:** Port community systems are being developed to provide a single window to manage port operations, and real time demand management to offer Just In Time services.
- **Aviation:** Passengers can select flights based on CO2 emissions which are published alongside cost and schedule information.
- **Rail:** Service and ticketing information are available within transport applications, allowing the user to decide which service to use in their journeys.
- **Water:** Limiting consumption is necessary at times of water shortage (e.g. hose pipe bans in periods of drought). The sector promotes water saving actions/devices and water meters for accurate usage profiles.
- **Banking:** It was not possible to draw a comparison with the use cases identified under the Consumption category. The research undertaken focused on the Open Banking Initiative itself and did not carry out a review of the vast downstream of FinTech applications that emerged from the competitive customer service market it enabled.
- **CReDo:** These use cases is not specifically relevant to this initiative other than improved information to consumers should services be impacted by such an event and potentially mitigation strategies adopted in advance.

4

Lessons applicable to the Virtual Energy System

Lessons applicable to the Virtual Energy System overview

Overview

The research, expert interviews, and benchmarking assessment process highlighted several socio-technical lessons that could be applicable to the development of the Virtual Energy System.

It is considered that these lessons are not an exhaustive list, and that more lessons will become apparent as the domain of connected digital twins matures and further information becomes available on the case studies.

The socio-technical lessons have been grouped by the following categories, as summarised to the right.

- **People**
- **Process**
- **Technology**
- **Data**

The full details are given on pages 63 to 69:

People

- Skills
- Capability
- Key roles

Process

- Government
- Regulatory involvement
- Political support
- Transparent Engagement
- Contractual relationships

Technology

- Cyber security
- Computing power
- Connectivity
- Security and privacy
- Trust in distribution
- Open software
- Ease of reliable interoperability
- Modelling
- Cost of technology

Data

- Data best practices
- Data completeness
- Harmonise existing data standards
- Interoperability
- Common taxonomies and ontologies
- Data visibility

People

1. Skills

In all countries and sectors starting, or on, the journey to implementing digital twins, there is a need for digital and data science skills. There have been large investments made by infrastructure owners in data science and cyber security teams in order to progress the digitalisation of organisations. These skills are however in short supply and not always attracted to work in the sector.

Skills though are not just in the digital space, there is a large business change often which is required to move towards a more digitalised and connected sector. This requires business process definition and training - which could be provided by operational change consultants. A skilled senior leadership is also essential to enable to ascertain value and viability of initiatives as we well as understand the resources and capital required.

2. Capability

It is clear in sectors where there was previously little digitalisation that a significant effort is required to capture information into a digital form. Where digital records exist there is also significant effort required to connect previously siloed systems.

There is a clear need for a business case to adopt and develop skills in this area. There may not be enough skilled individuals in the field available to organisations to complete the complex data modelling / manipulation and system development that is potentially required. Partnerships with established innovators can reduce the risk associated with exploring new technologies and approaches.

3. Key roles

There will be many stakeholders in all examples of a connected digital twin implementation, due to the wide range of benefactors, and contributors to its success. These stakeholders will be within academia, public, and private sectors, and so will respond to different incentives to adopt, contribute to, or implement the change.

The role of an integrator or coordinator has to be taken on by a central body, for example AEMO which has the sector wide reach, or by an independent body or think tank such as the Open Energy initiative or CDBB and the National Digital Twin programme.

Government has a significant influence on energy organisations through its policy on sustainability and net zero carbon, and the timescale of its commitments.

Depending on the nature of the sector, its regulation, and the priorities for managing the national network's infrastructure condition, the regulator plays a key role in instigating change. The regulator are instrumental in incentivising the digitalisation of assets and systems; requiring roadmaps for planning and implementation and working with government to effect legislative changes where these would enable and benefit progress.

However, the main drivers for change must come from within an operational organisation, as they fund and adopt the business change. This will need to be driven, in the most part, from the business case for change. They will need to meet the requirements of the regulator and respond to shifting energy markets, but significant benefits can come from operational efficiencies and improvements through digitalisation.

Different sectors and countries which have started on the journey of implementing digital twins often have done so through partnerships with innovation leaders and implementing pilot projects.

Initiatives such as Open Energy and CReDo are essential to demonstrate the benefits of connected data and ecosystems of digital twins, before the investment and collective movement towards implementation will exist.

Process

1. Governance

Across most of the case studies investigated, a well-established governance framework is at the core of the initiatives. A governance framework helps participants to execute their responsibilities by defining delegated limits of authority and clarity around role and responsibilities. It establishes effective escalation routes for issues and change requests.

In some instances, the governance landscape has been defined by a focused group of actors, particularly where either governments or regulators are the initiator of initiatives (e.g. Open Banking in the UK, and the energy sector digital twins in Singapore and Australia).

Alternative approaches observed include collaboration with industry players driving the creation of governance frameworks around specific purposes from the bottom up, such as in the aviation and shipping industries.

Regardless of the provenance, critical factors for success include:

- The ability to involve all the key stakeholder in a structured process;
- Consistent and regular communication on the process and progress.
- Evolving and communicating the status of the governance framework as the needs of the initiative evolve throughout the entirety of its lifecycle.

Leveraging existing governance arrangements and building on those is also an effective way of ensuring the right engagement and identifying critical dependencies.

It is recommended that National Grid ESO explore synergies with the Open Energy initiative, where advisory groups bring together key actors across the energy sector, as well the National Digital Twin programme, Energy Data Task Force, Energy Digitalisation Task Force, the Modernising Energy Data programme, and the Data and Digitalisation Steering Group hosted by the ENA.

Finally, a governance framework that is to be used by a complex stakeholder ecosystem, such as at an industry scale, should be designed around a clearly defined scope as it will not be possible to satisfy all players' agendas. In the case of Open Banking a successful approach was to solely prioritise customer needs.

2. Regulatory Involvement

The active role of the regulator is an almost consistent influence identified across the case studies.

The regulators involvement is critical as either initiator, sponsor, facilitator, enforcer, and/or observer. It is determined that these initiatives need to thrive in pre-existing regulatory contexts and consolidated market behaviours.

The support and collaboration with the regulator is therefore essential to create and keep momentum, enable the change required to support new initiatives and enforce new and innovative business planning.

As an example, in the UK banking, global aviation, and global shipping industries the involvement from national and international regulators facilitated the pace of innovation and removed legal uncertainties. This was assisted through the standardisation of key aspects, such as data sharing protocols, and by setting directives for key enablers such as data openness.

It is recommended National Grid ESO determine how to best continually engage with the regulator (Ofgem) to support the ambitions of the VirtualES across the GB energy system.

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Process

3. Political support

Political buy-in is an essential enabler across the case studies researched.

Government support (including financial investment) is a recurring characteristic of early stage initiatives such per the case of the Singaporean and Australian initiatives. This is usually done through funding of preliminary research or working groups.

Wider industry support is key to operationalisation and successful adoption of initiatives. This is often driven by “capstone” players, i.e. players which are able to propagate changes across an industry. It is considered that National Grid ESO has the potential to play this critical role.

There is often a financial dimension which signals wider industry support. This is crucial due to the scale of change. In the case of UK Open Banking, banks financed the delivery of the initiative, while in other sector international industry bodies finance the forum for engagement.

4.Transparent Engagement

Openly engaging groups of stakeholders has often being used as an effective way of driving change and adoption as it can facilitate visibility, trust creation, and shared ownership. These groups often assumed the role of:

- Advisory groups, providing advice and feedback such as in Australia and Open Energy
- Working or development groups, where work is carried out, such as in Open Banking and aviation.

Key factors of successful implementation of these groups have included:

- Setting out and communicating a clear scope
- Involving stakeholders across the ecosystems.
- Appointing a strong role for the Chair and Co-Chair of the group with a track record of delivery. Enabling and empowering those roles to make decisions, mandate work, and push agreement.
- Active involvement of the regulator or governmental actors, at the least as observers. In Open Banking, whilst the regulator was present and would provide offline steers, it was retrospectively considered that a more active role of the regulator would have been welcomed. This potentially did not happen for fear of industry backlash.

5. Contractual Relationships

In competitive markets, one of the biggest barriers observed was the need to stipulate new contractual relationships.

A prominent example is the sharing of data. In certain industries, data is withheld and constrained by NDAs, which hinders progress due to the resources required to repeatedly manage the process.

In the case of CReDo, the data sharing agreements took a significant amount of time to broker and had to be developed as bespoke agreements, so cannot be easily reused.

It is recommended this is addressed by adopting open data principles and foster an ecosystem of data sharing between key stakeholders. For example, in the Open Banking initiative the use of open data standards helped broker data licencing and reusable agreements in the banking industry.

In Energy progress has been made. Ofgem have introduced Data Best Practice guidance, the Energy Data Task Force introduced the “presumed open” principle for energy data, and Open Energy are developing standard licenses for commercial data.

Technology

1. Cybersecurity

The application of IoT and asset sensor hardware is key to achieving two-way integration between an existing physical object and its digital twin. However, the rapid growth of IoT raised the threat of cyber-attacks. It is essential that the implementation of IoT or other connected hardware adheres to the latest practises, legislation and security regulation. This is fundamental to protecting critical infrastructure and consumer data.

Implementation must follow international and industry standards and protocols and evolve to follow future specifications, and involve the relevant Government bodies (i.e. CPNI in the UK). The shipping industry is at the forefront of promoting robust cybersecurity practices due to a history of high-profile attacks.

2. Computing power

Implementing ML and other complex simulation & modelling techniques, and planning for AI as part of a digital twin landscape, requires high performance infrastructure which can fulfil processes consistently - despite uneven demand patterns. Computing capacity needs to be scalable and flexible as the digital twin will evolve over time. Cloud computing with its on-demand GPU services presents the optimal current solution.

3. Connectivity

Connectivity challenges are still prevalent, particularly when trying to achieve real-time monitoring of large processes of assets. This is due to the high volumes of sensors connecting at the same time - which can lead to outages, software errors, etc.

It is recommended that the connectivity layer, whether a fibreoptic backbone, wireless networks (WLAN and 4G/5G mobile networks, low latency and local network) is part of the testing, staging, and validation environment when developing connected digital twins to ensure end-to-end validation of new services and connections.

4. Security and privacy

With the vast flow of data used in digital twins, it is essential that data is collected, sorted, organised, and stored to ensure it can be accessed, used, and reported on securely. Enforcing clear authorisation protocols for data usage, as well as providing data integrity and immutability, are key for securely storing data.

Security and privacy are a fundamental design principle particularly for commercially sensitive or national infrastructure data, which can become a significant security risk - as demonstrated by CReDo.

5. Trust in distribution

Digital twins need a trusted source of data regarding an assets' information, behaviour, and other insights. Therefore, as part of the data governance landscape, data management components are considered critical elements of the connected digital twin ecosystem.

However, given the complexity and variety of data sources involved in the creation of connected digital twins across stakeholders (e.g. high number of legacy systems, new sensors, third party data), it is conceivable that enterprise style Master Data Management (MDM) and data virtualisation solutions might prove too difficult to achieve at the proposed scale of VirtualES.

Learning can be taken from the Open Banking initiative as well as the global aviation, and global shipping industries. The use and enforcement of global standards across the ecosystem through shared identifiers, way of registering data, and quality control techniques ensures that those consuming different data assets receive a consistent and integrated experience.

The use of data will need to be facilitated by tools that track data provenance, lineage, and versioning; and tools for distributed data governance, data cleaning, and data integration.

Technology

6. Open source software

It is recommended that open source software is explored and evaluated as far as possible.

Key characteristics of open source software - such as simpler licencing management, transparency of the source code, and flexibility - could encourage trust across the energy ecosystem and lead to wider engagement and connectivity. It also protects against software obsolescence and vendor lock-in.

The use of open software can enable wider innovation engagement and help grow the number of practitioners that contribute to further enhancing development. This was seen with the Singapore National Power Grid, where the network modelling component uses an open source software framework based on leading international research efforts.

The use of open source software would be advisable when exploring complex modelling requirements. It is recognised there could potentially be intellectual property challenges and considerations to address with some solution providers.

7. Ease of reliable interoperability

Software and data interoperability and ease of integration and connectivity should be a key focus for the technology system architecture. It is also important for the technology system architecture to account for capacity and the potential need for high performance.

Clear structure and documentation around the architecture of software interfaces (e.g. API, API Gateways, microservices) will be critical in enabling connection and reuse of components across a connected ecosystem.

The Open Banking initiative establishing open API standards across the UK banking industry is a good example of how to achieve this. This is also being demonstrated and addressed through the Open Energy programme.

8. Modelling

Modelling is a key component for digital twins and can involve simulations, applications of AI and Machine Learning, and other data analysis techniques - as seen across the case studies researched. However, there is no standardised approach to modelling when it comes to digital twins.

This can make it difficult for domain users to understand and trust the outputs.

Validating models, by verifying they are performing, will be key to ensure user confidence.

9. Cost of technology

It is considered that the majority of technology required to created ecosystems of connected digital twins already exists.

The cost will be a function of the number of components in the digital twin, the connections among the components, the complexity of the modelling implement, the amount of hardware deployed, and the know-how required to build the digital twin.

Re-use and connect’, versus a ‘build’ approach would help reduce costs. For example, the use of the OpenAPI in Open Banking to connect directly to customer account data was chosen instead of the creation of a master national copy of the data.

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Data

1. Data best practices

The Open Banking example has demonstrated that with the right approach and incentives a sector can move to a common open data standard for sharing information.

The Open Energy initiative has evolved from the founders of Open Banking, and is therefore able to adopt, adapt and evolve many of the principles and key lessons. Nevertheless, it is relatively early in its development compared to Open Banking.

The Aviation sector has demonstrated the benefits of the ACRIS and AIDM models for information sharing between systems, and improving the operation and efficiency of various aspects of airports as a result.

Similarly the shipping sector (i.e. IMO Compendium) has harmonised existing standards for the sector improving the ability to share key information.

These initiatives have demonstrated there is value in the process of data being open, with a need for authorised access.

However, it requires focus across the sector to collaborate in advisory groups and working committees to make this a reality.

The National Digital Twin programme's Information Management Framework (IMF) provides an approach to working towards a common way of working and data sharing in the sector and beyond.

In Energy progress has been made. Ofgem have also introduced Data Best Practice guidance, and the Energy Data Task Force introduced the "presumed open" principle for energy data.

2. Data completeness

Representing complex infrastructure systems in order to operate and maintain the asset requires sufficiently granular detail of the asset systems including, for example, the relationships between assets where they have a dependency.

Therefore, much of the development of digital twins is reliant on having a good standard of asset information and operational data.

It has been observed in the sectors reviewed that they have invested in data improvement activities, which has benefited their own organisational needs as well as supporting the digital twin roadmaps.

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Where data is to be shared, this requires sector wide cooperation to determine agreement on data standards

Data standards must contain an appropriate level of detail and contextual information to add value to other organisations for collaboration, whilst protecting IP and commercial sensitivities.

3. Harmonise existing data standards

In some instances, organisations have developed data standards within their own business. However, in order to share data between organisations, sectors and countries, there needs to be a harmonisation of competing or conflicting data standards at a sector level.

In most of the case studies reviewed this has been achieved through working groups (with industry representatives), committee, or an independent body to define/merge those data standards.

Alternatively existing standards are adopted and investment focuses on wide-scale roll-out.

Clear articulation of the benefits is crucial to the successful adoption. In some cases adoption is enforced through regulation or legislation.

Data

4. Interoperability

Several examples exist of how different suppliers differ in data standards, which prevents effective data sharing.

Agreed exchange formats are necessary, and these need to be recognised and adopted by software and technology vendors for effective and accurate import & export between systems.

5. Common taxonomies and ontologies

To facilitate effective interoperability and data exchange it is necessary to define agreed taxonomies and ontologies, which includes metadata standards.

The National Digital Twin programme's Information Management Framework (IMF) aims to create the upper ontology and foundation data model for the built environment, with each sector creating and owning the sector-specific reference data library. It is considered that the Virtual Energy System can fulfil this sector-specific role, and connect into the National Digital Twin programme

Within energy, the development of agreed metadata standards is being developed by Open Energy, and through programmes of work such as the Energy Data Visibility Project (EDVP).

6. Data visibility

Across the case studies researched there were examples of data being shared via data portals and visualised through central dashboards - which are often made visible to a wide range of stakeholders, including the general public.

For example, energy use charts and tables are available for Australia and Singapore, with industry sharing operational and monitoring data.

Dashboards were also observed to be provided by a third party, based on data made available via open APIs or data sharing agreements.

Data visibility provides additional value through information combination and aggregation. It supports information for public interest and greater transparency of a sector.

Appendix

A.1

References & sources

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References & sources

Theme	Description	Date	URL
Australia	AEMO Press release AMO published its 2021 Inputs, Assumptions and Scenarios Report (IASR)	July 2021	https://aemo.com.au/newsroom/media-release/2021-inputs-assumptions-and-scenarios-report
Australia	AEMO Current inputs, assumptions and scenarios	2022	https://aemo.com.au/en/energy-systems/major-publications/integrated-system-plan-isp/2022-integrated-system-plan-isp/current-inputs-assumptions-and-scenarios
Australia	AEMO Distributed Energy Integration Program (DEIP)	2021	https://arena.gov.au/knowledge-innovation/distributed-energy-integration-program/
Australia	H4 Rewarding flexible demand: Customer friendly cost reflective tariffs and incentives opportunity assessment, Race for 2030	November 2021	https://www.racefor2030.com.au/wp-content/uploads/2021/11/H4-OA-final-report-17.11.21.pdf
Australia	AEMO Emerging Generation and Energy Storage – Grid Scale	2019	https://aemo.com.au/en/initiatives/trials-and-initiatives/emerging-generation-and-energy-storage-eges-grid-scale
Australia	Integrating distributed energy resources for the grid of the future: Economic regulatory framework review 2019	2019	https://www.aemc.gov.au/news-centre/media-releases/delivering-grid-future
Australia	Electricity Demand Forecast Methodology Final Report and Determination	May 2021	https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2020/electricity-demand-forecasting-methodology/final-stage/electricity-demand-forecast-methodology-final-determination.pdf
Australia	Increasing Visibility of Distribution Networks Funding program	2017	https://arena.gov.au/projects/increasing-visibility-of-distribution-networks/
Australia	Open Energy Networks Project Energy Networks Australia Position Paper	2020	https://www.energynetworks.com.au/resources/reports/2020-reports-and-publications/open-energy-networks-project-energy-networks-australia-position-paper/

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Theme	Description	Date	URL
Australia	Joe Locandro, Managed and drove first global innovation of the Australian National Energy Grid Simulator (Digital Twin)	Not dated	https://www.linkedin.com/in/joe-locandro/?trk=public_profile_browsemap&originalSubdomain=au
Australia	AEMO's world-first simulation tool to help generation and storage projects connect to the grid	August 2021	https://aemo.com.au/newsroom/media-release/world-first-simulation-tool
Australia	International Review: Maintaining Power System Security with High Penetrations of Wind and Solar Generation October 2019: International insights for Australia	October 2021	https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/future-energy-systems/2019/aemo-ris-international-review-oct-19.pdf?la=en
Australia	NEM Engineering Framework Operational Conditions Summary	July 2021	https://aemo.com.au/-/media/files/initiatives/engineering-framework/2021/nem-engineering-framework-july-2021-report.pdf?la=en
Australia	OPAL-RT TECHNOLOGIES Press release	November 2020	https://www.opal-rt.com/news/opal-rt-technologies-to-provide-advanced-transmission-simulation-support-to-the-australian-energy-market-operator-aemo/?fbclid=IwAR2EN6vojdl-4AgDMZNWB_b3Rlm3UyC0J6QAo5wFi4-gxXha29lAkOJOo5U
Australia	Real-Time Simulator press release	Not dated	https://aemo.com.au/en/initiatives/trials-and-initiatives/real-time-simulator
Australia	Real-Time Simulator project update	October 2021	https://aemo.com.au/newsroom/news-updates/aemo-real-time-simulator-project-update
Aviation	AIRM - ATM Information Reference Model - used within SWIM	Not dated	www.airm.aero
Aviation	Aviation - Airports Council International (ACI) Community Recommended Information Services ACRIS - standard for IM and data exchange	Not dated	https://acris.aero/
Aviation	Flight Database & Statistics | Aviation Analytics | OAG. OAG is the world's leading provider of digital flight information, intelligence and analytics for airports, airlines and travel tech companies.	Not dated	https://www.oag.com/

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Theme	Description	Date	URL
Aviation	Future role of digital twins in the aerospace industry	January 2019	https://www.challenge.org/insights/digital-twin-in-aerospace/
Aviation	Modern Baggage Messaging Baggage XML project is working towards a sustainable standard for messaging in the area of baggage.	Not dated	https://www.iata.org/en/programs/ops-infra/baggage/baggagemessaging/
Aviation	Rolls Royce Digital twin - City Airbus demonstrates our ambitions to power the Urban Air Mobility market	2021	https://www.rolls-royce.com/media/our-stories/discover/2021/city-airbus-demonstrates-our-ambitions-to-power-the-urban-air-mobility-market.aspx
Aviation	Rolls Royce Digital twin - How Digital Twin technology can enhance Aviation	2019	https://www.rolls-royce.com/media/our-stories/discover/2019/how-digital-twin-technology-can-enhance-aviation.aspx
Aviation	System-wide information management (SWIM)	Not dated	https://www.eurocontrol.int/concept/system-wide-information-management
Aviation	The New Experience Travel Technologies (NEXTT) initiative brings stakeholders together to build the air travel journey of the future.	Not dated	https://www.iata.org/en/programs/ops-infra/airport-infrastructure/nextt/
Aviation	We help manage ATM-related information and its exchange between qualified parties through interoperable services.	May 2021	https://www.faa.gov/air_traffic/technology/swim/
Aviation	White Paper: Aviation Data - Data Science Hype or Ripe for Aviation?	June 2019	https://www.iata.org/contentassets/d72edc56c3814aac8ec508fdf8555a52/data-science-hype-or-ripe-for-aviation-white-paper.pdf
Aviation / Maritime	Risks of Digital twins from Aviation for Maritime	October 2019	https://www.researchgate.net/publication/337248079_On_Risk_of_Digital_Twin_Implementation_in_Marine_Industry_Learning_from_Aviation_Industry
Carbon intensity	Carbon intensity API - NG ESO, EDFE, UODCS and WWF	Live	https://www.carbonintensity.org.uk/

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Theme	Description	Date	URL
Cyber Security	OPAL-RT21 Conference Panel Discussion: Cybersecurity on Power Systems Secure and Resilient Cyber-Physical Energy Systems	September 2021	https://www.opal-rt.com/resource-center/document/?resource=Mkt_0027399
Dafni	DAFNI as a digital Twin - Report	Not dated	http://dafni.ac.uk/wp-content/uploads/2021/05/DAFNI-as-a-Digital-Twin-Platform-Final-report.pdf
Digital Twin	CREDO	Not dated	https://digitaltwinhub.co.uk/projects/credo/what-is-credo/
Digital Twin	Digital twin Hub - Building a Digital twin specification: using wind energy to extract green hydrogen from seawater	Not dated	https://digitaltwinhub.co.uk/case-studies/building-a-digital-twin-specification-using-wind-energy-to-extract-green-hydrogen-from-seawater-r38/
Digital Twin	Digital Twin of Rennes metropole	Not dated	https://digitaltwinhub.co.uk/case-studies/digital-twin-of-rennes-metropole-%E2%80%93-sustainable-urban-development-r15/
Digital Twin	Virtual Singapore: Singapore's Innovative City Project - Dassault Systems.	July 2016	https://www.youtube.com/watch?v=Dix-8SNxlAo
Digital Twin - Chile	Prospection in Energy digitalisation in Chile	November 2020	https://www.energypartnership.cl/fileadmin/user_upload/chile/media_elements/Studies/CHL_20201130_Prospection_in_Energy_digitalisation_in_Chile_01.pdf
Digital Twin - Siemens	Siemens.com Electrical Digital Twin Brochure	Not dated	https://assets.new.siemens.com/siemens/assets/api/uuid:66c9013092b493265e091c154a33f9dd38d36c20/electricaldigitaltwin-brochure-final-intl-version-singlepages-no.pdf
Energy Data Taskforce	Energy Data Taskforce: A Strategy for a Modern Digitalised Energy System	2019	https://es.catapult.org.uk/report/energy-data-taskforce-report/
Energy Data Taskforce	Modernising Energy Data - Energy Data User Needs	August 2017	https://modernisingenergydata.atlassian.net/wiki/spaces/MED/pages/816218113/Energy+Data+User+Needs
Energy future scenarios	entsoe	Not dated	https://tyndp.entsoe.eu/

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Energy Services	Uses of the digital twins concept for energy services, intelligent recommendation systems, and demand side management: A review	November 2020	https://reader.elsevier.com/reader/sd/pii/S2352484721000913?token=77EA093C460ECA65A2BF8F6A7840E560C230FF468FD92DDFFF2BBC111B9470FDCA0429815EF0EAD10E207F6B063651CE&originRegion=eu-west-1&originCreation=20211111104239
Maritime & Shipping	C-Ports: A proposal for a comprehensive standardization and implementation plan of digital services offered by the “Port of the Future”	September 2021	https://arxiv.org/ftp/arxiv/papers/2104/2104.13175.pdf
Maritime & Shipping	ACCELERATING DIGITALIZATION Critical Actions to Strengthen the Resilience of the Maritime Supply Chain	December 2020	https://thedocs.worldbank.org/en/doc/773741610730436879-0190022021/original/AcceleratingDigitalizationAcrosstheMaritimeSupplyChain.pdf
Maritime & Shipping	IAPH global ports survey on the implementation of electronic data exchange to conform with the IMO Convention on Facilitation of International Maritime Traffic (FAL)	January 2021	https://sustainableworldports.org/wp-content/uploads/IAPH-FAL-Survey-Report-Jan-2021.pdf
Maritime & Shipping	Antwerp Port Information & Control Assistant (APICA)	Not dated	https://www.portofantwerp.com/en/news/meet-apica-our-digital-brain
Netherlands	Digital twins and their use in future power systems Netherlands	September 2021	https://digitaltwin1.org/articles/1-4/v1
Netherlands	Netherlands: Developing a digital twin for the electricity grid (tudelft.nl)	Not dated	https://www.tudelft.nl/en/eemcs/current/nodes/stories/developing-a-digital-twin-for-the-electricity-grid
Open Banking	CMA: Update on Open Banking	November 2015	https://www.gov.uk/government/publications/update-governance-of-open-banking/update-on-open-banking
Rail	France SNCF Réseau - use of Digital Twins	July 2021	https://www.globalrailwayreview.com/article/120552/digital-twins-french-railway-network/
Rail	Interview with Andrew Smith, Bentley in Rail mag about value of digital twins	August 2020	https://www.railexpress.com.au/going-data-insights-the-value-digital-twin-rail/
Rail	Netherlands ProRail - use of Digital Twins	July 2021	https://www.globalrailwayreview.com/article/120750/digital-twins-prorail/

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Rail	NR Intelligent Infrastructure Update	June 2021	https://www.networkrail.co.uk/wp-content/uploads/2021/06/Intelligent-Infrastructure-Rail-Live-June-21-1.pdf
Rail	Outcomes of ORBIS programme	May 2019	https://www.railengineer.co.uk/orbis-an-unsung-but-unqualified-success/
Rail	Russia - use of digital twins	July 2021	https://www.globalrailwayreview.com/article/122490/digital-twins-maintenance-railway-infrastructure/
Rail	Virtual testing of Rolling Stock and tools	Not dated	https://rail.ricardo.com/project-delivery/testing-services/virtual-testing/ignite
Regulator Ofgem	Consultation on the initial findings of our Electricity Transmission Network Planning Review	November 2021	https://www.ofgem.gov.uk/publications/consultation-initial-findings-our-electricity-transmission-network-planning-review
Singapore	Digital Twin Hub Case Studies: Digital Twin: Singapore Smart City	Not dated	https://digitaltwinhub.co.uk/case-studies/digital-twin-singapore-smart-city-r16/
Singapore	Singapore's First Digital Twin for National Power Grid	October 2021	https://www.ema.gov.sg/cmsmedia/News/Media%20Release/2021/271021_Press-Release-First-Digital-Twin-National-Power-Grid.pdf
Singapore	MESMO - Multi-Energy System Modelling & Optimisation	Not dated	https://www.tum-create.edu.sg/research/project/mesmo-multi-energy-system-modelling-optimisation
Singapore	SP Group – NTU Joint Laboratory	Not dated	http://eeeweba.ntu.edu.sg/power_projects/SPGroup-NTU/0_default.asp
Use cases (energy)	The Energy Transition: Key challenges for incumbent and new players in the global energy system	September 2021	https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/09/Energy-Transition-Key-challenges-for-incumbent-players-in-the-global-energy-system-ET01.pdf
Water	BIM4Water Case Studies	Not dated	https://www.britishwater.co.uk/page/BIM4Water-CaseStudies

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Water	Digital Twins for Wastewater Infrastructure - Royal HaskoningDHV Digital White Paper.	Not dated	https://global.royalhaskoningdhv.com/digital/resources/publications/digital-twins-for-wastewater-infrastructure
Water	Digital Water - capitalising on the commercial opportunities for UK plc	May 2020	https://www.theukwaterpartnership.org/wp-content/uploads/2020/05/UKWP-Digital-Water-White-Paper%20plc.pdf
Water	Digital Water Operational digital twins in the urban water sector: case studies	2021	https://iwa-network.org/wp-content/uploads/2021/03/Digital-Twins.pdf
Water	U.S. Department of Energy - Solar driven desalinisation	2019	https://www.energy.gov/eere/solar/solar-desalination
Water	Water Industry Forum Conference slides - How could Digital Twins add value to the water sector?	August 2020	http://www.waterindustryforum.com/documents/uploads/WIF%20Webinar%20260820%20on%20Digital%20Twins%20-%20Master%20Slides.pdf
Water	Wessex Water case study - Using AI to Detect Early Blockage Formations in Wastewater Networks	Not dated	https://stormharvester.com/wp-content/uploads/2021/03/V9-Wessex-Case-Study.pdf

A.2

Defining a digital twin

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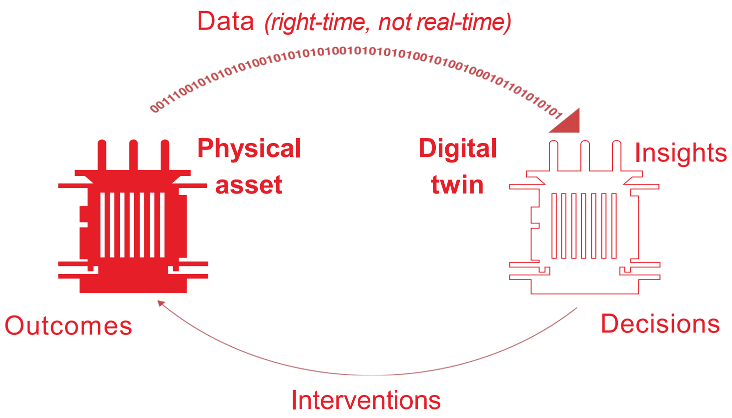
Defining a digital twin

Defining a digital twin – what does it mean?

Digital twin can mean many things. As a definition: a 'digital twin' is a digital replica of a physical thing - a 'twin'. Depending on maturity, this replica can range from a simple 2D or 3D model of a local component, all the way to a fully integrated and highly accurate model of an entire asset dynamically linked to engineering, construction, and operational data.

Importantly, a twin is developed to a level of accuracy or detail proportionate to its intended purpose or use-case. What distinguishes a twin from any other digital model or replica is a connection or relationship between the physical and digital.



A digital twin is a methodology, not a technology

Digital twins promise more effective asset design, project execution, and asset operations. By dynamically integrating data and information throughout the asset lifecycle, they will offer short and long-term efficiency and productivity gains.

More than just Building Information Modelling (BIM) or a 3D model, twins are a data resource that can improve the design of new assets and understanding of existing asset condition, verify the as-built situation, run 'what if' simulations and scenarios, or provide a digital snapshot for future works. This has the potential to reduce errors and discontinuities present in more traditional methods of information management. It also allows for insight into how different performance characteristics affect components without having to either, physically test, or produce potentially dangerous conditions.

As asset owners and operators pivot away from document silos and toward dynamic and integrated data systems, the digital twin will become like a node in a network, alongside potentially many other twins for different assets or systems. Dynamic and accurate (like any corporate financial or HR system), it should represent a living, as-built version of the operating asset, delivering value to the business.

There is no single solution or platform used to provide a digital twin, just as there is not one CAD package used to create a drawing or a 3D model. It's about the process and methodology, not the technology. It is a way of working, underpinned by full-lifecycle information & data management.

The aim is to create a 'single version of truth' of the infrastructure, where all data can be accessed and viewed throughout the design-build-operate lifecycle. This is distinctly different from a 'single source of truth', as a digital twin is about using a constellation, or ecosystem, of technologies that work and connect.

It is important to understand that complexity is not necessarily the ultimate focus, and the extent of connectedness of the twin should also be considered. What is essential is that the purpose and value of this increased complexity and connectedness is clearly identified, justified and realised – which relies on effective implementation and management.

Whilst a fully responsive, automated, holistic system provides a future vision, we can already deliver value through the first small steps. As technology and techniques improve, the convergence of these individual parts will allow the emergence of much complete, connected twins.

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A.3

Benchmarking evaluation matrix

A.3 - Benchmarking evaluation matrix

Use Case Category	Energy System Segment	Use Case Title	Use Case Description
Strategy & planning	Generation, Transmission, Distribution, Retail, Consumption	1. Transition to net zero	In response to the need for achieving net-zero, and the changing landscape of generating, managing and consuming energy, it will be necessary to simulate real world scenarios, develop decarbonisation strategies to build long term strategic pathways, and guide diversification into non-carbon intensive areas – whilst accounting for policy and regulatory processes.
Managing Assets	Generation, Transmission, Distribution	2. Asset monitoring & predictive maintenance	Understanding the performance of their assets and where maintenance would be needed. This will reduce the producer's risk of downtime and inefficiencies of production, extend the operational lifetime of assets, and reduce costs. Whilst monitoring and maintenance is already conducted, this use case considers greater digitally enabled asset management.
Managing Assets	Generation	3. Optimisation of energy production	Better planning, monitoring and control of the energy system assets to improve power plant efficiency. A representation of the current state of a system combined with external sources such as forecast models (e.g. weather, demand, pricing) will allow energy producers to more accurately estimate and optimise energy production and reduce the risk of energy being curtailed or not monetised.
Strategy & planning	Generation	4. Linking electricity & gas networks	Understanding the dependencies and growing synergies between electric and gas production and transmission, such as heat pumps or hydrogen conversion. A connected virtual representation of both systems, from generation to transmission and distribution, will help coordination and will optimise the operation of the gas and electricity networks.
Managing Assets	Transmission, Distribution	5. Real time balancing and forecasting	Balancing real-time & predictive supply and demand within constraints of the overall system to inform network reinforcement decisions. This can help with network understanding and anticipating where there are capacity constraints, greater intermittent generation, etc. This is based on integration across energy systems and producers, distributors networks, and retail and demand.
Assurance	Transmission	6. Flexibility modelling for increased renewables	Monitoring of generation plants, storage and demand can help to improve the predictability of the systems and increase the rate in which renewable generation is added onto the network. Flexibility in the power system becomes crucial for maintaining reliability and cost-effectiveness, impacting how infrastructure is planned and operated long term.
Assurance	Transmission, Distribution	7. Model energy storage needs	Ensuring reserves are sufficient and the system delivers the power to meet needs. Energy storage can give the ability to rapidly respond to large fluctuations in demand and can make the grid more responsive. However, there needs to be methods in place to determine when best to store energy, and at what scale to store it in.
Assurance	Transmission, Distribution	8. Dynamic power modelling	Power system operators must be equipped with the knowledge that the grid is going to be able to continue to run seamlessly, and fluctuations in generation are modelled and accounted for. Power systems modelling should be able to account for a variety of new generation techniques, network storage and consumption equipment, as well as all market, customer and regulatory issues in a whole system context to create a far more responsive, predictable and dynamic power system.

Use Case Title	Singapore (Energy Sector) Evaluation	Singapore (Energy Sector) Description	Estonia (Energy Sector) Evaluation	Estonia (Energy Sector) Description
1. Transition to net zero	Will partially meet	The Digital Twin for Singapore National Power Grid uses modelling and simulations to determine the impact of additional loads (such as charging of electric vehicles) and distributed energy resources (such as solar photovoltaics and energy storage systems) on the grid.	Will partially meet	The availability of greater information within Estonia and status of origin available to all within the sector provides greater transparency of fuel mix available, pricing and moves towards flexible markets which could in time be simulated. Estonia also pays subsidies for renewable generation, but they must have guarantees of origin certificates (issued by Elering) to receive.
2. Asset monitoring & predictive maintenance	Will meet	The Asset Twin components aim to optimise the planning, operations and maintenance of Singapore's grid assets.	Meet	Due to the availablility of a central hub of smart meter data, there is much better monitoring of the network by DSOs. They are able to perform preventative maintenance due to monitoring of electrical resonance on the network and keep their customers better informed.
3. Optimisation of energy production	Does not meet	Not applicable	Meet	Better knowledge of consumption information enables improved planning of generation. The current sytem information is available via e-elering and elering live and so can be optimised
4. Linking electricity & gas networks	Does not meet	Not applicable	Partially meet	Elering are responsible for both electricity and gas transmission, and are considering both in their planning process and information management
5. Real time balancing and forecasting	Will partially meet	The Network Twin component is being built to assess the impact on grid. This uses modelling and simulations to determine the impact of additional loads (such as charging of electric vehicles) and distributed energy resources (such as solar photovoltaics and energy storage systems) on the grid.	Partially meet	Estonia are trying to incentivise industry where possible to use periods of lower cost energy to plan their heavy usage at times of lower demand, or greatest available energy. This can only be done by having the renewable energy portal and also the data hub and its associated applications providing the information for these decisions
6. Flexibility modelling for increased renewables	Will partially meet	On both the key outcome of Singapore National Power Grid Digital twin is to enable optimisation of asset investment, by identifying potential synergies between asset renewal and upgrades for load growth without compromising grid resilience.	Will meet	Working on project within EU Horizon 2020 project, INTERRACT where they have a demonstrator project with Latvia and Finland for flexible markets. Modelling of transmission etc is no different to other countries using the standard available modelling tools.
7. Model energy storage needs	Will partially meet	The Network Twin component is being built to assess the impact on grid and understand aspects such as future storage needs.	Does not meet	No information about storage was available to assess this requirement.
8. Dynamic power modelling	Will meet	The Network twin uses Multi Energy System Modelling & Optimisation (MESMO) an advanced software framework that combines simulation of electrical grids and optimisation techniques ad market simulation.	Will partially meet	The fact that energy meter data is available, pricing and hourly certificates of source of fuel, it is hoped there will be some change in demand patterns as a result through incentivisation.

Use Case Title	Australia (Energy Sector) Evaluation	Australia (Energy Sector) Description	Water Evaluation	Water Description
1. Transition to net zero	Will meet	AEMO delivers a range of planning and forecasting publications to inform decision making including the Electricity Statement of Opportunities (ESOO), the Gas Statement of Opportunities (GSOO) and the Integrated System Plan (ISP). AEMO uses scenario modelling and cost-benefit analysis to determine the most efficient ways to meet power system needs through the energy transition and in the long-term interests of consumers. The approach aligns with the new Integrated System Plan (ISP) Rules and the intent of the Australian Energy Regulator's proposed Cost-Benefit Analysis Guidelines for the ISP and regulatory investment tests. https://aemo.com.au/-/media/files/major-publications/isp/2020/2020-isp-overview.pdf?la=en	Partially meet	Key areas of carbon reduction are planned in treatment works, especially use of oxygen - a by product of Hydrogen production is being considered. Also pumping & treatment works energy use being reduced / optimised with alternative sources of energy
2. Asset monitoring & predictive maintenance	Will partially meet	Some organisations are exploring, e.g. Australian Gas Light (AGL). https://explore.osisoft.com/power-utilities/wp-power-how-pi-supports-cbm?lx=Xcna7i Products are on the market. This is being planned for within organisations. Long lead time, and it's not clear if all organisations will have the capacity to implement this.	Meet	Considerable amount of modelling used in water distribution and treatment. Sensors put in place on overflows and at treatment works
3. Optimisation of energy production	Will meet	No coordinated plan or modelling between states yet, possibly within organisations. The Operational Simulation Model is being developed to be launched in 2022. this is part of the overarching program Australian Energy Simulation Centre (AESC) through a staged approach. If fully implemented, the AESC will encompass data and models of electricity and gas transmission, distribution and fuel dependencies. The AESC will provide an integrated real-world view of the energy system with 'what if?' analytical capability, built and maintained with actual operating data.	Partially meet	Water generation i.e. capture or desalination is carbon intensive due to dam construction / energy consumption. Some research into solar driven desal in place. Not many alternatives to concrete for Dams
4. Linking electricity & gas networks	Will meet	Western Victoria - Portland, hydrogen gas mix trial. Hydrogen is one of the 5 key Australian Energy Scenarios. AEMO 2021 Inputs, Assumptions and Scenarios Report (IASR).	Does not meet	Not applicable
5. Real time balancing and forecasting	Will meet	Amount of solar power means there are issues with balancing too much power at certain times, requiring Battery on poles. Also Demand / Supply domestic initiatives to stop pool pumps etc at times of high demand directly	Partially meet	E.g. storm harvester level predictions and alerts on blockage in sewage network using AI and predictive analysis
6. Flexibility modelling for increased renewables	Will meet	Much modelling is currently 'static', many initiatives to improve and make the modelling dynamic. E.gs. Operations Simulator The Distributed Energy Integration Program (DEIP) is a collaboration of government agencies, market authorities, industry and consumer associations aimed at maximising the value of customers' distributed energy resources (DER) for all energy users.	Partially meet	Use of hydrological modelling based on predicted rainfall is used but no water 'alternatives' exist
7. Model energy storage needs	Will meet	Battery capacity, Virtual Power Plants and Community batteries etc, are recognised as very important to make use of domestic solar panels. there are various trials across the country. The clean energy roadmap laid out by the NSW Government has provided the market with the confidence to invest in renewable generation supported by large battery storage. (https://www.energy-storage.news/worlds-biggest-battery-storage-project-announced-by-australian-renewables-fund/ https://www.westernpower.com.au/community/news-opinion/latest-battery-storage-trial-to-benefit-hundreds-of-wa-homes/ https://arena.gov.au/assets/2020/08/community-batteries-cost-benefit-analysis.pdf) but not sure if modelled	Meet	Significant amount of modelling is conducted in water and sewer drainage systems for many years with SCADA systems in place etc. Models water storage and treatment requirements
8. Dynamic power modelling	Will meet	Modelling is still 'static' Tasmania As part of empowering You trial, TasNetworks encouraged a customer led shift to time of use network tariffs. TasNetworks Demand Management Engagement Register is open to all our stakeholders including residential, commercial, agricultural and industrial customers and demand management suppliers. page https://aemo.com.au/-/media/files/initiatives/engineering-framework/2021/nem-engineering-	Partially meet	Water demand analysis likely forms part of water storage and distribution planning, and also amount of treatment capacity due to rainfall / runoff.

Use Case Title	Aviation Evaluation	Aviation Description	Rail Evaluation	Rail Description
1. Transition to net zero	Does not meet	Air transport will not be net zero unless they offset as one of the major carbon emitters however with new aircraft technology/fuels are improving	Partially meet	Not a major focus, though some work in electrification and use of hydrogen fuelled trains
2. Asset monitoring & predictive maintenance	Partially meet	Air traffic control is constantly sharing digital data about flights, Plus engine monitoring by Rolls Royce. Aircraft Health Monitoring is common place on modern aircraft to analyse key metrics of its operation	Partially meet	Initiatives in place for predictive maintenance based on operational and infrastructure condition data. More right time than real time. Taking the LADS case study, monitoring of track condition allows for safer operation of the railway, and finding of route cause of issues
3. Optimisation of energy production	Partially meet	If you consider aircraft to be the electrons in this scenario, aircraft are modelled and simulated in their design and production. their use of fuel in flight / taxiing etc is monitored to reduce costs.	Partially meet	Rolling stock manufacture makes use of virtual modelling of operation in design and manufacture but not to extent of aviation. E.g. Ricardo Rail virtual testing and IGNITE software for rolling stock
4. Linking electricity & gas networks	Does not meet	not applicable	Does not meet	not applicable
5. Real time balancing and forecasting	Partially meet	Sharing of data for ticketing and baggage systems means that airlines know of other airlines availability and connection info	Does not meet	Load balancing not easily done within rail, timetable only changes very infrequently
6. Flexibility modelling for increased renewables	Does not meet	not applicable	Does not meet	not applicable
7. Model energy storage needs	Does not meet	Not dynamic enough, though plans for airspace management to improve capacity happening	Does not meet	not applicable
8. Dynamic power modelling	Does not meet	Other than transport planning of use of airlines, not really equivalent	Partially meet	Network modelling is being developed within the Intelligent Infrastructure programme. Timetable is already modelled but very slow time.

Use Case Title	Maritime & Shipping Evaluation	Maritime & Shipping Description	Banking Evaluation	Banking Description	Climate resilience demonstrator (CReDo) Evaluation	Climate resilience demonstrator (CReDo) Description
1. Transition to net zero	Will partially meet	World Ports Sustainability Program looks to promote the creation of a more sustainable industry by sharing single initiatives with he wider maritime community. Several ports have or are evaluating how to decrease their emission. Some example of this work in the UK include: - Carbon calculator for PORT: An online tool which will help ports forecast the future infrastructure required to meet potential increased demand for electricity from zero emission port operations has been developed by National Grid Electricity Transmission (NGET) in partnership with Siemens. - Portsmouth Port Digital Twin: looking to help deploying renewable and clean fuels as well as optimizing the logistics of onshore equipment and sea-going vessels refuelling to reduce emissions.	Does not meet	not applicable	Partially meets	Credo is simulating real world scenarios. Outcome of the connected digital twin is showing which assets could suffer from natural disasters (flooding currently modelled
2. Asset monitoring & predictive maintenance	Will partially meet	Several example of where single port are trying to achieve this use cases across their assets. Probably the most advance example of a Digital Twin covering this use case is the ongoing Digital Twin being built for the Port of Antwerp. This use case is also core to some of the other streams of the Smart Port Connected Catapult initiative which aim to look at Automated Asset Inspection and Port Sector Maintenance Insight and Intelligent monitoring and maintenance of Aids to Navigation.	Does not meet	not applicable	Meet	CReDo will develop a digital twin of the infrastructure system comprising Anglian Water's water and sewerage network, BT's communication network and UKPN's power network in a specific location. The digital twin maps a weather scenario from a present or future climate to system-level consequences, through a series of components as in the diagram, for support of operational and capital planning decisions.
3. Optimisation of energy production	Will meet	Several singular Port initiatives across some of the biggest ports intend to better manage energy demand, consumption as well as local production. In the UK some examples include the Smart Port Connected Catapult initiative is exploring the use case of Shore Power to Support Vessel Operations. Likewise this is a use case that seems to be important for the Portsmouth Port Digital Twin as well	Does not meet	not applicable	Does not meet	not applicable
4. Linking electricity & gas networks	Does not meet	Not applicable	Does not meet	not applicable	Does not meet	not applicable
5. Real time balancing and forecasting	Will meet	Several singular port initiative undergoing. For example: -Shanghai Port community system provide a view of the all sea intramodal transport for the entire Yangtze river to improve operation management. - Singapore Digital Port ecosystem : The digital port ecosystem helped to reduce the administrative burden of shipmasters in port call and reporting formalities, allowing them to focus on their primary responsibility of navigating ships safely. It has also helped to save an estimated 100,000 man-hours per year for the industry. New services such as crew change application and Just-in-Time services are also being rolled out as Singapore MPA continues its efforts to drive the transformation of the maritime industry during the COVID-19 pandemic.	Does not meet	not applicable	Does not meet	not applicable
6. Flexibility modelling for increased renewables	Will partially meet	There are singular port initiatives that look at this use cases. Some example can be found in the repository of the World Ports Sustainability Program. (https://sustainableworldports.org/portfolio/type/port-projects/?area-of-interest=climate-and-energy)	Does not meet	not applicable	Does not meet	not applicable
7. Model energy storage needs	Partially meet	There are singular port initiatives that look at this use case. Some example can be found in the repository of the World Ports Sustainability Program. (https://sustainableworldports.org/portfolio/type/port-projects/?area-of-interest=climate-and-energy)	Does not meet	not applicable	Does not meet	not applicable
8. Dynamic power modelling	Partially meet	There are examples of the response component of this use case. Port and offshore logistics management systems currently allow port to respond to demand. Other initiatives such as Antwerp Digital Twin and the Portsmouth Port digital twin look to enhance and optimize operations with decision-support tools according to demand.	Does not meet	not applicable	Partially meet	Credo is simulating if end users will continue to have access to power in the event of a/a series of failures in the system.

Use Case Category	Energy System Segment	Use Case Title	Use Case Description	Singapore (Energy Sector)		Estonia (Energy Sector)		Australia (Energy Sector)		Water	
				Evaluation	Description	Evaluation	Description	Evaluation	Description	Evaluation	Description
Strategy & planning	Transmission	9. Planning the future transmission network	Improve the creation of future energy scenarios (FES), Electricity Ten Year Statements (ETYS), and Network Options Assessment (NOA) by better accounting for players across the entire energy system and other external factors. For example, FES currently only models large renewable energy produced. This will help to better model how to best run the network, while minimising cost to the consumer, selecting investments needed and helping the rest of the industry align.	Will partially meet	The Singapore Twin aims to improve the network planning analysis and have a better network utilisation when balancing new or peak electricity loads.	Will partially meet	Estonia have several initiatives as part of the renewable energy subsidy and Ceritificate of Origin and Renewable portals to provide more information about what is currently provided in the fuel mix. They are working closely within the EU to encourage greater sharing of information to provide more flexible markets for energy	Partially meet	AEMO has published its 2021 Inputs, Assumptions and Scenarios Report (IASR) incorporating five future energy scenarios, ranging from 'slow change' to 'hydrogen superpower', which will inform AEMO's 2022 Integrated System Plan (ISP). Compared to the 2020 ISP scenarios, these scenarios have been refined with respect to the economic and technological change expected over the coming decades. Specifically, the pace of economy-wide decarbonisation, the ongoing consumer investment in distributed energy resources, and the growth of transport and industry electrification. Currently limited by state boundaries and competition.	Partially meet	There are plans to distribute sewage water between catchments potentially and how CSOs operate to prevent spills
Assurance	Transmission, Distribution	10. Optimise connectivity capacity	Both transmission and distribution operators are seeing an increased set of assets connecting to their network. Bringing together accurate information around current performances with the ability to model several impact scenarios for new connections on the system will help determine the best path forward. This can also assess the use and impact of multi-purpose interconnections to allow several assets to connect to the grid (e.g. an interconnectors cable from another country together with an offshore wind farm connection).	Will meet	The Network Twin component will be able to provide SP with a high-level assessment of the impact of demands on the grid and any upgrades required for different scenarios.	Meet	Elering has created a webmap and dashboard open to the public called e-gridmap, which provides the current and future status of substation connections. It provides location and information on capacity and cost information for new connections to a substation.	Will partially meet	Is going to be continuously challenged by the number of ad competition within Distribution Operators and State boundaries. Current development of the Connection Simulation Tool (CST). Further development to come as a number of other tools are developed to deliver the Australian Energy Simulation Centre (AESC).	Partially meet	
Managing Assets	Transmission, Distribution	11. Model stability of network	With the increase of renewable energy sources, there is an increased risk that disturbances due to a change in demand or generation (e.g. loss of a circuit or generator) propagate more rapidly through the network. Bringing together data on the typology of the network, electric characteristics, power system generation models, network conditions, and variance of energy production from renewable will allow for better understanding of the stability of the network and how to mitigate potential system instability.	Will meet	Network Twin for impact assessment on grid. This uses modelling and simulations to determine the impact of additional loads (such as charging of electric vehicles) and distributed energy resources (such as solar photovoltaics and energy storage systems) on the grid.	Will partially meet	Standard modelling tools were being used by Elering to model the network stability. However with more information about consumption being available, it provides DSO's the ability to better understand the consumer behaviours and therefore plan for that. Plans were not clear how future modelling will be conducted however.	Will meet	The Connection Simulation Tool (CST) a cloud-based resource available for developers to test and tune power system models for new generation projects planning to connect to Australia's National Electricity Market (NEM). Which aims to reduce risks, costs and time to approve the connection of new generation projects.	Partially meet	With environmental focus on reducing spill and energy usage, there does need to monitor and better understand the network impact
Managing Assets	Transmission, Distribution	12. Visibility of transmission & distribution interface	Both transmission and distribution networks have increasing numbers of commercial arrangements with different market players providing power and balancing services, within the market rules and service definitions. Service providers can enter into agreements with both transmission and distribution networks. Making visible those commercial layers and agreements, and monitoring when services are called upon, will reduce the risk of conflicts created by contrasting instructions being given to service providers.	Does not meet	Not applicable - One single distribution and transmission entity	Will meet	Elering in demonstration project for flexible markets called INTERRACT.	Will partially meet	Is going to be continuously challenged by the number of ad competition within Distribution Operators and State boundaries. Mor needs to be developed around regulatory frameworks, and market conditions Current development of the Connection Simulation Tool (CST). DER Visibility and Monitoring Best Practice Guide - [https://www.aemc.gov.au/sites/default/files/documents/rule_change_submission_-_erc0301_-_solar_analytics_updated_-_20210114.pdf] Open Energy Networks Project Energy Networks Australia Paper - Open investigated solutions to optimise and manage DER on the distribution network, and to facilitate DER participation in the wholesale energy markets. Distribution markets are just one potential solution to enable this participation. [https://www.energynetworks.com.au/resources/reports/2020-reports-and-publications/open-energy-networks-project-energy-networks-australia-position-paper/] Increasing Visibility of Distribution Networks funding ARENA	Does not meet	Not applicable
Managing Assets	Generation, Transmission, Distribution	13. Hazard event & threat impact simulation	The energy system can be characterised by unprecedented levels of uncertainty and new emerging risk. For example, climate change, equipment failure, cybersecurity, outages, and security of supply. Simulating the propagation of hazardous events across the energy system will help evaluate the sequential impact these events have across the industry, and assess the system vulnerabilities.	Will partially meet	The Digital Twin aims to improve Singapore's grid reliability and resilience but enabling the monitoring and testing of different scenarios based on a virtual replica of the grid.	Will partially meet	This is being considered by the Ministry of Interior within Estonia, and the resilience of infrastructure, but not specifically referenced within the energy sector.	Will meet	A key consideration for Australia with climate change . The Electricity Sector Climate Information (ESCI) Project Support NEM decision-makers to access and use tailored climate information to improve long-term climate risk planning. the Australian Energy Sector Cyber Security Framework (AESCSF) responds to the Finkel National Electricity Market Review recommendation 2.10, AEMO in 2018 worked in collaboration with industry and government partners to develop a tailored cyber security framework for the Australian energy sector. (https://aemo.com.au/en/initiatives/major-programs/cyber-security)	Partially meet	Anglian Water were part of the CReDo initiative and looking at the impact of a severe flood. Most treatment works though have backup generators should power outage occur.
Managing Assets	Generation, Transmission, Distribution	14. Multi-pathway resilience modelling	Given the limited amount of data around the impact on the energy system created by extreme events (e.g. climate change), multi-pathway modelling of the resilience of the energy system and its components will help build understanding on what the best potential resolutions should be.	Will partially meet	The Digital Twin aims to improve Singapore's grid reliability and resilience but enabling the monitoring and testing of different scenarios based on a virtual replica of the grid.	Partially meet	happens as BAU but nothing enhanced by the work of digital	Will meet	A key consideration for Australia with climate change . Incorporated in to ISP. Specific appendix on resilience and climate change (including cyber security and fuel security)	Partially meet	No evidence found not to say its not being considered, especially where severe droughts / flooding more common
Managing Assets	Generation, Transmission, Distribution	15. Asset monitoring for improved modelling	Several energy asset models are run on a static set of assumptions (e.g. generation profile based on a summer and winter parameter, transmission modelling and maintenance budgets based on static values, performances factor fixed on a static rate with assets running at optimal state at all time, etc.). Accessing more granular and timely information about the performance and condition of assets would help improve energy network modelling and allow for more accurate optimisation of the network.	Will partially meet	The Asset Twin is able to remotely monitor and analyse the condition and performance of assets and identify potential risks in grid operations early. This allows SP Group (SP) , the transmission and distributor operator, to make informed decisions.	Partially meet	The availbility of central smart meter information provides the suppliers with the ability to better monitor sudden changes in demands and therefore through analysis determine where issues are occuring within the network.	Will meet	Australian Energy Simulation Centre (AESC) through a staged approach. If fully implemented, the AESC will encompass data and models of electricity and gas transmission, distribution and fuel dependencies. The AESC will provide an integrated real-world view of the energy system with 'what if?' analytical capability, built and maintained with actual operating data.	Meet	With more severe rainfall events there is a focus on monitoring the stormwater assets for risk of spill / overflow and impact on treatment works.
Assurance	Distribution	16. Predict localised energy production	Visibility of interconnection across distributed energy generation systems, local aggregators and Smart Local Energy Systems (SLES) and prosumers together with advance forecast modelling of energy production will be key to enable DNOs gaining a correct picture of the load on their networks. Better modelling of localised and decentralised energy production can enable DNOs in balancing supply and demand locally securely and reliably.	Does not meet	Not applicable	Partially meet	DSO's in Estonia are already able to analyse the consumer flows of energy from a centralised data hub hosted by Elering which partially provides this ability to model. However the modelling capability is not yet in place.	Will meet	Due to high amounts of solar, too much reverse power is becoming an issue which having to deal with. The key deliverables of the Community Models for Deploying and Operating DER project include the development of analysis software to assess the value of different community energy models deployed throughout Australia. These analysis tools will then be used to provide recommendations for new tariffs that incentivise community energy models and underpin more efficient use of distributed generation and storage. The project will also provide recommendations that will allow future practical demonstration of these community energy models in Australian communities. https://arena.gov.au/news/distributed-energy-projects-awarded-nearly-10-million/	Does not meet	Not applicable - water typically distributed in catchments, or ground water tightly regulated due to ground water aquifer management.

Use Case Title	Aviation		Rail		Maritime & Shipping		Banking		Climate resilience demonstrator (CReDo)	
	Evaluation	Description	Evaluation	Description	Evaluation	Description	Evaluation		Evaluation	Description
9. Planning the future transmission network	Partially meet	Sharing and openness of airline and airport data means that forward planning is possible	Partially meet	Future needs for transport are modelled depending on developments etc	Will partially meet	There are single ports initiatives. For instance the Portsmouth Port digital twin is aims to assist the deployment of renewable and clean fuels.	Does not meet	not applicable	Will partially meet	As well as providing practical insights, this MVP will demonstrate how the Information Management Framework (IMF) of the National Digital Twin programme supports interoperability of data between organisations. The ambition of the project extends beyond this, however, and plans extend also to consider network restoration and resilience, as well as considering whether a more detailed engineering model of the three networks is required.
10. Optimise connectivity capacity	Meet	Significant amount of flight and airport use data is available commercially via OAG which allows people to use data to analyse market opportunities for new services etc.	Partially meet	A system of systems approach has been discussed in NR since ORBIS times. Difficult to achieve but work is underway in Intelligent Infrastructure / Digital Railway	Will partially meet	There are singular port initiatives that look at this use case. Some example can be found in the repository of the World Ports Sustainability Program. (https://sustainableworldports.org/portfolio/type/port-projects/?area-of-interest=climate-and-energy)	Does not meet	not applicable	Does not meet	
11. Model stability of network	Partially meet	Air traffic control is in effect this control mechanism, and there have been consistent data models/interoperability created, e.g. Euro control (SWIM Data Model)	Partially meet	Network modelling is part of NR's intentions, but not joined up. Have LADS to bring together monitoring and infrastructure	Partially meet	Port operation control has similar control mechanism to ensure stability of its operation and to avoid delays. Many port have use digital platform to guarantee stability of operations. Both the port of Antwerp and Shanghai smart port could be used as examples.	Does not meet	not applicable	Partially meet	lessons to be learnt on collecting data on assets/what data is already available
12. Visibility of transmission & distribution interface	Partially meet	If you consider passengers to be the electrons, data is available on seat numbers, flights and airports to determine numbers flying and available flights or airport slots to accommodate them.	Does not meet		Meet	Information around, ship , cargoes is exchanged with port to coordinate operations on a day to day basis. Single ports are going further to integrate this information across region or with supply and trade industry and try to bring all stakeholders in the maritime value chain to interface in a single place to facilitate direct berthing on arrivals and on-time departures, to reduce wait time at anchorages as well as to enhance ship turnaround time in the planning and scheduling of port resources. Some global efforts have also been initiated efforts to promote wider integration and global coordination are being championed both by businesses, regulators and global players.	Does not meet	not applicable	Partially meet	lessons to be learnt in linking sectors
13. Hazard event & threat impact simulation	Partially meet	Security is a top priority in aviation and so passenger information is shared and also security measures in airports. Not clear if simulated however	Meet	There are a number of initiatives in NR such as the WRACCA	Will meet	There are initiatives in the industry that explore Operational Forecasting and Climate Change Impact Prediction Simulation albeit confined to a specific entity or geographic area. For example, the Smart Port Connected Catapult initiative is looking to explore Climate-Resilient of River Operations in London by Predictive Digital Twin.		not applicable	Meet	Credo is simulating real world scenarios. Outcome of the connected digital twin is showing which assets could suffer from natural disasters (flooding currently modelled)
14. Multi-pathway resilience modelling	Does not meet	Extreme events such as the Icelandic volcanoes eruption does impact flights, however air traffic control dictates the reaction	Partially meet	Various projects in NR looking into resilience of network to climatic impacts	Will partially meet	There are singular examples across the industry such as the Port Resilience Shift work (https://www.resilienceshift.org/resilience4ports/	Does not meet	not applicable	Meet	CReDo will develop a digital twin of the infrastructure system comprising Anglian Water's water and sewerage network, BT's communication network and UKPN's power network in a specific location. The digital twin maps a weather scenario from a present or future climate to system-level consequences, through a series of components as in the diagram, for support of operational and capital planning decisions.
15. Asset monitoring for improved modelling	Partially meet	Example of Rolls Royce engine modelling for one companies optimisation of performance of aircraft.	Meet	Railways regularly monitoring network for condition assessment. Brought together in tools like LADS with infra data for root cause analysis and intervention strategy	Will partially meet	There are singular port initiatives that look at this use cases. Some example can be found in the repository of the World Ports Sustainability Program (https://sustainableworldports.org/portfolio/type/port-projects/?area-of-interest=digitalization)	Does not meet	not applicable	Does not meet	
16. Predict localised energy production	Does not meet	not applicable	Does not meet	not applicable	Does not meet	Not applicable	Does not meet	not applicable	Partially meet	There could be lessons to be learnt from linking weather data to energy data here.

Use Case Category	Energy System Segment	Use Case Title	Use Case Description	Singapore (Energy Sector)		Estonia (Energy Sector)		Australia (Energy Sector)	
				Evaluation	Description	Evaluation	Description	Evaluation	Description
Managing Assets	Distribution	17. Real time distribution network optimisations	By collecting continuous and real-time data on the state of transmission and distribution lines at various points (e.g. temperature, voltage, or current) as well as other complementary datasets through digital sensors, efficiency gains can be achieved by lowering the rate of losses in the delivery of power to consumers. Remote monitoring allows equipment to be operated more efficiently and closer to its optimal conditions, and flows and bottlenecks to be better managed by grid operators.	Will partially meet	Network Twin is able to provide SP with a high-level assessment of the impact of demands on the grid and any upgrades required for different scenarios.	Will partially meet	Elering have existing remote monitoring on the network like other TSOs, and in addition to the full coverage of smart meters which is centrally available provides the ability to monitor the network. As it moves from hourly to half hourly data in future this is moving towards near-time monitoring of energy consumption.	Will partially meet	This is going to be particularly challenging to implement in the current environment of such a distributed and disjointed set or energy organisations
Managing Assets	Distribution	18. Optimise energy storage usage	Optimise the usage of energy storage to better manage distribution networks and defer the need to reinforce networks as demand grows. This will be key to help balance the increasingly localised supply of energy.	Will partially meet	The Digital twin aim to help the optimisation of asset investment which could include storage.	Does not meet	Not a significant focus on this aspect by Elering but it is likely with the policies in place that storage will also be considered in future with the increasing mix of renewable energy.	Will meet	The Emerging Generation and Energy Storage (EGES) work identified improvements to the regulatory arrangements for registration and participation of grid-scale resources in the National Electricity Market (NEM). This work identified the challenges and opportunities facing proponents of new grid-scale generation and load business models, including improving the NEM's arrangements to facilitate better integration of grid-scale energy storage systems (ESS) and 'hybrid' models. AEMO considers this work a priority because they anticipate continued growth in the connection and registration of ESS energy storage technologies to support variable or renewable generation and, more broadly, the national grid. https://aemo.com.au/en/initiatives/trials-and-initiatives/emerging-generation-and-energy-storage-eges-grid-scale
Strategy & planning	Distribution	19. Planning future distribution network	By bringing together data around demand forecast (e.g. travel, heating), network models, any assets connected (including those behind the meter), upcoming connections, network components, usage conditions, performance data, and more, DNOs can better simulate future networks needs and more accurately plan their medium and low voltage networks.	Will partially meet	The Digital twin aim to help the optimisation of asset investment and better network planning.	Partially meet	Having the central data hub of all consumer smart meter information allows DSOs to monitor performance of their supply network.	Will meet	*The Australian Energy Simulation Centre (AESC) will encompass data and models of electricity and gas transmission, distribution and fuel dependencies. The AESC will provide an integrated real-world view of the energy system with 'what if?' analytical capability, built and maintained with actual operating data. *Integrating distributed energy resources for the grid of the future - https://www.aemc.gov.au/sites/default/files/2019-09/Final%20report%20-%20ENERFR%202019%20-%20EPR0068.PDF
Assurance	Retail	20. Improve demand forecasting	By collecting and aggregating in real time energy consumption information, retailers will be able to understand actual consumption patterns. This will enable better services to be delivered to their customers, and if shared would benefit the overall balancing of the grid. More granular consumption data can then drive sophisticated analysis and modelling to predict and forecast demand more accurately.	Does not meet	Not applicable	Meet	Hourly Smart meter data is available in a central hub hosted by Elering, available (with consent) to suppliers who can offer consumers deals based on their consumption patterns.	Will partially meet	AEMO Electricity Demand Forecast Methodology Document https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2020/electricity-demand-forecasting-methodology/final-stage/electricity-demand-forecast-methodology-final-determination.pdf
Strategy & planning	Retail	21. Better services to customers	By utilising aggregated open data on electricity consumption, production by source, trade, CO2 emissions, transmission line capacity, and price the on wholesale market, new consumer products and services can be developed. This will enable retailers to lower consumer turn-over and provide more holistic solutions.	Does not meet	Not applicable	Meet	Consumers are provided hourly information about the CO2 emmissions and origin of energy so they can make decisions. They are also informed about energy prices, packages and outages via apps. This has improved customer satisfaction greatly and also reduced the number of enquiries being dealt with by the DSOs	Will partially meet	the different regions are not connected, but within the regions the connections are reasonable. There is an EV Grid integration working group to address the Challenge "There is no one forum, work stream or organisation responsible, or focussed on EV grid integration" While the ISP Rules pave the way for actionable transmission projects through the RIT-T process, there is no similar regulatory mandate for other resources, such as generation and storage. Rather, the ISP offers a signal to inform the decisions of private developers. Market design is therefore crucial for both regulated and private investment to deliver the least-cost outcome for consumers. (https://aemo.com.au/-/media/files/major-publications/isp/2020/2020-isp-overview.pdf?la=en)
Managing Assets	Consumption	22. Smart demand response	Digitalisation will allow for a greater number of electricity consumers to respond flexibly to signals from the system. Digital connectivity allows appliances and equipment to be monitored continuously and connected to the grid. This connection could be used to shape demand profiles to respond to specific supply scenarios – with consumers and/or their assets receiving and acting upon specific signals and instructions from the network.	Does not meet	Not applicable	Partially meet	This is certainly the intention of the original smart grid plan, however users are not utilising the application or taking flexible plans in the numbers expected	Will partially meet	There are consultations and pilot projects and in South Australia, New South Wales and Victoria. These are focusing initially on demand response initiatives with air conditioners, electric vehicle chargers, pool pump controllers, and electric resistive storage water heaters. The Distributed Energy Integration Program (DEIP) is a collaboration of government agencies, market authorities, industry and consumer associations aimed at maximising the value of customers' distributed energy resources (DER) for all energy users. Also: DEIP Standards, Data and Interoperability Working Group DEIP Dynamic Operating Envelopes workstream Distributed Energy Integration Program Access and Pricing Work Package DEIP EV Working Group DEIP Interoperability Steering Committee (ISC) https://arena.gov.au/knowledge-innovation/distributed-energy-integration-program/
Managing Assets	Consumption	23. Prosumers	Matching demand to the needs of the overall system in real time opens up the opportunity for millions of consumers and producers to sell electricity or provide valuable services to the grid. With sufficient connectivity it allows the linking, monitoring, aggregation and control of large numbers of individual energy-producing units and consuming equipment - so these can be used to best match demand. These assets could be, for example, a rooftop solar PV system on a home, or a boiler on an industrial site, or an EV.	Does not meet	Not applicable	Does not meet	No information about this requirement was available	Will partially meet	Connection Simulation Tool (CST) a cloud-based resource available for developers to test and tune power system models for new generation projects planning to connect to Australia's National Electricity Market (NEM). Which aims to reduce risks, costs and time to approve the connection of new generation projects. Large amounts of Solar power by consumers. An Small Generation Aggregator (SGA) supplies electricity from one or more small generating units to the National Electricity Market (NEM) and is financially responsible for the electricity provided. Community batteries.
Strategy & planning	Consumption	24. Planning of local LCT implementation	Bringing together data from several parties around local distribution networks, demand forecasting, power generation forecasting, and emissions monitoring will enable local actors such as Local Authorities and Smart Local Energy Systems (SLES) to model and understand the best mix of Low Carbon Technology to achieve 2030 net zero goals. A specific Local Authority use case is currently being delivered through Modernising Energy Data Access (MEDA) via Open Energy. MEDA is also exploring EV set up in housing developments.	Does not meet	Not applicable	Does not meet	Not applicable	Will partially meet	Have formed a Distributed Energy Resource working Group but still differences by state, multiple equipment suppliers (e.g. EV charging)

Use Case Title	Water		Aviation		Rail		Maritime & Shipping		Banking		Climate resilience demonstrator (CReDo)	
	Evaluation	Description	Evaluation	Description	Evaluation	Description	Evaluation	Description	Evaluation		Evaluation	Description
17. Real time distribution network optimisations	Partially meet	Increasingly used to monitor flows in stormwater / sewage systems, SCADA in pressured water systems	Partially meet	This is the equivalent of Airport management of aircraft, passengers and their baggage	Partially meet	Certain assets on network are monitored such as S&Cs and signals which could cause operational issues	Partially meet	Several example of where single port are trying to achieve real time management of ships and port operations across . Probably the most advance example of a Digital Twin covering this use case is the ongoing Digital Twin being built for the Port of Antwerp.	Does not meet	not applicable	Does not meet	
18. Optimise energy storage usage	Meet	Water requires storage in reservoirs to balance periods of high / low rainfall. Also effluent stored until treatment works have capacity. Also leak detection in network to reduce wastage in system	Does not meet	not applicable	Does not meet	not applicable	Will partially meet	There are singular port initiatives that look at this use cases. Some example can be found in the repository of the World Ports Sustainability Program. (https://sustainableworldports.org/portfolio/type/port-projects/?area-of-interest=climate-and-energy). For instance the Port of Guangzhou is looking to improve the Rate and Reliability of Onshore Power Supply.	Does not meet	not applicable	Does not meet	
19. Planning future distribution network	Meet	Water networks for new developments constantly being modelled by water companies.	Partially meet	Arup has created an Airport Demand Analyser tool based on OAG data to determine where opportunities lie	Partially meet	Future transport needs are being considered by rail networks based on development etc and demand change at each station / line	Partially meet	Port operators plan for future demands as part of their ongoing management practices.	Does not meet	not applicable	Partially meet	model would show which assets are at threat and therefore DNO would be able to better decide which assets need reinforcement.
20. Improve demand forecasting	Partially meet	Water companies will monitor water consumption and in times of drought impose bans such as hosepipe bans to restrict usage. This ability to manage periods of drought used by water planners for areas as certain parts of country have higher demand than supply.	Partially meet	passenger demand is constantly evolving and so I assume there is significant amount of analysis completed. Also analysis of flight slot availability conducted by airlines to determine new services, however dependent on constraints such as airport boarding and air traffic limitations	Partially meet	Rail do not really work in such a retail environment. TOCs possibly do more so in their ticketing strategies, unlikely sophisticated modelling though	Partially meet	Ports capacity and cargo handling and demand information are key input to the wider shipping, logistics and trade industry. Port traffic demand information are essential output for several connected industries. There are currently several digitalization initiatives led and supported by international bodies aiming to create a global interconnected maritime supply system	Does not meet	not applicable	Does not meet	
21. Better services to customers	Partially meet	The delivery of water / sewerage supply to customers is planned by companies, with the aim to improve customer satisfaction for aspects such as water pressure etc.	Meet	Clearly many flight aggregation websites making flights available to customers such as Skyscanner / Kayak.com etc. This is not necessarily forecasting however	Meet	Open data such as put out by TfL has enabled 3rd party apps to present the real time train information for customers to make transport decisions.	Partially meet	Ship and cargo positioning data provided by onboard AIS transponders a is widely used across the industry. Several ports have built on increase digitalisation of process to build better services for a variety of stakeholders. Some good example of this are seen in not Shanghai and Singapore ports.	Meet	The introduction to open standard for Application Programming Interfaces in UK banking helps customers have more control over their data and to makes it easier for financial technology companies (FinTech's) or other businesses to make use of bank data on behalf of customers in a variety of helpful and innovative ways. This helps to drive more competition in banking to improve outcomes for customers.	Partially meet	Credo promotes better services to customers by keeping the lights on, due to better system resilience brought about from better decisions made using the digital twin.
22. Smart demand response	Does not meet	No evidence found not to say its not being considered, especially where severe droughts common and water restrictions imposed. Increased installation of water meters means users charged for actual water use compared to a standard charge previously but not in any dynamic way.	Partially meet	Although flight schedules will change rapidly to passenger demand due to the airport slots, ticketing etc. due to the data sharing, individual passengers can be reallocated flights on cancellations etc	Does not meet	Rail not as dynamic to respond to such changes	Will partially meet	Several example of where single port are trying to achieve real time management of demand by streamlining the clearances needed to enter ports. Some good example of this are seen in not Shanghai and Singapore ports.	Does not meet	not applicable	Does not meet	
23. Prosumers	Does not meet	not applicable mainly other than own borehole which is metered usually for personal use only	Does not meet	not applicable	Does not meet	not applicable	Does not meet	Not applicable	Does not meet	not applicable	Does not meet	
24. Planning of local LCT implementation	Partially meet	Treatment works especially planned for lower energy use and use of Oxygen from green hydrogen production by product for sludge treatment	Partially meet	More websites are showing the CO2 of flights, and so if aircraft are more efficient with one airline over another - it will potentially impact demand.	Partially meet	Rail will do demand forecasting for rail services in terms of timetable planning and train per hour nos.	Will meet	There are singular port initiatives that look at this use cases. Some example can be found in the repository of the World Ports Sustainability Program. (https://sustainableworldports.org/portfolio/type/port-projects/?area-of-interest=climate-and-energy)	Does not meet	not applicable	Does not meet	

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