UK Energy Research Centre

# Whole Energy Systems

## An Energy Data Centre Introductory Guide

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## Introduction to UKERC

The UK Energy Research Centre (UKERC) carries out world-class, interdisciplinary research into sustainable future energy systems.

It is a focal point of UK energy research and a gateway between the UK and the international energy research communities.

Our whole systems research informs UK policy development and research strategy.

UKERC is funded by UK Research and Innovation.

## Document Purpose

This document is an introductory guide to the topic of 'Whole Energy Systems'. It highlights the main concepts, policies and technologies which influence this topic area in the UK, and is written for those with limited prior knowledge of whole energy systems. This document will not cover all relevant issues in this area but will serve as a starting point for those looking to research further.

The 'research and innovation' section is based largely on projects which can be found in the UK Energy Research Centre - Energy Data Centre's (UKERC EDC) projects database. This section is not exhaustive and focuses on publicly, rather than privately, funded research; as such, it will not cover all research in this area.

When referring to the role of UK Governments, the document focuses on policies rather than regulations or specific funding packages. Policies help to give a broad sense of Governments' direction without getting into the technical details which may: a) distract from the key messaging of the document and b) be subject to frequent change.

This document avoids using technical language or acronyms where possible and is written in plain English. As the use of some technical language is unavoidable in such documents, this guide lays out definitions and explanations as these terms arise.

The contents of this guide have been reviewed by domain specialists to ensure they are a useful and accurate introduction to the topic.

Suggestions about factors which should be included in future editions are welcome and should be sent to EDCManager@stfc.ac.uk

# 1. Overview

A ‘whole systems’ approach to energy seeks to encompass all aspects of the energy system and its interdependencies by developing evidence to support scenario building and models that demonstrate how this system will evolve (UKRI, 2024). It provides insights into how changes to individual components can influence broader system behaviour (Energy Systems Catapult, 2024).

This approach integrates engineering, economics, and physical, environmental, and social dimensions, viewing the energy system as dynamically complex. It broadly encompasses the technologies, physical infrastructure, institutions, policies, and practices within the UK that work together to deliver energy services to consumers.

Prior to the UK Government’s Energy Review in 2004, the delivery of energy in the UK was largely managed via three separate systems - electricity, natural gas and liquid hydrocarbons. Although there were interactions in the margins of these three systems (not least the use of natural gas for electricity production), they were largely dedicated to separate end uses – an electricity system, a natural gas system for heat, and liquid hydrocarbons system for transport.

The 2004 review, authored by the Cabinets Office’s Performance and Innovation Unit, was purposed with driving the transformative change required to modernise the UK’s energy system. It took a more holistic perspective, emphasising the need for a strategic and integrated approach to dealing with the UK’s energy challenges and, in doing so, laid the foundations for whole systems thinking within the energy sector.

Key characteristics of a whole systems approach include:

- **Relatively unconstrained and highly flexible** - the approach is designed to accommodate emergent characteristics, like the integration of renewable energy production, reflecting the volatile nature of the energy system.
- **Interdisciplinary** – drawing on inputs from a broad range of disciplines, to offer a rounded perspective and maximise social, economic, and environmental benefits.
- **Holistic problem-solving** - by considering the entire energy system, whole systems thinking addresses interdependencies, ensuring that changes in one part of the system do not lead to unmitigated negative consequences elsewhere. It also facilitates cross-vector integration (e.g. the greater use of electricity to supply the transport and heat sectors), enabling a more coordinated approach to infrastructure development.

# 2. Government direction

## 2.1 The UK Government

Since the Energy Review in 2004, the UK Government has generally sought to take a whole systems approach to addressing energy challenges in the UK. More recently, in 2020, by releasing 'The Energy White Paper: Powering our Net Zero Future', the UK Government implicitly aligned achieving their net zero goals with principles of whole systems thinking. While 'whole systems' goes unmentioned, the paper introduces the idea of treating the energy system holistically, referencing a need for cross-sector collaboration. An explicit commitment to whole systems thinking however, arrived soon after, in the release of the 'Net Zero Strategy: Build Back Greener', in October 2021. The narrative features numerous mentions of 'whole systems', using it to address issues of cross-vector interconnections and integration. This line of thinking became intrinsic to central government energy policy from that point onwards; reappearing in the 'UK Hydrogen Strategy' and being the driving force behind the inception of the National Energy System Operator (NESO) – an independent body set up to oversee the integration of electricity and gas networks and manage how they interact with demand sectors. NESO's whole systems approach is well demonstrated in both their Clean Power 2030 and Future Energy Scenarios (FES) reports.

## 2.2 Devolved governments

In Scotland, a whole systems approach to managing the energy system was first outlined in 2017, in the 'Scottish Energy Strategy', published by the Scottish Government. In this document, a whole systems methodology is acknowledged as key to achieving the country's energy ambitions. This sentiment is echoed in the 'Energy Strategy and Just Transition Plan' published in 2023, and in the Distribution Future Energy Scenarios documents produced by the operators of the various energy networks in Scotland.

In Wales, the 'Well-being of Future Generations Act', published in 2015, set the tone for whole systems thinking across all sectors, including energy. Then, in 2021, in the 'Net Zero Wales Carbon Budget 2', published by the Welsh Government, whole systems terminology started to emerge. In this report, Welsh Government committed to a major programme of LAEP roll-out, demonstrating their vision for the role of whole systems thinking in the energy transition. A whole systems methodology was also adopted to help develop the 'Heat Strategy for Wales' in 2024.

Whole systems terminology first emerged in Northern Ireland around the same period. In 2021, 'The Path to Net Zero Energy' document, published by the Northern Ireland Executive, committed them to using a whole systems approach on their journey to net zero energy. Their involvement in the Integrated Single Electricity Market (I-SEM) with the Republic of Ireland – an integrated wholesale electricity market arrangement – demonstrates their commitment to whole systems thinking.

## 2.3 Local authorities

Parallel approaches to whole systems thinking have also been adopted at regional and local levels. Pioneered initially by the Energy Systems Catapult in 2017, through the formulation of a whole systems framework for the development of Local Area Energy Plans (LAEPs), it has since been reinforced by the Energy Revolution Consortium (EnergyREV), part of the UKs Prospering from the Energy Revolution (PFER) programme. Both EnergyREV and PFER were funded by UKRI and, deeply rooted in whole systems thinking, sought to accelerate the innovation of smart local energy systems (UKRI, 2018). The latest development is NESO's role as Regional Energy Strategic Planners, tasked with 'enabling the coordinated development of the energy system across multiple vectors' (Ofgem, 2024).

# 3. Key context

## 3.1 Background

The UK energy system, once heavily reliant on coal, has undergone significant changes over the past century. Initially, in the wake of the oil crises of the 1970s, these changes were driven by concerns about energy security, resulting in a more diversified network. Yet, a major dependency on fossil fuels persists - gas for heating and electricity, and petrol and diesel for transport. This reliance accounts for 79% of energy demand (NESO, 2024) and 70% of territorial emissions (DESNZ, 2024). However, as the system has evolved with time, so have the drivers behind its change.

Beyond continuing concerns about energy security, especially amid rising geopolitical tensions, the requirement for contemporary transformation reflects diverse factors, including national commitments to reduce greenhouse gas emissions, the need to address ageing infrastructure, energy affordability, and growing consumer demand (UKRI, 2024). These factors collectively underscore the urgency of a decisive and accelerated shift from fossil fuels to renewable energy sources, highlighting the need for systemic change.

The direction the system is heading to address these demands, is counterintuitive to the way it has traditionally functioned. For decades the electricity, gas, and liquid fuel systems have been managed in isolation. However, as the grid transforms to accommodate more renewables, the energy system is undergoing a transition to become more cross-vector and interlinked (Energy Systems Catapult, 2024). This necessitates a shift away from linear thinking about energy, where siloed solutions overlook the complexity of the overall system. Instead, a whole systems approach is needed – one that holistically integrates energy, environmental, and societal dimensions to deliver sustainable and equitable outcomes.

## 3.2 Energy system transformation

The need for a whole systems approach is made clearer by looking at the changes that will be required and considering the implications of these changes, both to the energy system and to other sectors. NESO's FES report offers the most comprehensive prediction of how the UK energy system will change as we progress towards 2050.

- **Integration of renewable technologies** – as fossil fuel power plant are being phased out, the grid is losing its primary mechanism for balancing supply and demand. Variable and less predictable renewable generation, such as wind and solar, has to be supplemented by complementary solutions like energy storage, grid flexibility, and demand-side management.
- **Electrification of heat and transport** – as low-carbon-technologies, such as heat pumps and electric vehicles become increasingly widespread, the use of fossil fuels in residential heating and road and rail transport will gradually decline. Since these two sectors are the biggest consumer of fossil fuels, this highlights the scale of electrification that will be required. To meet demand, there will have to be substantial grid reinforcement and extensive development of new connections.
- **Transition to hydrogen and low-carbon fuels** – hydrogen and other low-carbon fuels offer a close substitute for fossil fuels, making them essential for hard-to-decarbonise sectors such as industry, aviation and shipping. However, these lower carbon fuels face challenges due to their resource intensive production processes. Hydrogen production (which in the FES scenario is predominantly delivered using renewable electricity) is highly energy intensive, significantly increasing electricity demand. Meanwhile, low-carbon fuels, such as biofuels and biogas, require significant land resources, raising concerns about land use competition and other environmental impacts.
- **More decentralised grid** – unlike fossil fuels, many low-carbon generation technologies – such as wind (limited by wind availability) and nuclear (restricted by planning constraints) – can't be geographically located close to areas of high demand. Additionally, as renewables increasingly penetrate the grid, there will be a gradual shift away from the centralised network of today, where large-scale electricity generation is transmitted through high-voltage lines to end-users, to a more distributed system where the sources of generation are more embedded across the system. This necessitates innovative solutions, such as smart grids, to handle and use electricity closer to its source, reducing transmission inefficiencies and alleviating stress on transmission lines. This shift towards smart grids will also support widespread adoption of electric vehicles, as charging infrastructure can serve as a flexible mechanism to manage supply and demand, improving grid stability while optimising renewable energy usage.

## 3.3 Interdependencies

The increasing interconnectedness of energy systems creates interdependencies, wide-ranging influences well beyond the immediate supply and demand context. As the system evolves, both internal and external interdependencies will emerge, encompassing a wide range of dynamics.

- **Energy supply and infrastructure** – as fossil fuel plants are phased out, cross-vector interdependencies will play a critical role in ensuring energy demand continues to be met. The electrified sectors and those running on hydrogen (assuming the majority of production is via electrolysis, as in the FES report), will both rely on renewable energy technologies to produce enough electricity to match their demand. In turn, renewable generation sources will be reliant on energy storage technologies and smart grids, to manage their intermittency.
- **Digitalisation** – the emergence of an increasingly cross-vector energy supply, smart grids, and demand-side management necessitate advanced management software and modelling to handle large volumes of data and optimise supply and demand. This reliance exposes the energy system to risks, such as cyber-attacks or equipment damage, which could compromise software functionality, resulting in system failure.
- **Resources** – fabrication and installation of new technologies will rely on secure supply chains and a skilled labour force. The security of these supply chains, costs, and speed of production, will all be underpinned by critical material supply constraints.
- **Policy** - government policy will ultimately dictate the direction, and pace, of system reform. New renewable projects will depend on the Government establishing market conditions that facilitate profitability. Successful system transformation will be hinged on geopolitical relations, which significantly influence taxation rates and the availability of critical materials. Also, as regional interdependencies deepen, with countries becoming increasingly dependent on cross-border energy exchanges, these connections could become a vulnerability in times of heightened geopolitical tension.
- **Geography** – in addition to any geopolitical tensions, both the production of biofuels and the roll-out of renewable technologies will compete with existing land-use requirements and have to overcome planning procedure regulations.
- **Environmental** – legislation like Biodiversity Net Gain (introduced in the Environment Act 2021) creates a direct dependency between project approval processes and ecological improvements. It mandates that developers leave habitats in a better state than they found them. Furthermore, as climate change increasingly strains freshwater supplies, and water-intensive processes like critical mineral mining and hydrogen production become more widespread, the relationship between water and energy – coined the water-energy nexus – will have to be carefully managed to maintain a sustainable balance. Critically, the Environment Agency stipulates that all project developments require permits for activities that may affect air, water, or land

quality. This includes stringent oversight of emissions handling and waste management, particularly the safe disposal of hazardous and radioactive waste and captured emissions, ensuring no long-term risks to ecosystems or public health.
- **Social** – widespread adoption of new technologies and maximisation of demand-side management will be dependent on consumer acceptance and engagement. Ultimately, affordability and accessibility will be the main drivers behind adoption rates. If people feel they are excluded from the transition, hostility around the net zero goal could be aggravated, making energy system progression vulnerable to political weaponisation, potentially stymying progress.

# 4. Research and innovation

## 4.1 Energy data and modelling

Data, and its management, are increasingly seen as the enabler to energy system decarbonisation. Currently however, poor data quality, missing or non-digital information, and restricted access, limit data's informational value, stifling innovation and efficiency (Energy Systems Catapult, 2023). Research into energy data focuses on improving cybersecurity, operational data use, and AI integration to optimise energy systems and drive innovation. Some projects address these challenges by exploring real-time data use for flexibility and demand management, while others promote accessibility and interoperability, to ensure that data can be easily discovered, shared, and utilised by various stakeholders. Meanwhile, digital-mapping and digital-twin technologies enhance infrastructure planning by allowing for real-time visualisation, analysis, and simulation of energy networks and assets.

There is a long history of energy modelling in the sector, and resultant software like TIMES (a widely used model created by University College London), ESME (Energy Systems Modelling Environment) and ITAM (Infrastructure Transition Assessment Model) also feature in the research.

## 4.2 Energy systems for heat

Research at a national level largely focusses on decarbonising the heating network, trying to address this by developing improved whole systems scenarios for heat. These aim to utilise cross-spectrum inputs to inform political narratives, behaviours, and market changes. At a more local level, research is focused around optimally tailoring different low carbon heat solutions to meet location specific requirements. Part of this involves identifying solutions to better manage interdependencies between heat and other energy vectors; particularly in the case of hybrid heating systems, where heating demand will be met by both hydrogen and electrification, and in industrial heartlands, where applications of waste heat are being explored. Using heat as a source of flexibility, to help supply and demand is another pertinent area of research. This focuses on ways to leverage the heat network and its assets, such as thermal storage or smart meters, to store and shift energy, in both centralised and decentralised settings.

## 4.3 Energy for mobility

Research surrounding energy for mobility explores key aspects of the transition to sustainable transport, focussing on passenger vehicles and broader mobility systems. Projects explore the relative constraints and opportunities presented by the usage of alternative fuels, particularly hydrogen, and a transition to electric vehicles.

There is a focus on the readiness of power networks to facilitate widespread electric vehicle adoption, with research looking at how the sharp increases in peak demand, caused by electric vehicle charging, can be mitigated with the development of markets to incentivise smart charging. Meanwhile, other research focuses on reducing reliance on personal car ownership by promoting alternative modes of travel. This includes optimising road usage through better integration of micromobility vehicles, shared mobility services, and autonomous vehicles, fostering more sustainable and efficient transport networks.

Research also explores how a widespread transition to electric mobility can be inclusive of disabilities and vulnerable groups. Some studies examine how electric mobility can be both environmentally beneficial and socially equitable.

## 4.4 Energy infrastructure transitions

One aspect of infrastructure research is centred around transmission, focussing on ways to improve grid network resilience, and efficiency, as grid reliance increases. The research focuses on cable asset management, forecasting the impact of temperature extremes, enhancing network capacity with renewable generation, and addresses issues such as declining system inertia, and assessing the impact of cogeneration. This research extends to system resilience and adaptability, whereby projects have outlined the necessity of storage solutions to build out system flexibility and explored the function of battery energy storage systems to restore power in energy outages. Some of the outputs include recommendations for planning, coordination strategies, and roadmaps to electrical system decarbonisation.

Another key area of infrastructure research is concerned with the governance of major system change, and how these changes can be used to bring positive benefits to communities; reshaping governance by moving away from the idea of individuals being ‘passive energy consumers’, empowering them to make their own energy related decisions, and encouraging transition engagement through community ownership.

There is also research that concerns the gas distribution network, and its management throughout the net zero transition, exploring in what capacity it should be maintained or repurposed (for hydrogen) to keep some flexibility in the energy system.

## 4.5 Energy, environment and landscapes

Critical sustainability challenges also appear in the research, from assessing biodiversity impacts in energy supply chains to looking at advancements in nuclear decommissioning to bring positive changes to local ecosystems. Principles of circular economy also feature to transform waste into valuable products, especially for critical minerals and construction and agricultural industries.

The water-energy nexus is another theme which is explored – seeing how renewable energy and green hydrogen impact water resources, what challenges this creates for water infrastructure, and how to make the water system resilient enough to withstand this increased consumption. Innovation includes modelling tools for water-energy dynamics, adaptive water-use strategies for hydrogen (such as using wastewater, to help facilitate hydrogen production in isolated communities without extensive water infrastructure), and frameworks for water demand planning in energy transitions.

## 4.6 Local and regional energy systems

At a local level the research predominately pertains to energy planning. There is a focus on the development of online, self-service, tools to help support councils in the Local Area Energy Planning process. Meanwhile, other projects explore the benefits of using community labour in Smart Local Energy Systems to help inform policy on ownership, incentives, and benefit-sharing to ensure fair integration of community energy. On the theme of decentralisation, there is research that touches on improving energy system resilience in urban environments through increases in self-consumption of local energy resources, by re-structuring the energy network to include flexible microgrids linked to local generation and storage resources.

The modelling approaches mentioned previously are also used to inform infrastructure requirements, and their associated costs, in regional decarbonisation pathways.

## 4.7 Public engagement/equity

Projects focus on driving community engagement to overcome technical, social, and economic barriers in energy transitions, particularly in decarbonizing heat and enhancing energy access for vulnerable communities. Emphasis is placed on creating consumer archetypes and leveraging insights from local stakeholders to improve energy planning. Additionally, governance reforms aim to involve the public in energy system innovation, while studies explore how community-driven initiatives in the UK are reshaping energy for social and economic transformation. These efforts contribute to the development of inclusive, redistributive policies for equitable decarbonization, ultimately striving for a fair, sustainable, and resilient energy future for all.

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