Systems Intelligence – an imperative for the energy transformation

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Context

Australia's commitment to reaching net zero emissions by 2050 implies a fundamental transformation of the economy and society. Energy system transformation is necessarily the foundation for achieving net zero, due both to the sector's high direct contribution to current emissions[1] and the role of clean energy in enabling broader decarbonisation across other economic sectors.

A decarbonised future-state energy system will be more decentralised, interconnected, and dynamic than today. Sectors and disciplines that have not traditionally been closely connected are becoming coupled. Energy users are facing a paradigm shift towards becoming 'part of the system' rather than just being consumers of energy. Large-scale, structural change and innovation will be needed while maintaining operational performance, economic prosperity, and community support.

Energy transformation is a systems problem

Reconfiguring our interconnected, carbon-heavy energy flows to net zero in a few decades is a formidable integrated systems challenge. Power system transformation, large-scale electrification and fuel switching, and regional economic transitions are all interconnected and complex. A successful energy transformation will not be achieved by creating new technologies, regulations, economics, environmental or social considerations in isolation; rather, it will be enabled by these factors coming together as an integrated and coherent system-of-systems resting on a sound system architecture.

Our urgent and multifaceted energy transformation demands state-of-the-art 'socio-technical systems intelligence': deep societal engagement to shape the future of energy to benefit all Australians; integrated analytical capabilities to guide and de-risk energy transition pathways; and secure digital intelligence for efficiency and equity in future energy system operations. Using contemporary systems science and engineering methodologies will be essential 'to ensure the pieces work together to achieve the objectives of the whole'[2], with a balanced scorecard of societal outcomes – sustainability, resilience, equity and economic opportunity – as the aim.

We will need to leverage the systems expertise from other sectors and other countries to support our energy system transformation. The powerful capabilities of model-based systems engineering (MBSE), developed specifically to structure and de-risk complex engineered system design and transformation, are presently being used to a limited extent in the Australian energy sector. There is a significant

[1] Australia's National Greenhouse Accounts, Department of Climate Change viewed 17 September 2024 https://greenhouseaccounts.climatechange.gov.au/
[2] Systems Engineering Vision 2035 report by INCOSE, Value Statement, page 4 https://www.incose.org/publications/se-vision-2035

opportunity to collaborate with partners in countries like the UK and US that are embracing MBSE for energy applications, as well as opportunities to benefit from the knowledge and transferable skills of systems practitioners in other sectors like defence, aerospace, transportation and ICT, where modern systems approaches are well-established.

Model-based systems engineering (MBSE) is well-established in sectors such as aerospace.

Place is key

Our national energy transformation is the aggregation of many local transitions in energy infrastructure, industries and communities. Infrastructure assets are being commissioned and decommissioned; individual businesses and industries are investing in new technologies; households are making choices on energy solutions, vehicles and appliances; and climate change is playing out with geographical variations across the country. Changes can be clustered in precinct-, community- or regional-level initiatives, and further into broader jurisdictional decisions and regulation. Local conditions and preferences are always important.

Energy systems intelligence must capture and respect these local nuances. Contextualised, granular and trans-disciplinary analysis is required to inform decisions across spatial scales from precinct level to national level, flexibly and coherently. Modern systems science and engineering can help to organise and quantify the key elements in such a challenge. A multilayered approach is needed that can consider and integrate the buffers and flows of mass and energy, data, money, rules, and behavioural norms in a consistent manner.

Adjacent systems matter

The energy system does not operate in isolation. Not only must highly interdependent yet historically siloed energy types such as electricity, natural gas, oil, and coal be considered as a holistic system, but the transformation must also take into account carbon, water, climate, mineral resource, manufacturing, and land-use constraints as practical and evolving realities.

The future of energy cannot be analysed independently of future climate. Sun and wind are critical for power generation; water is essential for hydropower generation and storage, cooling lakes, and the emerging hydrogen ecosystem; and weather conditions influence both energy demand and the risks to energy supply from natural hazards. Energy systems intelligence must incorporate connections to the climate system.

The future of energy cannot be analysed independently of future climate.

There is a growing dependency between energy and telecommunications. In our increasingly distributed, connected and dynamic energy system, digitalisation and innovative digital solutions are vital for efficient system operations, asset utilisation, load flexibility, buffer management, system reliability, and affordable and equitable outcomes for consumers. Resource orchestration offers substantial benefits if implemented carefully, with preserved consumer agency. However, digitalisation also brings with it the heightened need for cyber-resilience, strong standards and privacy protections, and the development of robust system architectures across both energy and digital domains.

An important part of systems intelligence for the energy transformation is to incorporate resilience as an explicit design goal, recognising the influence of the concurrent trends of climate change and digitalisation on the future energy system. Both short-term and long-term resilience need to be addressed and an adaptive approach taken, given the inherent uncertainties and evolving nature of these areas.

Community involvement is vital

The energy transformation will present new ways for people to relate to energy, and will generate new concerns, risks, and opportunities[3]. There is a need to help people understand the energy transformation, help them to identify and realise the benefits that the transformation can provide, and to help mitigate the risks of negative outcomes that may emerge. Mis- and disinformation require active mitigation. The polarisation of community sentiment in regions where large-scale renewable developments like wind farms are being proposed is an example of this. The energy end-user can no longer be considered a passive participant served by infrastructure operators, but rather must be

[3] See, for example: Understanding Australian attitudes toward the renewable energy transition, 2024, https://www.csiro.au/en/research/environmental-impacts/decarbonisation/energy-transition

empowered to provide social licence and actively participate, where willing, in the energy system transformation and operation.

Caption: Some renewable energy projects have stalled due to community opposition. Community involvement and co-design is important from the outset.

Energy is shifting from a seemingly endless, easily controllable, centralised, private resource to one that is more constrained, less predictable, less centralised, and more publicly shared. Ideally, Australian households and businesses will adapt to these changes in a way that maintains their quality of life and their capacity to choose. The transformation will provide some new opportunities, but access to and benefits from these opportunities may be distributed inequitably without careful consideration of outcomes for people and businesses in vulnerable circumstances (e.g. people in isolated communities, renters, apartment dwellers, and people on low incomes). The transformation also requires extensive new and expanded energy infrastructure, which will impact some people and communities more than others.

There is immense opportunity in improved energy performance, demand flexibility solutions, richer and more accessible data, shared infrastructure, and the integration and orchestration of Consumer Energy Resources such as rooftop solar and home batteries. The aggregate potential of these areas is quantitatively highly significant from an overall system perspective. However, they all rest on genuinely involving energy users, both residential and industrial, in solution design and decision-making. Energy is a means to an end, and Australia's energy consumers can be the blockers or facilitators of the transition. Consumer-centricity must be an integral component in energy systems intelligence.

Innovation is essential

The energy system was structurally stable for a long time. Unlike other sectors, such as communications, that have been through transformational change, developments in energy have been more incremental in nature – until now. With dramatic and interconnected shifts ongoing across power systems, transportation, fuels, storage, and regional economies, conditions are ripe for innovation in technology, business models, supply chains, markets, and regulation. The case for innovation is strengthened by rapid developments in adjacent sectors like ICT that offer powerful new capabilities that can be deployed to add value in energy contexts.

In a more distributed and dynamic system, the potential for digital innovations to optimise asset utilisation, operational performance and end-user outcomes is higher compared to a more centralised and static system. Digital solutions can simplify energy management and customer offerings, e.g. Energy-as-a-Service, but also risk adding complexity and contributing to adverse outcomes if implemented poorly. Novel constructs across sectors such as the Warm Home Prescription program in the UK[4] show great promise, and low-carbon industrial processes are evolving rapidly.

Trialling innovative solutions before large-scale deployment will be important to understand the real implications for consumers, businesses and the broader energy system, and to mitigate risk. Systems intelligence for the energy transformation must include an ability to trial and learn in faster cycles, more easily, and with greater sharing of data and insights than has previously been the case.

There is a growing dependency between energy and telecommunications

We need enduring capability and collaboration

Transformation of the energy system and the journey to net zero will be ongoing for decades, touching every part of Australian society. They require a level of collaboration and coordinated action beyond that typically seen in a steady-state scenario. Technologies and society will evolve over that time in ways that we cannot fully predict. We will need enabling capabilities that are both enduring and adaptive, that can support longitudinal analysis, and that can catalyse the ongoing coherent progress that is required for success.

CSIRO is looking to establish a new piece of national research infrastructure, the National Energy Analysis Centre (NEAC)[5], to provide an enduring and adaptive capability that integrates human and system components to support whole-of-system energy transformation. NEAC will consist of:

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[4] Warm home prescription trial: https://es.catapult.org.uk/project/warm-home-prescription

[5] National Energy Analysis Centre: https://research.csiro.au/neac/

- a Living Lab, inspired by and in collaboration with Energy Systems Catapult's Living Lab in the UK[6], with thousands of people in real homes and businesses across Australia, pre-recruited and ready for research
- a Data Nexus with rich, curated datasets, structured in a coherent multi-energy systems framework using contemporary MBSE, in collaboration with the Laboratory for Intelligent Integrated Networks of Engineering Systems[7] in the US, headed by Amro M. Farid, professor at the Stevens Institute of Technology
- an Insights Platform with powerful analytical and data visualisation capabilities, backed by modern systems science
- extensive Innovation Networks of NEAC users and collaborators.

NEAC is intended to be an independent, robust and collaborative multi-energy systems data and research capability that lifts all boats – empowering decision-making, catalysing innovation, and placing people at the centre of the energy transformation. NEAC aligns with CSIRO's role as the national science agency to promote innovation, and host and share world-class infrastructure to serve the nation. The NEAC design concept deliberately integrates contemporary systems science and MBSE, place-based change, multi-energy and adjacent systems, community involvement, and innovation networks. It aspires to help catalyse the systems intelligence we need for Australia's energy transformation.

About the author

Dr Stephen Craig is Smart Energy Lead at CSIRO, Australia's national science agency.

Stephen has more than 25 years of experience in applied research, strategy development and commercial innovation in systems engineering, digital technologies, and communications. Prior to joining CSIRO, Stephen led the national Centre of Excellence for Digital Engineering at Boeing Defence Australia, and was Head of Strategy and Business Development at a spatial data analytics start-up.

Stephen received his PhD in climate system modelling from Stockholm University. He spent many years in Sweden in leadership roles in mobile communication systems research, development and optimisation at Ericsson before returning to Australia in 2015.

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[6] Energy Systems Catapult Living Lab: https://es.catapult.org.uk/tools-and-labs/living-lab/

[7] Laboratory for Intelligent Integrated Networks of Engineering Systems: https://liines.net/