RACE for 2030

Scenarios for Future Living

The Value of Model-Based Systems Engineering for Scenarios for Future Living

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The Value of Model-Based Systems Engineering in the Living Lab for Scenarios for Future Living

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Project team

Research partners

- Monash University
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- Ausgrid
- Citipower/Powercor/United Energy
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Acknowledgement of Country

The authors of this report would like to respectfully acknowledge the Traditional Owners of the ancestral lands throughout Australia and their connection to land, sea, and community. We recognise their continuing connection to the land, waters, and culture, and pay our respects to them, their cultures, and to their Elders, past, present, and emerging.

What is RACE for 2030?

RACE for 2030 CRC is a 10-year cooperative research program with AUD 350 million in resources to fund research towards a reliable, affordable, and clean energy future. https://www.racefor2030.com.au

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KEY FINDINGS

This report applies Model-Based Systems Engineering (MBSE), using the SysML v2 graphical modelling language, to explicitly represent the Work Package 7 (WP7) Living Lab for Scenarios for Future Living as a system. It demonstrates the relevance of MBSE methods for modelling energy systems and connecting household-scale attributes to the larger Australian multi-energy system. It clarifies the distinctions, relationships, and relative importance of the following subsystems, as well as the models used to represent them:

- WP7 Living Lab measurement instruments and direct observations;
- WP7 Living Lab participant household environments;
- The Australian national multi-energy system;
- The Australian national residential sector of the energy system;
- (Future possible) Living Lab hardware and software for storage and processing of data and information.

The representations presented here are internally consistent while remaining flexibly extensible and editable, allowing metadata from other relevant information sources to be incorporated readily. They provide a rigorous way to locate observational data and quantitative models more precisely within the broader Australian energy system context, analogous to how an atlas situates both urban street maps and topographic landscape maps within a wider geographic frame.

The same modelling language can place the residential sector within a broader multi-energy system, including commercial and industrial demand and systems for coal, oil, gas, electricity, hydrogen, water, and wastewater. Where compatible formal schemas exist, dataset relationships are easier to infer. This provides a minimally required conceptual basis for scaling Living Lab observations into wider energy-system and demand models.

The full value of SysML representation as a design and communication tool is yet to be demonstrated. Like most specialised tools, it requires initial investment in skills development and application effort. Its ultimate value will become clear only through full-scale implementation. However, the examples presented in this report suggest that MBSE is a promising approach for integrating household-scale dwelling characteristics, behavioural and other social data into the management of the complex multi-energy system transition.

Australia's energy future is being redefined with the launch of "Scenarios for Future Living," an initiative from the RACE for 2030 Cooperative Research Centre (RACE for 2030 CRC).

Across seven interconnected work packages, this three-year initiative provides a more plausible, people-centred understanding of future Australian household energy consumption.

EXECUTIVE SUMMARY

This report demonstrates how Model Based Systems Engineering can represent measurement instruments, household characteristics, and selected relationships between household observations and the broader multi-energy system.

The transition of engineered energy systems towards greater sustainability and resilience entails complex coevolution within a socio-technical system of systems. As this transition unfolds, a diverse array of consumer and civic values may be realised and must be recognised in how energy systems are understood and managed.

Making this complexity explicit is a first step towards managing it. Systems engineering has long been applied to complex socio-technical systems such as aerospace and telecommunications, and Model-Based Systems Engineering is especially useful because it can represent complex system-of-systems relationships and integrate data from numerous cross-disciplinary sources.

This report demonstrates these capabilities through an initial application of the SysML v2 modelling language to represent the households in the CSIRO WP7 Living Lab as a system and to situate them in relation to other relevant systems. The WP7 Living Lab monitors electricity and broader energy use in several dozen NSW and Queensland households to examine social and behavioural dimensions of the energy transition. This requires understanding consumers' diverse attitudes and preferences, which shape energy demand and expectations of system performance.

The SysML_v2 language is used to represent data-collection instruments and the household elements they monitor and explain. This helps to organise quantitative monitored data alongside qualitative survey data. By making dataset relationships explicit, it provides a systematic framework for linking heterogeneous Living Lab information to wider system models.

This approach has clarified the distinctions, relationships, and interactions among the following subsystems and their representations (or models).

- Living Lab measurement instruments and direct observations
- Living Lab participant household environments
- The Australian national multi-energy system as a whole
- The Australian national residential sector of the energy system
- (Future possible) Living Lab hardware and software for storage and processing of data and information

As expected, the representations generated here are internally consistent, while remaining flexibly extensible and editable. They can

also readily incorporate metadata for other relevant information sources.

In this initial application, the report demonstrates that such explicit representations support the development and quality assurance of novel and emerging energy forecasting mechanisms. They can help document, verify, justify, and suggest specific structural choices for forecasting-model design across multiple system scales, thereby supporting decisions about appropriate trade-offs between accuracy and simplicity. An initial example of such an electricity forecasting method is presented. It is expected that this case study exercise, demonstrated using data from households in the WP7 Living Lab, will generalise to data that can be obtained from other living labs associated with Scenarios for Future Living.

These applications are consistent with our prior expectations that MBSE is a promising way to integrate socio-psychological data relevant to energy systems into the management of the complex multi-energy system transition.

Many studies have examined how Australian energy end-use technologies affect aggregate electricity demand. However, these studies do not always make their structural assumptions obvious. Compared with an MBSE approach, relationships among sectors, component technologies, and modelling assumptions are commonly represented less formally. This can make it harder to test consistency across studies or to identify where important assumptions remain unexamined. MBSE's ability to communicate across models relies on its formal representation of part-whole decompositions, boundaries of representation and analysis, component elements and interfaces; its support for alternative views of a common underlying structure; and its ability to make explicit the distinction between models and the things that they represent. Although these MBSE models provide limited detail, they represent a broader energy-system scope, allowing an explicit map to be created of the connecting components between other more tightly scoped and more detailed models of human energy use.

Future work will seek to realise the full value of SysML and MBSE. This includes using MBSE as a communication tool that transparently relates Living Lab data from multiple sources, and as a design tool that specifies the nature, type, and flow of real-time data as it is collected, processed, and analysed in a living lab setting. One important use case is the application of MBSE to forecasting models that integrate data from disparate sources. Another important use case is managing the interoperability of sensed data streams as the number of sensor types and vendors proliferates.

GLOSSARY OF ABBREVIATIONS

CER: Consumer energy resources
CSIRO: Commonwealth Scientific and Industrial Research Organisation
EV: Electric vehicle
LL: Living Lab/Laboratory
MBSE: Model-Based Systems Engineering (see Sections 2 and 3)
NEAC: National Energy Analysis Centre
NSW: New South Wales
SFL: Scenarios for Future Living
SysML: Systems Modelling Language
UML: Unified Modelling Language
WP: Work Package

PROJECT BACKGROUND

Scenarios for Future Living (SFL) is a multi-disciplinary, collaborative research project designed to strengthen decision-making capacity in the Australian energy sector. It does so by developing scenarios, models, tools, and design innovations that centre people's everyday lives and expectations alongside emerging technology and energy trends. This requires both engagement with energy sector stakeholders and an understanding of how industry expectations about probable, possible, and preferable futures shape current decision-making.

SFL comprises seven work packages that collectively strengthen decision-making capacity for the Australian energy sector (see Table 1 below).

WP1: Understanding how people use energy	Delivers real-world foresight into how diverse households and home businesses will interact with energy in the future — tracking changing expectations, and analysing the impact of future everyday life values and practices to guide industry and policy decisions.
WP2: Anticipating emerging technologies	From smart home innovations to next-gen energy solutions, WP2 analyses new technologies and industry trends to understand their potential impact on energy use in homes and businesses.
WP3: Developing future energy scenarios	Uses social and design research, technology trends and climate science to create rich, evidence-based SFL narratives that help industry and government plan for plausible energy futures.
WP4: Advancing energy forecasting tools	Designing new modelling tools and processes that integrate real-world social trends into energy sector planning, ensuring more accurate predictions and better decision-making.
WP5: Designing people-centred energy solutions	Exploring how new energy products and services can align with people's evolving needs — helping deliver a low-cost, net-zero future while ensuring fair access for all consumers.
WP6: Leading Australian energy	Convenes representative groups of actors from across the energy system to explore

transition workshops	alternative futures for the Australian energy transition. It also seeks to build industry capacity in advanced foresighting practices.
WP7: Scaling and sustaining knowledge •	**Through collaboration with CSIRO's National Energy Analysis Centre (NEAC), WP7 extends the impact and longevity of the research by establishing a Living Lab of households with energy and indoor climate monitoring. MBSE provides a common framework for the organisation of information that connects Living Lab household-scale features to the larger Australian energy system.**

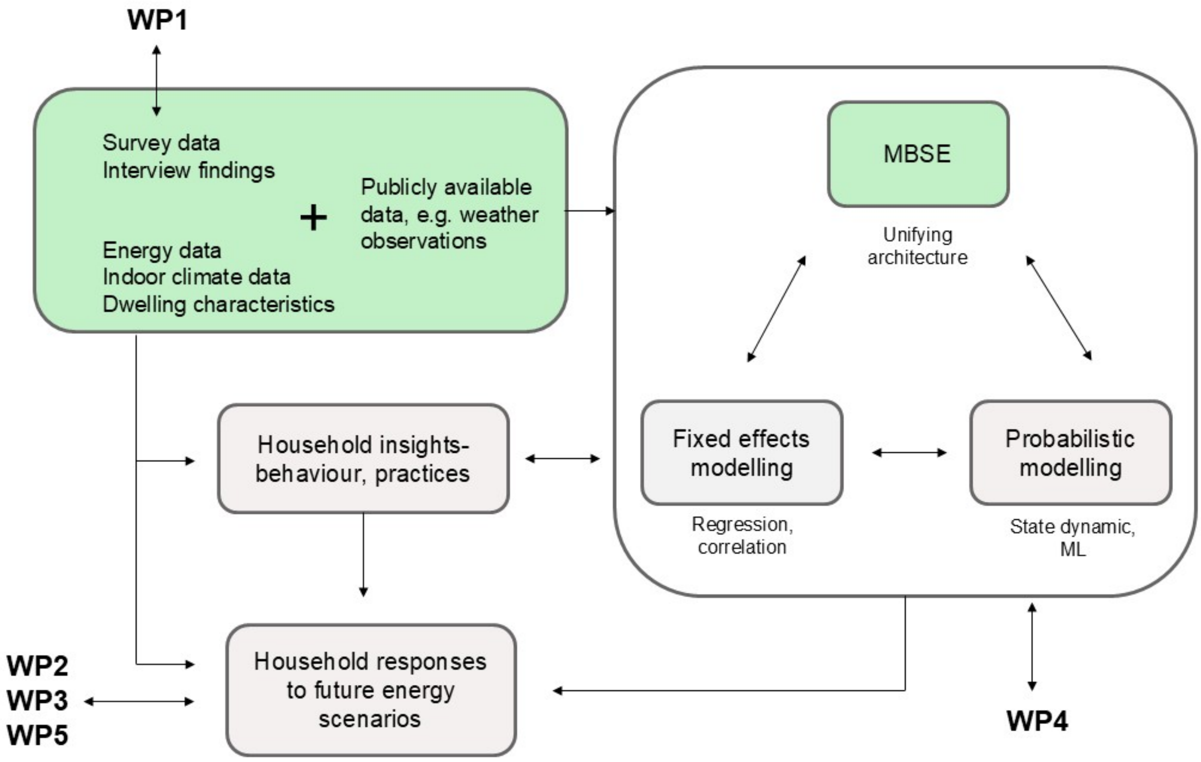

Figure 1: Relationship of WP7 to other work packages and focus of this report

Work Package 7

WP7 complements WPs 1-6 by collecting detailed indoor-climate and energy-use data from Living Lab households to deepen understanding of householders' practices and their relationship with energy use. It also examines how socio-technical knowledge generated through household instrumentation and engagement can be (1) scaled, and (2) translated, to address national scale challenges. In doing so, WP7 aims to extend the insights, models, and innovations from earlier work packages to a national scale, facilitating their integration into industry practice and long-term energy-transition planning.

WP7 activities: WP7 has established a 35-household Living Lab, where households share data and engage with researchers in surveys and interviews describing their energy use and indoor climate. These data, combined with publicly available datasets such as weather observations, form the basis for WP7 modelling activities. Modelling includes fixed-effects and probabilistic modelling, primarily focused on heating and cooling activities, and the use of Model-Based Systems Engineering (MBSE) as a unifying architecture, providing structure for data and metadata. Figure 1 provides an indicative overview of (1) WP7 activities, (2) WP7's relationship to other work packages, and (3) the focus of this report, which is shaded green in the figure. A key aim of WP7 is to extend the impact of research across SFL WP1-6 by creating pathways for findings to be scaled, translated, and applied nationally. To support this aim, MBSE can provide common data standards across models, allowing their outputs to be meaningfully synthesised or compared.

Modelling in SFL and relationship to other SFL work packages: Modelling in SFL includes basic fixed-effects regression of household parameters (reported in WP7 Household Research Report 1[1]), probabilistic modelling of air-conditioning usage (forthcoming), and MBSE, which is designed to act as a unifying architecture for describing modelled parameters. The WP7 modelling is designed to complement WP4's modelling of (a) disaggregation methods for smart-metered data and (b) household-scale technology-adoption scenarios (including solar, battery, and EV adoption) and their associated impacts on energy use.

This report demonstrates the value of MBSE for scaling by managing complexity, documenting diverse data sources, and tracking the relationships among directly observed measurements, models, and derived inferences, across multiple system scales.

Key Outputs – Work Package 7

- CSIRO Household Research Reports: Synthesises findings from social research. Delivered in 2026 (Snow et al. 2026, footnote

1), and 2027 (forthcoming).

- **MBSE Modelling Report**: Complements the Household Research Report, demonstrating Model-Based Systems Engineering (MBSE) tools and applications. Also intended to complement the work in WP4. Delivered in 2026 (this report) and 2027 (forthcoming).
- SFL Road Map Report: Outlines how SFL outcomes can be sustained, expanded, and integrated beyond the project. Delivered in 2027 (forthcoming).

This report is the first of the two MBSE modelling reports referenced above and complements the Household Research Report (Snow et al. 2026, footnote 1). The application of MBSE in SFL is complementary to CSIRO's application of the same approach to the National Energy Analysis Centre, which is creating a tool to model and analyse Australia's energy system as a whole.

[1] Stephen Snow, Murni Po, John Gardner, Joel Dabrowski (2026, to appear), ***Insights from an Australian Energy Living Lab:*** *Understanding Household Energy Use in Transition,* CSIRO and SFL

ABOUT THIS REPORT

Who should use these findings

This report would be of most interest to energy sector stakeholders, researchers and modellers who are interested in modelling multi-energy systems, and the application of the SysML modelling language to the representation of energy systems at multiple scales, from national to sub-household scale.

Like most specialised tools, MBSE methods require upfront investment in understanding fundamental concepts, skills development, and application effort. However, the examples presented here reinforce the view that MBSE is a promising approach for integrating social and behavioural data into the management of the complex multi-energy system transition. This is especially valuable where data are abundant but heterogeneous and incomplete, and where robust quantitative interpretation depends on understanding the structural relationships within the physical systems the data describe.

Method

This initial report presents a preliminary application of the SysML modelling language for representing key subsystems associated with the WP7 Living Lab for Scenarios for Future Living (SFL) with reference to where overlaps exist with other SFL work packages. This representation includes the WP7 Living Lab itself, the broader residential sector that the Living Lab is intended to help understand, and the wider multi-energy system (electricity, gas, solid fuels) in which the residential sector operates. The SysML representations are limited to conceptual models that decompose systems into constituent subsystems and smaller component elements. Systems engineering elaboration has also been applied to the initial household decomposition to more tightly connect the WP7 Living Lab participants with a pre-existing conceptual structural model of the multi-energy system.

The report outlines the rationale for applying MBSE methods to the Living Lab, demonstrating initial applications, and considering their possible future value.

1: INTRODUCTION

Addressing climate change requires a transition to a sustainable, resilient energy system. This transition is a complex socio-technical challenge[2],[3], involving interactions among infrastructure, industries, technologies, humans and households. In Australia, climate goals and the falling cost of renewable generation are accelerating decarbonisation of the power sector. Large-scale generation is shifting from dispatchable rotating machines to inverter-based wind and solar, supported by megawatt-scale batteries that smooth variability in both demand and supply. Electricity networks are also evolving from passive conductors to systems that actively manage voltage and frequency. United Nations Sustainable Development Goal 7 [4] requires the energy transition to be not only clean and reliable, but also affordable and accessible to all. Existing multi-energy systems already produce systemic inequities, and a poorly managed transition could widen the unequal distribution of benefits.

In Australia, the energy transition is often framed as primarily an electricity transition, owing to the substantial policy and planning focus on electricity and electrification, rapid developments in consumer energy technologies and evolving issues of peak electricity demand and system resilience. Yet understanding the transition solely through the lens of electricity risks overlooking Australia's broader multi-energy system, which includes gas networks, bottled gas (LPG), and solid fuels that continue to play important roles in households and industry. Residential heating, cooking, and hot water services remain partially dependent on gas in many regions, while firewood continues to be used for heating in some communities. The electricity and gas systems are increasingly interconnected: electrification policies affect gas demand, gas generators continue to provide reliability and firming services during the transition, and decisions about household fuel switching influence both electricity network demand and gas network viability. Modelling for the energy transition therefore requires multi-energy capability, which can be difficult where modelling expertise is often sector-specific.

In recognising the need both (a) to approach the energy transition as a multi-energy problem, and (b) to connect household-scale factors and behaviours to larger energy systems, WP7 is exploring the application of MBSE to organise knowledge and coordinate modelling. MBSE is a well-established engineering approach, supported by international standards such as ISO/IEC/IEEE 15288 and operationalised through modelling languages such as SysML. It provides a structured and machine-readable framework for representing complex systems, and is introduced and applied later in this report.

This report is one of several reports from WP7 and relates to the second of the three foundational research questions for WP7:

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[2] John C. Little, Roope O. Kaaronen, Janne I. Hukkinen, Shuhai Xiao, Tatyana Sharpee, Amro M. Farid, Roshanak Nilchiani, and C. Michael Barton, (2023) Earth Systems to Anthropocene Systems: An Evolutionary, System-of-Systems, Convergence Paradigm for Interdependent Societal Challenges, *Environmental Science & Technology*, 57 (14), 5504-5520, DOI: 10.1021/acs.est.2c06203

[3] John C. Little, Roope O. Kaaronen, Michael Muthukrishna, Sondoss Elsawah, Max S. Bennett, Inas Khayal, Janne I. Hukkinen, C. Michael Barton, Anthony J. Jakeman, and Amro M. Farid, (2026), One Earth + One Health: An Agile, Evolutionary, System-of-Systems Convergence Paradigm, *Environmental Science & Technology*, 60 (13), 9725-9743, DOI: 10.1021/acs.est.5c11895

[4] United Nations (2015), *Transforming our world, the 2030 Agenda for Sustainable Development*

(1) How are everyday practices, technologies, and social trends reflected in households' energy use and demand?
(2) How can the knowledge generated in WP1-6 be scaled up to address national energy challenges?
(3) How can research engagement with energy stakeholders be sustained long-term and translated into practical applications for policymakers, industry, and households?

Following an initial case study application of MBSE to the WP7 Living Lab, we demonstrate the capability of MBSE for organising diverse social and behavioural data and hence its potential to integrate and scale data from other SFL work packages to address system-level challenges.

In what follows, we (a) briefly outline the WP7 social research and Living Lab, (b) introduce MBSE and its existing applications, and (c) explore the applicability of MBSE to organising knowledge gained through social research and providing a common reference architecture that is applicable to various alternative modelling exercises.

WP7 Living Lab

Living Labs are defined as physical or virtual spaces used to address societal challenges through participation and collaboration. They involve real-life environments, heterogeneous stakeholders, and typically an emphasis on intentional experimentation.[5] WP7's Living Lab comprises 35 households across Greater Sydney, the NSW Central Coast, and Greater Brisbane. These households share energy-use, gas-use, and indoor-environment data with researchers and participate in surveys and interviews over time. This longitudinal connection enables engagement with the same cohort and supports analysis of participants' experiences of appliance purchase decisions and policy changes over time. The method enables triangulation of interview, survey, and time-series data from electricity, gas, and indoor-environment sensors.

All 35 households are fitted with electricity monitoring (Wattwatchers 6M Auditor), and indoor environmental monitoring (Tether EnviroQ). Households with a town-gas connection were additionally provided with gas monitoring using Tether Pulse.

- **Electricity monitoring:** (Wattwatchers 6M Auditor), provides individual circuit monitoring of up to six circuits per device (two or more devices installed in three-phase houses). Circuits gathered include Grid Incomer (mains), solar PV, and large loads depending on the fixtures installed. Data on usage and multiple electrical parameters is captured every 5 minutes.
- **Gas monitoring:** (Tether Pulse), fitted to gas meter pulse output, providing 1-hour readings for reticulated gas use in m^3.
- **Indoor environment monitoring** (Tether Pulse): installed in the living room of each dwelling, captures readings for temperature, relative humidity and carbon dioxide every 15 minutes.

Refer to Snow et al. (2026, footnote 1) for further details. Together, the monitoring provides detailed time-series observations that can be triangulated with self-reported survey and interview responses to form a rich picture of households' energy use and the behaviours, habits, and social factors that contribute to it. Understanding these factors then provides a basis for (both qualitative and quantitative) exploration of how households may respond to future conditions and trends, and also for exploring various alternative scenarios for future living.

[5] Hossain, M., Leminen, S., and Westerlund, M. (2019). A systematic review of living lab literature. *J. Clean. Prod.* 213, 976—988. doi: 10.1016/j.jclepro.2018.12.257.

The case for MBSE

The sustainable energy transition is not only a socio-technical challenge but also a complex multi-energy systems-of-systems challenge. Although it is often framed as the decarbonisation of electricity, modern energy systems still rely heavily on carbon-intensive fuels such as coal, oil, and natural gas. Replacing these fuels with renewable energy carriers such as electricity and hydrogen also requires major changes to the supporting infrastructure.

Climate change is reshaping energy systems, necessitating not only decarbonisation but also greater resilience. Energy systems must reduce emissions while becoming better able to withstand climate extremes. Bushfires, floods, cyclones, and ice storms can disrupt infrastructure and trigger cascading failures across interconnected systems. As such events become more frequent, resilience is increasingly important in climate adaptation.

Australia's modern energy system is a multi-energy system comprising multiple energy carriers and closely linked infrastructure, including water systems (see Figure 2 [6] and its earlier versions[7],[8]). Its behaviour is shaped by interdependencies across interacting systems, from the supply of material and energy inputs to the diverse energy services that support the economy and everyday life.

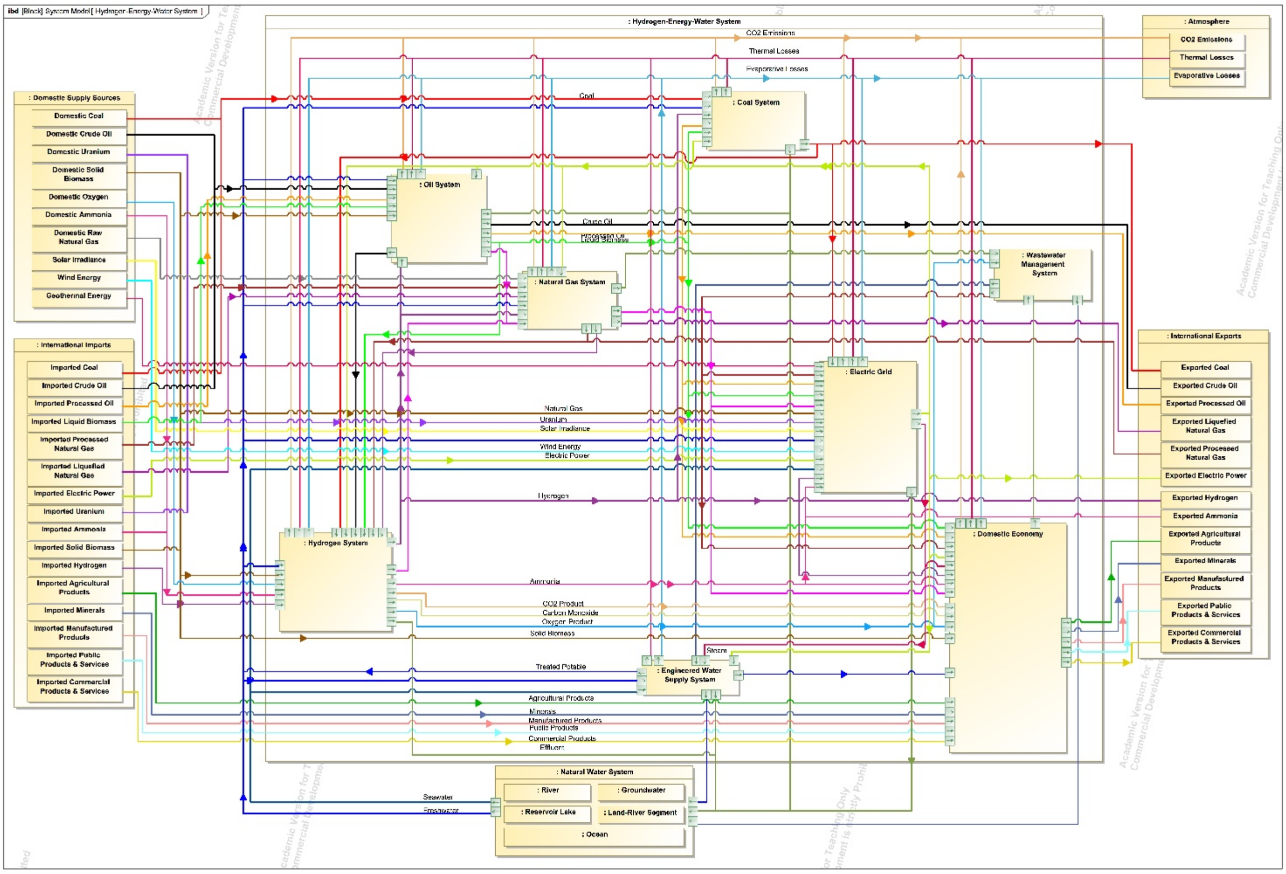

Figure 2: Interconnection diagram for a generic multi-energy system of systems [6]. It emphasises the complex interdependencies between

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[6] A. M. Farid. Taming the complexity in Australia's nexus infrastructure of energy, water, and hydrogen: A reference architecture. In *2023 INCOSE New England 5th Annual Fall Workshop Invited Seminar*, Storrs, CT, USA, 2023.
[7] W. N. Lubega and A. M. Farid. A Reference System Architecture for the Energy-Water Nexus. IEEE Systems Journal, pp(99):1–11, 2014
[8] D. Thompson and A. M. Farid. A Reference Architecture for the American Multi-Modal Energy System. Journal of Industrial Information Integration, 36:100521–100531, 2023.

energy infrastructures and cross-sectoral coordination required to realise a deep decarbonisation pathway to net zero emissions.

These interdependencies mean the shift from fossil fuels to renewable energy must be carefully coordinated. The retirement of major infrastructure, such as coal-fired power stations and internal combustion vehicles, needs to be matched by the rollout of replacements such as rooftop solar and electric vehicles. This need for coordination across multiple infrastructure systems reinforces the value of a system-of-systems approach to analysing and managing the sustainable energy transition.

Growing decarbonisation pressures and the expanding range of available energy technologies are adding complexity to the sustainable energy transition — not only because of the number of options, but also because of how they interact. For example, large-scale battery investments can reduce reliance on fast-ramping gas turbines to manage fluctuations in renewable wind and solar generation, as batteries can rapidly discharge stored electricity to meet sudden changes in demand.

The interdependent challenges outlined above require a systematic way to manage complexity. As the energy transition becomes more complex, the human values and behaviours that shape the energy system become increasingly important. The social dimensions of energy use are now recognised as central to understanding and managing energy systems [9]. However, existing multi-energy system modelling approaches and software typically do not represent household-scale factors in detail.

For example, AusTIMES (the Australian TIMES model), represents the Australian economy as an integrated energy system and is widely used to examine long-term decarbonisation pathways across sectors including electricity, industry, transport, buildings, and agriculture. [10] It is a highly capable multi-sector energy system model that optimises energy supply and demand at an aggregate scale. Its present design represents households as groups of consumers with shared characteristics, which is well suited to exploring behaviours that are common across households. However, representing behaviours that vary with individual household factors would require greater granularity.

MBSE can support this granularity by developing architectural models of the energy system and also of quantitative models, such as AusTIMES, used to represent it. MBSE methods can be used to represent alternative model modifications, assess their implications, and plan the implementation in advance. This capability will be particularly useful where more complex systems must be represented in greater detail.

This work therefore advocates for Model-Based Systems Engineering (MBSE) as one such framework. MBSE manages engineered systems throughout their lifecycle—from concept to operation—through the disciplined use of system models. Its core aim is to ensure consistency among models, so they accurately represent the system and its requirements. MBSE promotes digital models as the primary means of system representation and information exchange, while explicitly tracking relationships between models.

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[9] S. O. Muhanji, A. E. Flint, and A. M. Farid. eIoT: The Development of the Energy Internet of Things in Energy Infrastructure. Springer, Berlin, Heidelberg, 2019.

[10] Green, D.L., Reedman, L.J., Kanudia, A.*, Murugesan, M., Dollman, R., West, S., Dioguardi, E., Grant, A., Nolan, M., Singha, D.+, Maxwell, R. +, Li, M. +, and Havas, L. 2025. Multi-sectoral modelling 2024, CSIRO Report No. EP2025-1797, Australia. https://www.aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2024/2025-iasr-scenarios/csiro-2024-multi-sectoral-modelling-report.pdf

MBSE has been applied across a wide range of sectors including aerospace and telecommunications to develop complex (multidisciplinary) product systems[11][12]. Aerospace systems require extremely high reliability for mission-critical functions, and often involve bespoke or novel designs. Telecommunications systems, by contrast, involve millions of interoperable devices produced by thousands of manufacturers, and often rely on redundancy to ensure reliability. More recently, MBSE has also been applied to large-scale socio-technical infrastructure systems, including multi-energy systems (Lubega and Farid, 2014, footnote 7). It provides structured methods for incorporating and reconciling diverse stakeholder requirements, interfaces, and perspectives, which are often in conflict. Furthermore, SysML models can enable MBSE workflows that directly integrate energy management and decarbonisation decisions. For example, in one recent work, an MBSE-based workflow was used to optimise the design of an industrial hub with natural gas and hydrogen infrastructure,[13] identifying the combination of natural gas, water and electricity supply and routing options to meet the energy requirements of the industrial consumers at least cost. At a larger scale, an MBSE-based workflow was used to develop a multi-energy state estimator of the American multi-modal energy system[14]. These examples demonstrate how MBSE can add value to the understanding and management of multi-energy systems as a class of complex socio-technical systems of systems.

Original Contribution & Paper Outline

This work evaluates how MBSE could support the Living Lab for Scenarios for Future Living (SFL). Given that the sustainable energy transition is a complex, multi-dimensional socio-technical challenge, effective complexity management techniques are essential. This report focuses specifically on how MBSE can support understanding and managing the socio-technical dimensions of the transition.

Section 2 situates the WP7 Living Lab within the broader multi-energy system it is intended to inform, while introducing the precise modelling of energy system components and interactions that is required for MBSE methods. Section 3 demonstrates how modelling household sensor and energy-use technologies can improve the documentation of collected data, including qualitative survey data, enabling clearer interpretation, and facilitating integration. It provides an illustrative example, applying the developments of Sections 2 and 3 to the scaling up of insights from the household to suburb scale. Section 4 generalises the illustrative example by exploring how explicitly modelling the relationships among participants, collected data, and the wider energy system could support the scaling of insights from Living Lab observations into implications for the broader national energy system, including through integration with external datasets. Finally, Section 5 outlines directions for future work and concludes.

This report does not provide a comprehensive MBSE representation of the WP7 Living Lab. Instead, it presents examples to illustrate how MBSE tools could support its management and the broader role of modelling the energy systems it is designed to investigate. It includes an early demonstration of how Living Lab data can support residential electricity demand forecasting under changing demographic and technology conditions, such as rising electric vehicle adoption.

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[11] A. M. Madni and S. Purohit. Economic analysis of model-based systems engineering. Systems, 7(1):12, 2019.
[12] M. M. Schmidt, T. C. Zimmermann, and R. Stark. Systematic literature review of system models for technical system development. Applied Sciences, 11(7):3014, 2021.
[13] W. C. Schoonenberg and A. M. Farid. Hetero-functional Network Minimum Cost Flow Optimization. Sustainable Energy Grids and Networks, 31(100749):1—18, 2022.
[14] D. J. Thompson and A. M. Farid. A weighted least squares error hetero-functional graph state estimator of the American multi-modal energy system. Energy and AI, 24:100711, 2026.

2: SITUATING THE HOUSEHOLDS IN THE SUSTAINABLE ENERGY TRANSITION WITH MBSE

The WP7 Living Lab, along with other SFL work packages, focuses on households and aims to explore how individual household decisions can produce larger effects across the broader multi-energy system. Consistent with complementary modelling carried out by WP4, the WP7 Living Lab is also intended to project future household energy-consumption patterns, accounting for changes in demographic composition and household technology mix over time. Situating households within that wider system is therefore an important first step. We provide an example of this here, using attributes derived from WP7 Living Lab households.

Figure 3 presents a parts diagram of a modern energy system. It is a SysML v2 visualisation derived from an architectural model and adapted with minimal modification from an existing generic multi-energy and water systems model (the Hydrogen Energy Water System; Farid 2023, footnote 6). This illustrates one practical benefit of MBSE: models can be reused and adapted across related applications.

In general, energy systems transform, transport, and store energy resources from their natural states so that energy can be delivered where, when, and in forms that are practical and affordable for human use. Modern energy systems involve multiple energy carriers, including solid, liquid, and gaseous fossil fuels; electricity; hydrogen and other chemical energy carriers; and mechanical energy. They interact closely with other critical infrastructure systems, particularly water management, while supporting services such as heating and cooling, transport, cooking, lighting, telecommunications, and information processing. This broader context matters because the WP7 Living Lab is intended to inform the understanding of the residential energy use within that interconnected system.

To situate households within the sustainable energy transition, Figure 3 reinterprets the multi-energy system shown in Figure 2 in terms of its constituent parts. Figure 2 emphasises matter and energy flows between subsystems, whereas Figure 3 emphasises the part—whole hierarchical structure of the system. Together, the two figures show both how the system operates and how it is organised. The multi-energy system comprises several major subsystems, including established incumbent systems such as coal, oil, natural gas, and electricity, as well as emerging energy carriers such as hydrogen. Because energy and water systems are tightly coupled, Figure 3 also includes water supply and wastewater management systems and aggregates the remaining demand-side activities into a domestic economy block.

Beyond showing flows (Figure 2) and hierarchical structure (Figure 3), these diagrams help define subsystems consistently. This approach improves clarity, facilitates collaboration, and reduces the risk that separate groups use different labels or boundaries for the same system elements. In this way, MBSE helps establish a shared system ontology.

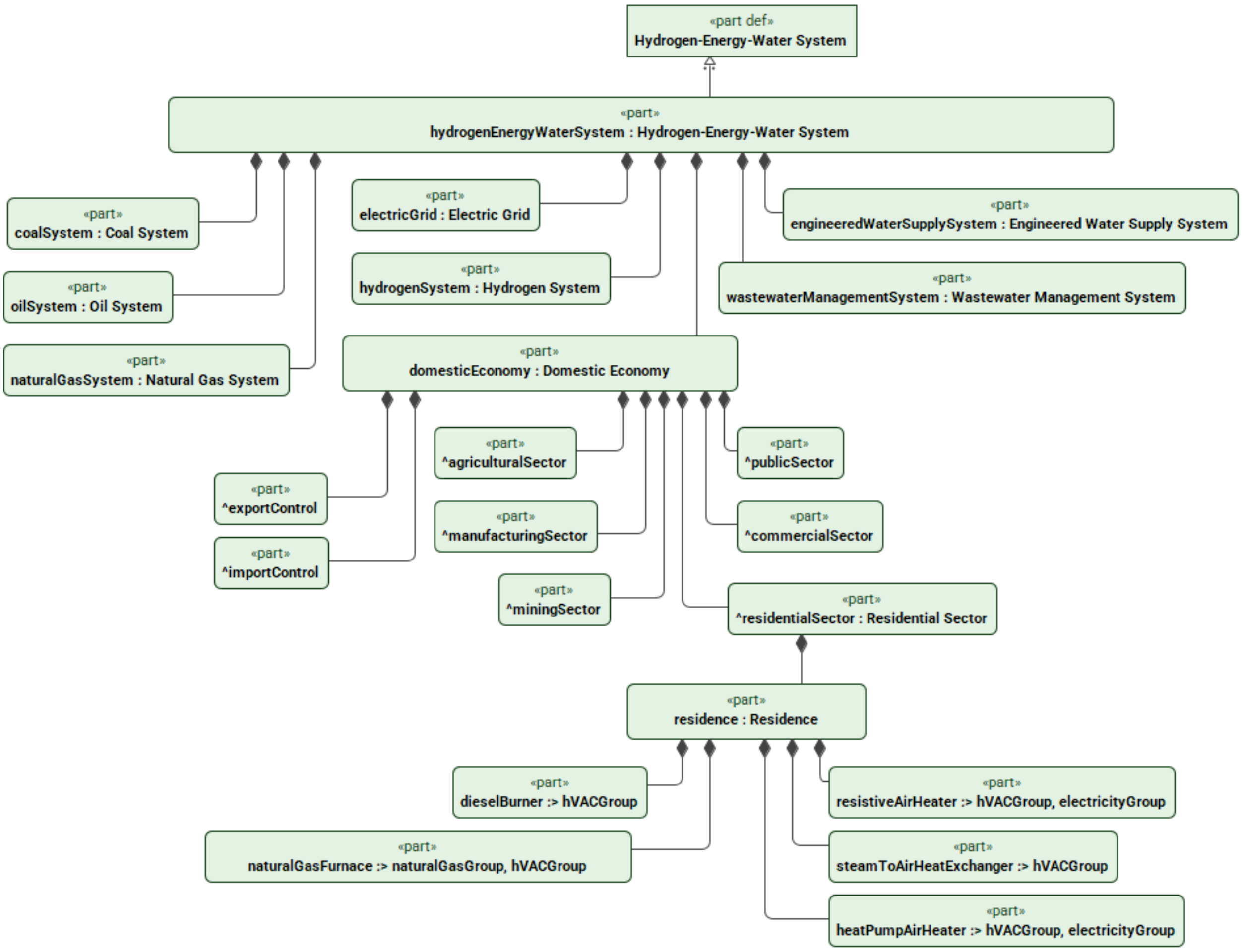

Figure 3: Parts diagram for a generic multi-energy (with hydrogen) and water system of systems

Further decomposition of the domestic economy in Figure 3 identifies the residential sector, which is itself composed of individual residences. This explicitly situates the 35 households participating in the WP7 Living Lab within the broader multi-energy system-of-systems. Establishing this connection is an important first step toward understanding how the Living Lab's quantitative and qualitative data can inform quantitative models of Australia's multi-energy system. In turn, these models can support major collective decision-making related to the sustainable energy transition. The relationship between the Living Lab and the broader multi-energy system is discussed in more detail below.

A systems engineering perspective: the laboratory as model

The system context above situates the Living Lab geographically and structurally. The next step is to clarify its role conceptually: the Living Lab is also a laboratory model of a wider residential population.

Any laboratory, including the WP7 Living Lab, is a multi-component system that contains models of the natural or human phenomena it seeks to understand. Laboratories typically combine specialised observation capabilities with some capacity for controlled, preferably reproducible, intervention, allowing researchers to investigate causal relationships more systematically than through casual observation. They are supported by data collection, storage, and analysis infrastructure designed to interpret the information they generate. In this sense, the WP7 Living Lab functions as an emulation model of residential subsystems within the broader Australian energy economy.

The WP7 Living Lab comprises a small sample of Australian households who share many attributes with WP1's more representative sample[15] but differ in terms of a higher-than-average ownership of Consumer Energy Resources (CER) such as solar PV, electric vehicles and batteries. The premise is that detailed observations of energy behaviour within participating households can provide insights relevant to other households with similar characteristics such as demographics, location, and dwelling construction.

Although the WP7 Living Lab is part of the Australian multi-energy system, this fact is not essential to its role as a laboratory. In principle, suitably selected households — for example, in California, New Zealand, or Germany (with similar climates, histories, cultures, CER availability, and economic development status, respectively) — could also serve as models for some Australian households, if sufficiently similar in characteristics relevant to the phenomena being studied. Laboratories need not be literal parts of the systems they represent; rather, they need only be comparable in relevant attributes. Even so, Australian households are likely to provide especially suitable models of the Australian residential sector because they share climatic, social, and regulatory conditions. If selected appropriately, a random sample of Australian households would support statistically valid inferences about the broader population. In this case however, the WP7 Living Lab households represent a sub-section of the Australian population with a relatively high CER adoption.

3: APPLYING MBSE TO THE WP7 LIVING LAB AS A CASE STUDY

This section applies MBSE to the WP7 Living Lab as a case study for extending multi-energy system modelling down to the household-scale by representing the WP7 measurement instruments, data sources, and household technologies within a consistent modelling framework. Examples show how this can improve documentation, interpretability, traceability, and integration across diverse datasets. The following section uses these developments to discuss how explicitly modelling the relationships among participants, demographic composition, and household technology mix can support the scaling of insights from living lab observations into implications for the broader national energy system.

As noted above, Model-Based Systems Engineering (MBSE) manages the design and operation of engineered systems through the systematic, explicit representation of all design-relevant aspects. It supports the full systems engineering lifecycle, from requirements specification through conceptual and detailed design, to analysis, verification, validation, and operational deployment. The discipline promotes the development of component subsystem models to the extent of qualitative or quantitative detail necessary to satisfy explicitly documented and evolving requirements.

Central to MBSE is the systematic management of information about engineered systems, especially the models used to represent them. It tracks relationships among these necessarily partial models to promote consistency, interoperability, and analytical traceability. MBSE emphasises not only the documentation of informational artefacts describing the system and its operational context, but also the metadata that defines relationships among them and the processes that keep both current, consistent, and coherent.

[15] Kaviani, F., Strengers, Y., & Dahlgren, K. (2025). *Scenarios for Future Living: Household and home businesses research, emerging lifestyles, preferences and practices survey*. Emerging Technologies Research Lab (Monash University). Melbourne, Australia.

Although the peer reviewed literature contains limited formal measurement evidence of MBSE's benefits to engineering practice,[16] its value is especially apparent in managing complex engineered systems-of-systems, where interactions between numerous components quickly become too difficult to describe rigorously without disciplined modelling methods. This is particularly important when different organisations or individuals are responsible for different subsystems. MBSE helps clarify the subsystem relationships that are critical to overall system behaviour and purpose. It is similarly valuable during operation, especially when different operators manage only particular subsystems or have limited visibility of the overall system state.

The examples below describe the physical variables monitored in the WP7 Living Lab and situate them within the broader domestic energy system. Each participating household is linked to several data sources:

(i) continuous monitoring of electrical power consumption on selected circuits;
(ii) continuous monitoring of indoor environmental climate conditions;
(iii) responses to SFL energy-use surveys; and
(iv) participant and household information provided during recruitment.

Additional external data sources, such as nearby weather station observations, can also be linked to each household.

Figure 4 shows the electrical power monitors installed in participating households and their associated measurement channels (six channels per monitor). Installed in the household meter box, each meter records multiple time-series data streams, including voltage, current, and power, across selected circuits. The number of sensors varies by household according to the loads being monitored. For example, households with three-phase power require multiple channels to monitor major loads and energy assets such as solar photovoltaic systems, batteries, large air conditioners, and incoming feeders. Other households may include additional high-power circuits, such as electric stoves or electric vehicle chargers, while some require fewer monitored circuits and therefore fewer channels and sensors. Figure 4 shows the channels associated with two sensors, "DD99999999961" and "DD99999999904", both linked to household "H_XYZ". Because this structure is represented in the underlying SysML v2 model, similar detail can be produced for any participating household as needed.

Explicitly documenting these sensor relationships supports reproducibility and long-term interpretability. Future phases of the project, or subsequent incorporation of other households with different available sensed data, may use different sensor models with different channel capacities, measurement variables, or reporting conventions. For example, some devices may record real and reactive power, others may record real power and power factor, and some may capture instantaneous values rather than interval averages. Future devices may also include additional measurements such as harmonics, frequency, or phase information. The model underlying Figure 4 makes these differences explicit, helping ensure that both existing and future datasets remain interpretable and comparable. In this way, MBSE representation can be sensor-agnostic and well placed to handle changes in sensors over time - for example, as direct access to smart air conditioner, battery and EV data becomes increasingly available from manufacturers via an application programming interface

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[16] Henderson K, Salado A. (2021) Value and benefits of model-based systems engineering (MBSE): Evidence from the literature. *Systems Engineering*, 24:51—66. https://doi.org/10.1002/sys.21566, the methodological challenges associated with the research of professional practice is well known — see Styhre and Sundgren (2005), Action Research as Experimentation, *Systemic Practice and Action Research*, Vol. 18, No. 1, February, doi: 10.1007/s11213-005-2459-3

(API) directly from the appliance[17] rather than sensed from electricity monitoring.

Figure 5 shows indoor environmental sensors (Tether EnviroQ) installed in participating households and the variables they monitor, including temperature, humidity, and indoor CO_2 concentration (represented as *attributes* in SysML v2). Each variable is linked to a time-series dataset indexed by date and time. Although sensors may be installed in different locations within a household, each device records the same core set of environmental variables.

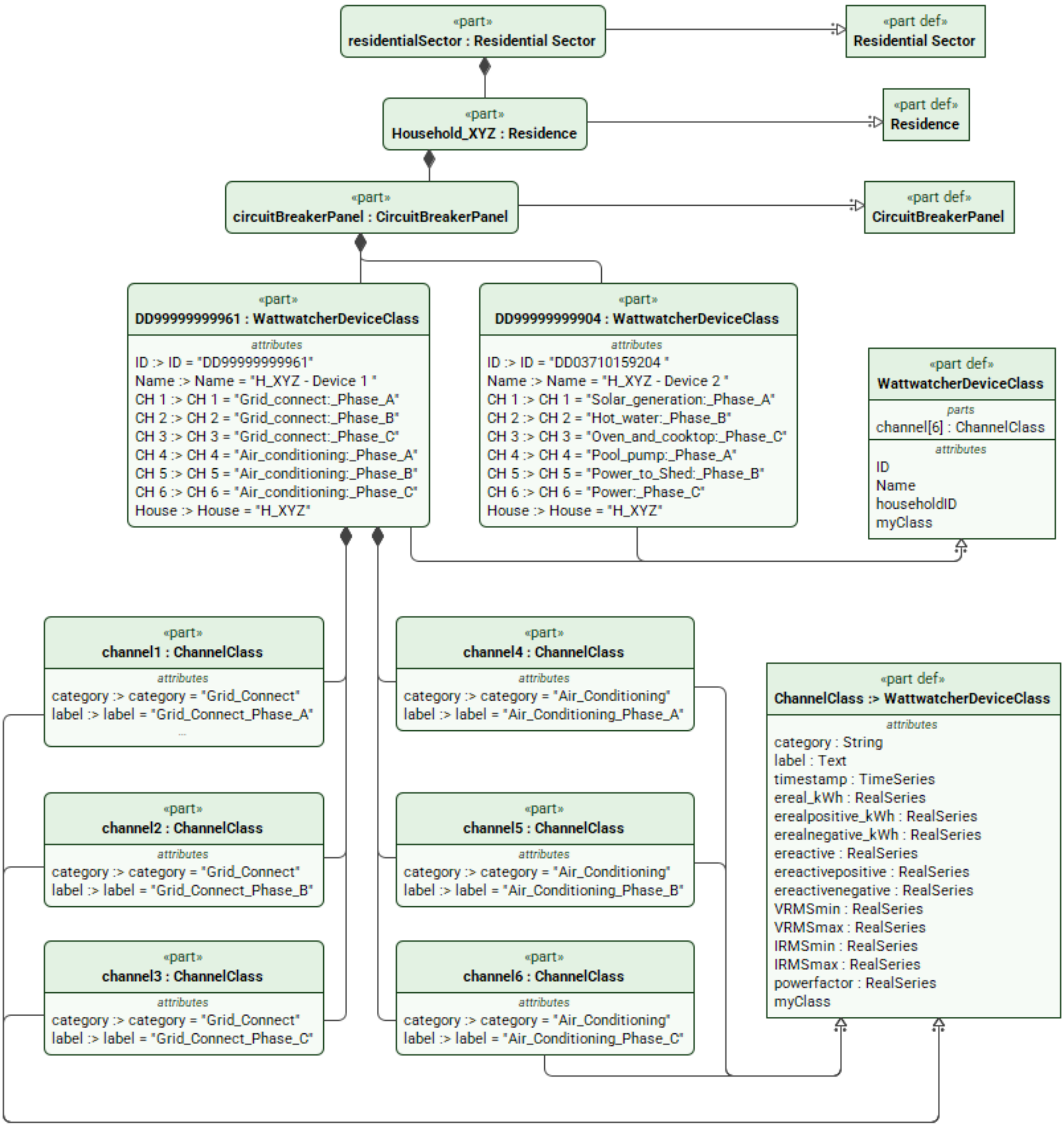

Figure 4: Electrical power sensors with measurement channels and variables

[17] For example: https://developer.sigencloud.com/

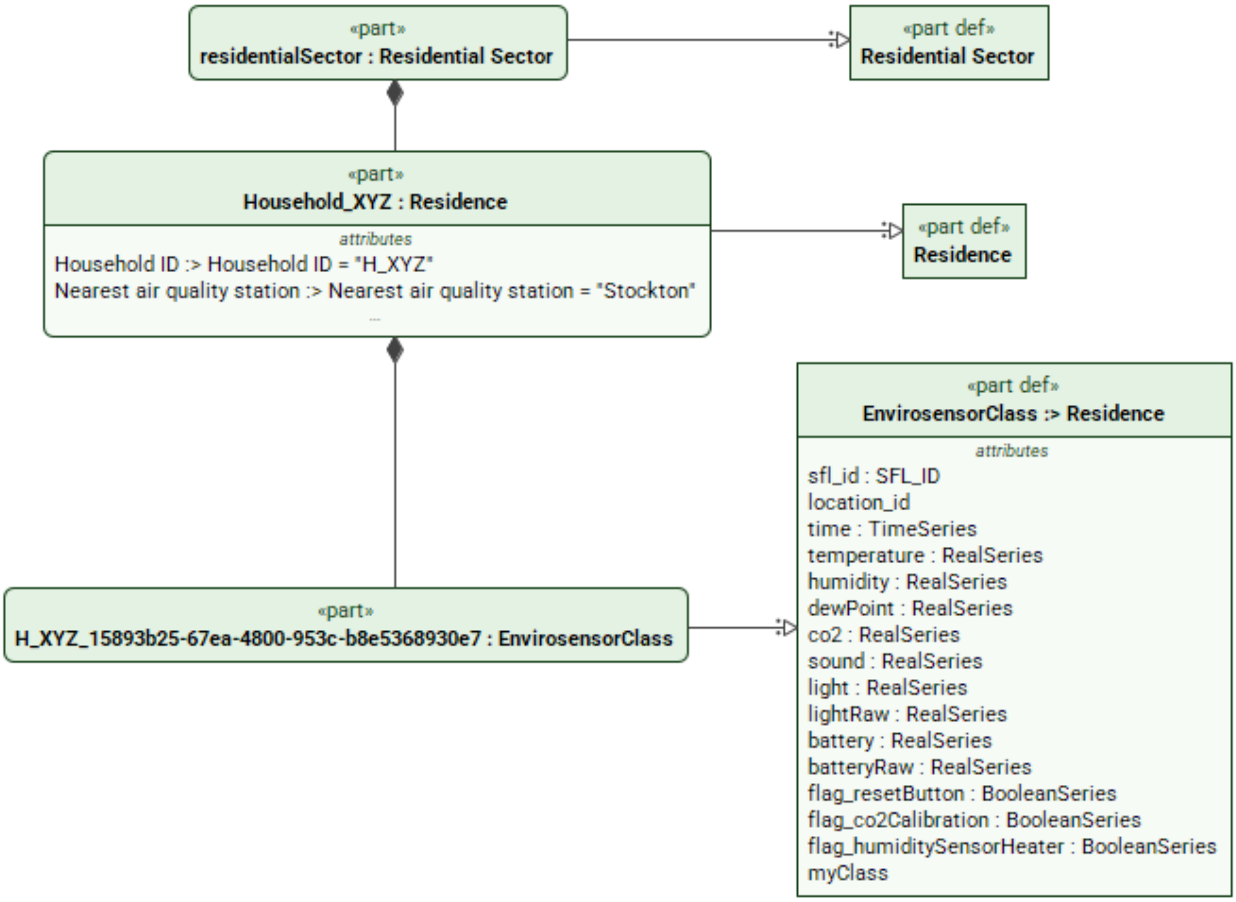

Figure 5: Environmental monitoring sensors and their measurement variables

Understanding energy behaviour also requires consideration of demographic, individual, and social influences. Figure 6, based on a UML diagram, shows how selected participant attributes can be linked to sensor data via the household, within the same modelling framework. This supports analysis of correlations between household characteristics and energy-use behaviour, including household composition, dwelling characteristics, and socio-demographic attributes.

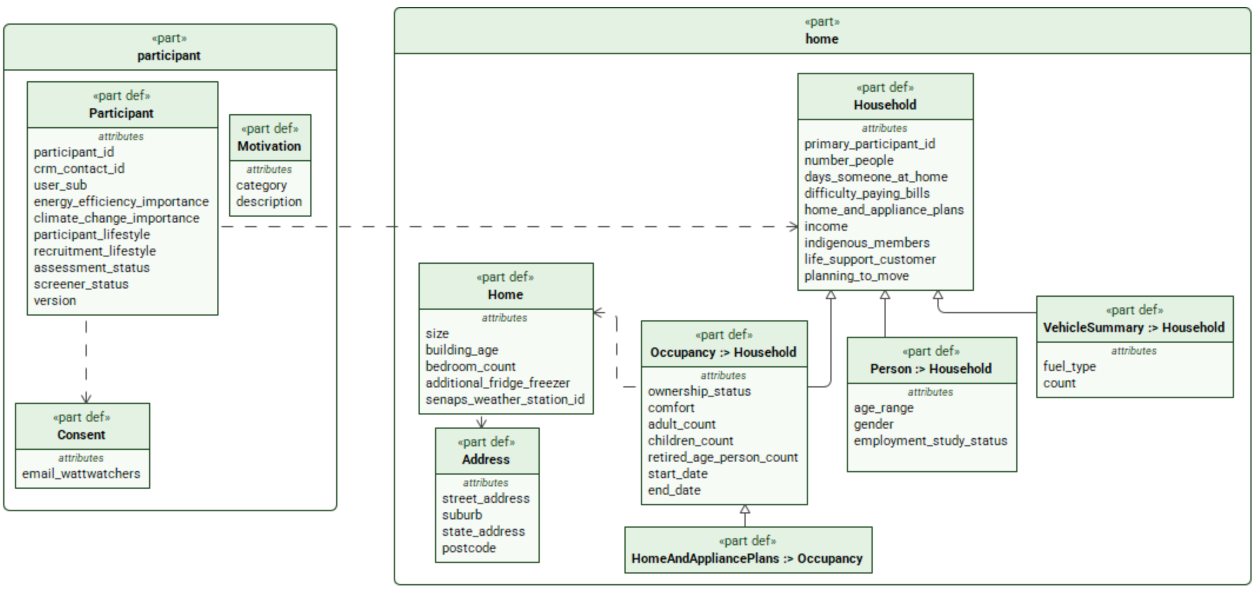

Figure 6: Adapted from a pre-existing Unified Modelling Language (UML) diagram supplied by Chris Sharman (CSIRO) that maps the class

structure for information collected from the participant application process

Figure 7 illustrates how household survey responses (Kaviani, Strenger and Dahlgren 2025, footnote 15) can be represented as household *attributes*. While WP7 survey responses are mapped below following our application of MBSE to the WP7 Living Lab, both the WP7 (Snow et al. 2026, footnote 1) and WP1 (Kaviani, Strenger and Dahlgren 2025, footnote 15) surveys capture information relevant to building energy efficiency, including building construction characteristics, appliance ownership and future purchase intention, which can be used to support analysis of present energy use, as well as future purchase intentions to inform projections of future patterns. Both WP1 and WP7 surveys collect information on energy-use practices, including occupancy patterns, working from home, laundry and cleaning routines, and electric vehicle charging (where owned). For analytical simplicity, these attributes can be coded into predefined (*enumerated*) categories (for example, “low”, “medium”, or “high”). Where a richer description is needed, more flexible qualitative responses can be used. Only attributes relevant to analysis need to be represented explicitly. Hence while Figure 7 is based on WP7 data, MBSE is capable of integrating data from multiple sources where equivalent attributes are captured.

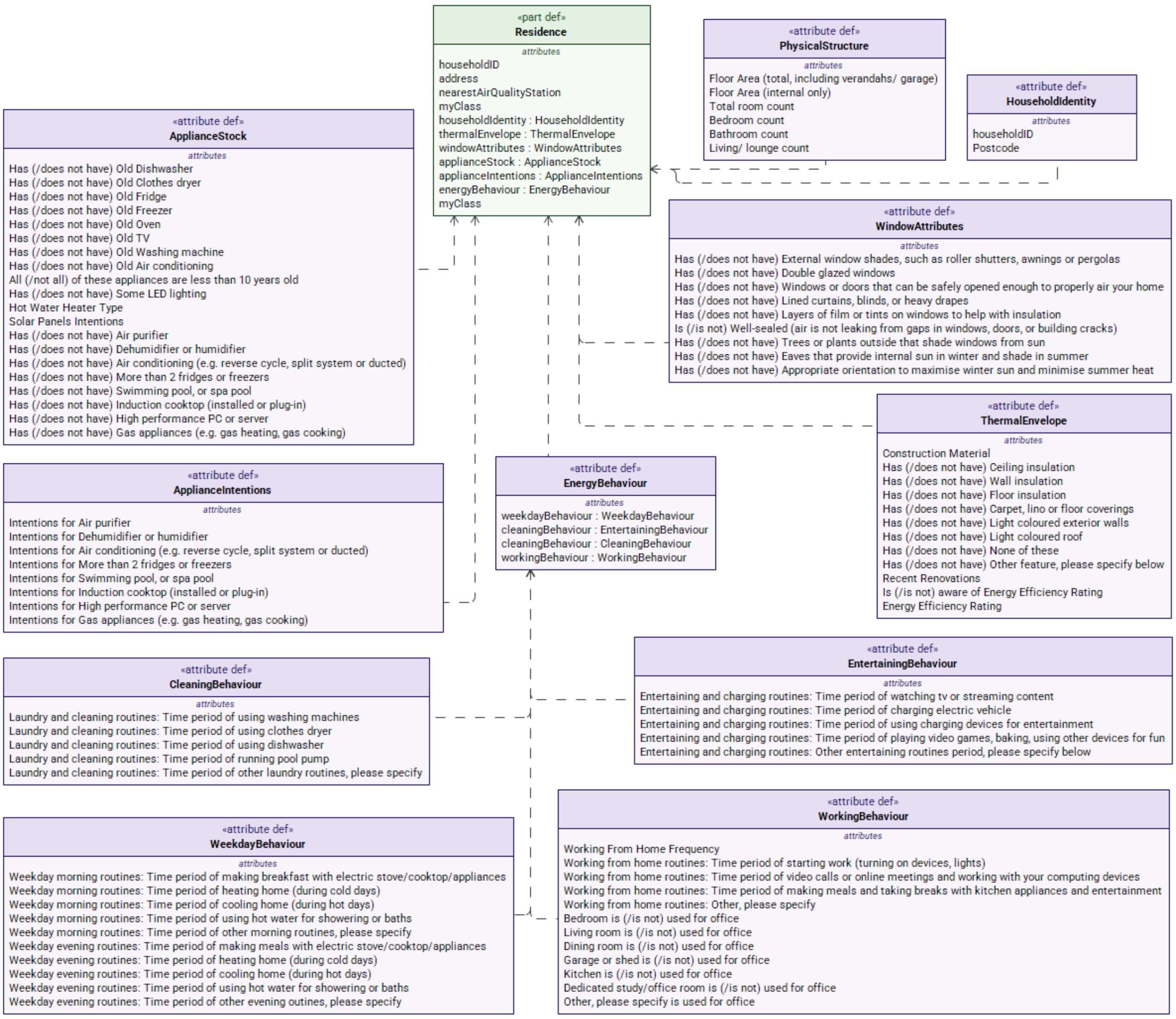

Figure 7: Sample of household attributes whose values can be inferred from answers to a household survey questionnaire

Model elaboration

Together, Figures 4, 5, 6 and 7 show how MBSE can organise observations and metadata. The next step is to connect those observations to the multi-energy system shown in Figures 2 and 3. This helps show how insights derived from household-scale research such as SFL can be scaled up to improve understanding of energy demand across the broader multi-energy system.

Figure 8 links participant households to a pre-existing residential decomposition[18] that identifies common energy-consuming technologies such as water heaters and air conditioners. It includes devices more typical of northern hemisphere households. Figure 9 extends this representation using technologies identified through household surveys (Snow et al. 2026, footnote 1). This makes it easier to associate monitored power circuits (Figure 4) with specific technologies, to incorporate additional technologies as explicitly modelled residential subsystems, and to represent residences as parts of a broader residential sector (Figure 3). Figure 9 also shows that system elements can belong to multiple categories. For example, an air conditioner can be classified both by energy source (electricity) and by building function (heating, ventilation, and air conditioning).

Existing ontological and information schemas can also be reused and adapted for this purpose. When machine-readable, such schemas improve interoperability with existing datasets and analytical tools. For example, several smart-building ontologies already represent common building devices and spatial features relevant to energy use. These include the Brick schema for organising physical and virtual assets (e.g. HVAC, fire, security and lighting systems) in commercial buildings, and RealEstateCore ontology[19] for classifying building elements and architectural features[20]. Similarly, the International Electrotechnical Commission (IEC) has developed a technical standard[21] (CIM) for representing electrical power networks.

Once key residential energy technologies are identified (in green in Figure 8)—including devices that consume, produce, or store energy—it becomes easier to identify the functions they perform (in orange) and the broader user needs or functional requirements they satisfy (in red). For example, resistive electric heaters, heat pumps, and natural gas heaters all contribute to occupant comfort by heating indoor space. This can be described as a “requirement” to enable the occupants to maintain a satisfactory indoor climate. Air conditioners may support the same requirement while also enabling cooling, humidity control, and air filtration. Iteratively linking technologies, functions, and user requirements in this way supports a richer representation of both existing and possible residential energy systems. Which technologies to include in the model ultimately depends on contextual relevance. For example, oil furnaces may reasonably be excluded in the Australian context because they are uncommon, whereas hydrogen furnaces may be retained to support exploration of future

[18] A. M. Farid. Taming the complexity in Australia’s nexus infrastructure of energy, water, and hydrogen: A reference architecture. In 2023 INCOSE New England 5th Annual Fall Workshop Invited Seminar, Storrs, CT, USA, 2023.

[19] Hammar K., Wallin E.O., Karlberg P., Hälleberg D. (2019) The RealEstateCore Ontology. In: Ghidini C. et al. (eds) *The Semantic Web – ISWC 2019*. ISWC 2019. Lecture Notes in Computer Science, vol 11779. Springer, Cham DOI: https://doi.org/10.1007/978-3-030-30796-7_9

[20] Zhangcheng Qiang, Stuart Hands, Kerry Taylor, Subbu Sethuvenkatraman, Daniel Hugo, Pouya Ghiasnezhad Omran, Madhawa Perera, Armin Haller, (2023) A systematic comparison and evaluation of building ontologies for deploying data-driven analytics in smart buildings, *Energy and Buildings*, Volume 292, 113054, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2023.113054. This reference compares four such schemas: the Brick Schema, Real Estate Core, Project Haystack and Digital Buildings.

[21] IEC 61970 (Energy Management Application Programming Interfaces), IEC 61968 (Information exchange standards between electrical distribution networks), IEC 62325 (Information exchange standards for Energy Market Communications)

household-scale hydrogen-energy scenarios, which are actively being explored in Australia[22].

The model can be adapted to different cultural, historical, and geographical contexts, as well as changing social norms. Any given representation may also remain incomplete until extended as needed. For example, indoor air purification was a relatively minor concern two decades ago, but the growing demand for improved air quality has increasingly influenced household preferences and technology adoption[23]. SFL WP2 research highlights air purification, including personal air purification systems and air filtration in HVAC systems such as air conditioners as emergent technological trends in Australia[24]. Similarly, modern urban transport needs may now include electric vehicle charging infrastructure, whereas rural households may instead require diesel fuel storage. The choice of which attributes and components to model in detail depends on the analytical problem being addressed. For instance, the number of bedrooms is a strong predictor of residential energy use[25]. At this stage, the model focuses primarily on selected high-energy-consuming devices, while retaining the flexibility to incorporate additional subsystems identified as relevant through literature, expert judgement, observation, or analysis.

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[22] Energy Networks Australia: https://www.energynetworks.com.au/resources/reports/hydrogen-appliances-for-homes/

[23] Utami, I. I., & Baroto, W. A. (2025). The perception of air purifiers on indoor air quality: effective or human herd behavior?. *City and Built Environment*, *3*(1), 6.

[24] Dahlgren, K., Kaviani F., Martin, R., Roberts, M., Strengers, Y. 2026. Scenarios for Future Living: Emerging technology innovation and development. Emerging Technologies Research Lab (Monash University). Melbourne, Australia

[25] Yunjeong Mo, Dong Zhao (2021) Effective factors for residential building energy modeling using feature engineering, Journal of Building Engineering, Volume 44, 102891, ISSN 2352-7102, https://doi.org/10.1016/j.jobe.2021.102891.

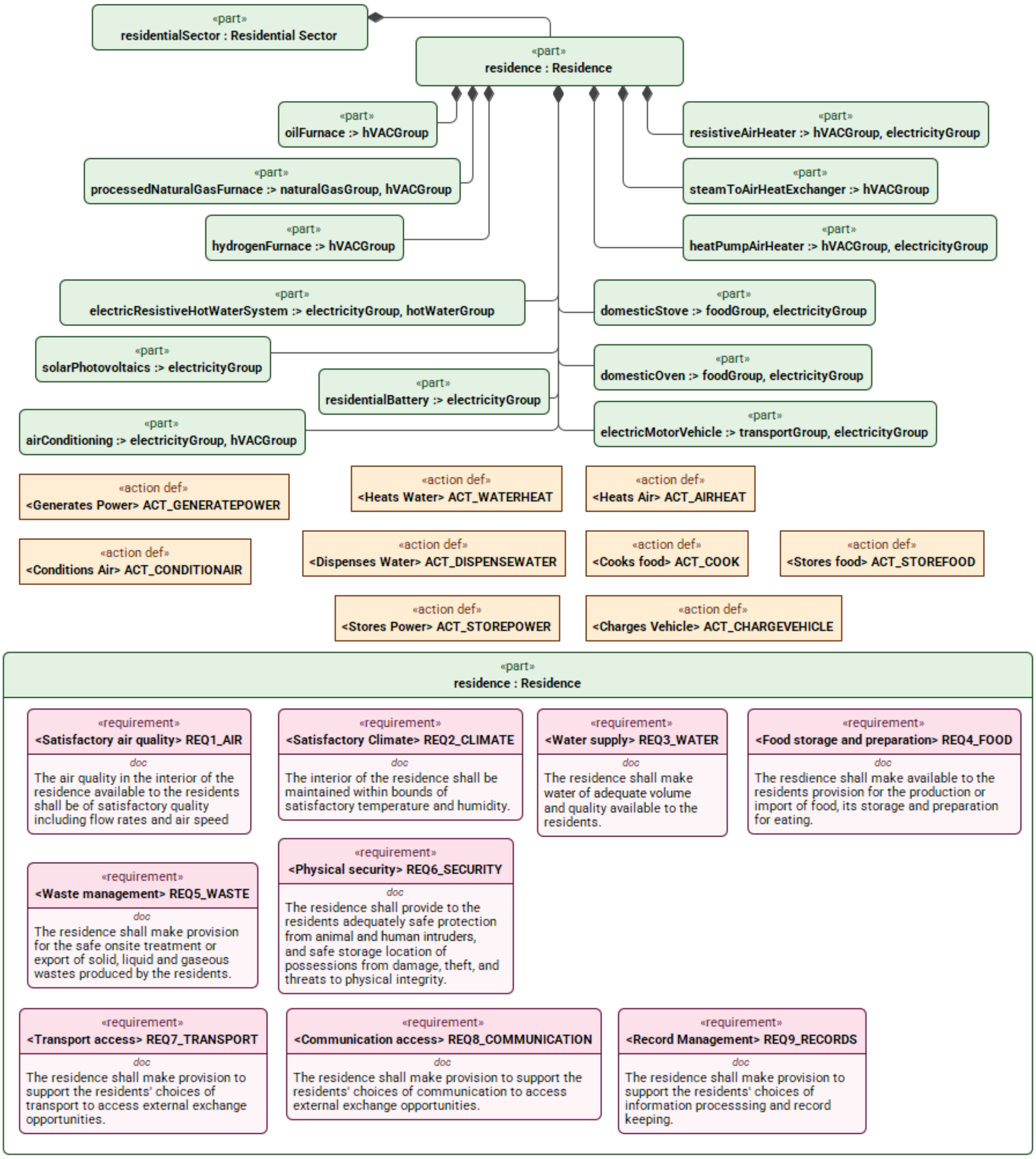

Figure 8: Elaboration of the residence decomposition for energy use

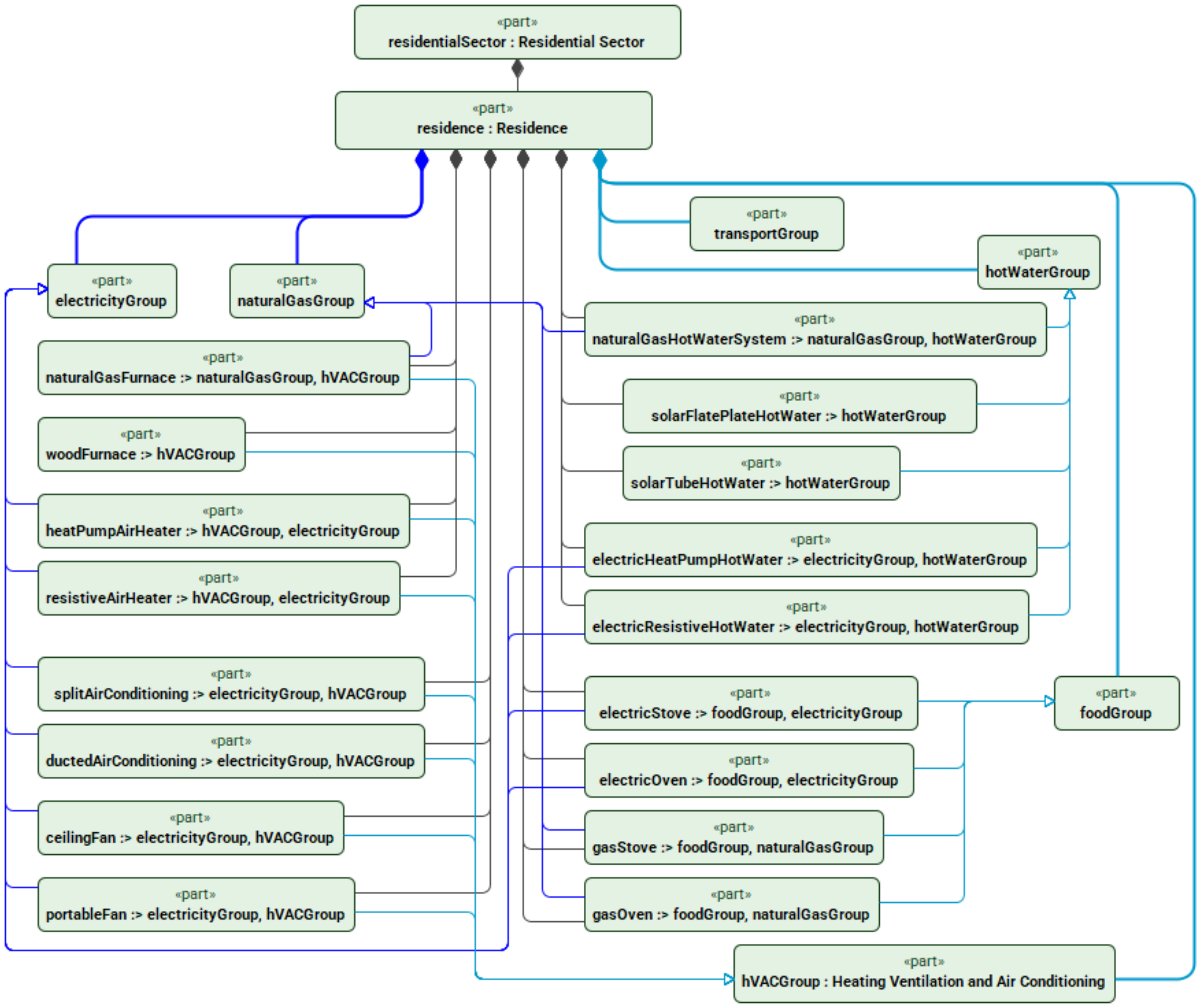

Figure 9: Parts decomposition diagram for a residence as a part of the residential sector

Using the case study of WP7 Living Lab households, Figures 3,4 and 8 show how MBSE tools can represent the household instruments, households, technologies and selected participant attributes within a consistent modelling framework. This improves explicitness, traceability, and completeness. Figures 5 and 6 show how the same framework integrates diverse multidisciplinary data sources while linking Living Lab observations to the broader residential energy system through explicitly defined relationships. Importantly, all figures are derived from corresponding machine-readable textual models, making them suitable for automated computational analysis and processing.

The following example briefly illustrates how these MBSE representations can support the scaling of Living Lab insights for wider energy-demand forecasting, by showing how the devices in Figure 9 contribute to overall energy flows in the national multi-energy system (Figure 2) under changing household conditions.

Illustrative example: electric vehicle and consumption profiles projections

This brief example shows how preliminary data from the case study may be scaled up to project future household electricity-consumption patterns, accounting for changes in demographic composition and household technology mix over time.

For this example, we consider a distribution feeder serving 150 households. To illustrate changes in demographic composition, we use conveniently available demographic variables (see Figure 6 and Figure 7 for how some of these data are organised in the metadata hierarchy):

- number of bedrooms
- whether the home is owned or rented
- the number of children, working-age adults, and retired adults.

To illustrate changes in the household technology mix, we consider electric vehicle ownership.

We create a sample population of households whose demographic characteristics and technology-mix (EV ownership) evolve in line with given target distributions (Figure 12) based on various plausible assumptions (see Appendix for details). Each sample household is then associated with a WP7 Living Lab household, selected with probability increasing with similarity in demographics and bedroom count. For households with an EV, an additional, similar, representative is selected from WP7 LL households that also own an EV.

The electricity consumption of each sample household is projected from the (first) representative household for all circuits except EV charging. For sample households with EVs, the EV charging load is taken from the additional EV-owning representative household. The aggregate result for 2025 to 2055 is shown in Figure 12 (in the appendix), based on only three months of data from November 2025 to January 2026. The simulated feeder peak demand increases over the projection period as the number of electric vehicles in the sample population grows.

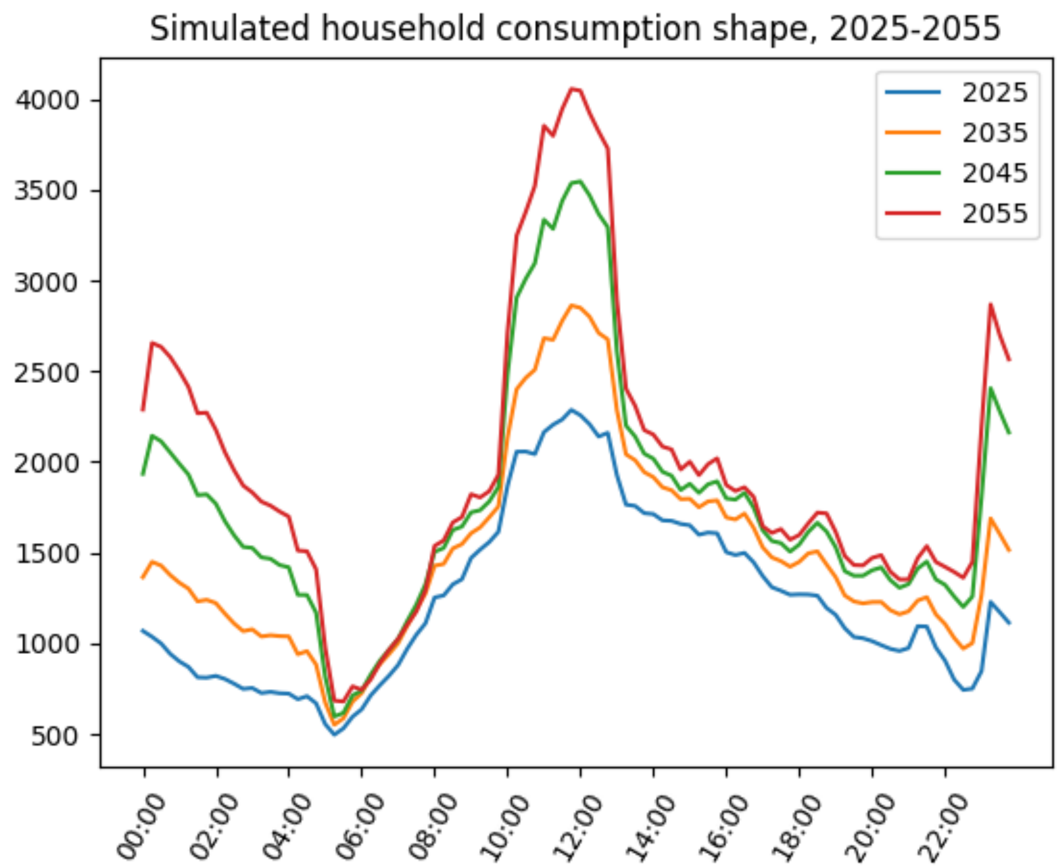

Figure 10: simulated consumption pattern by time of day and year

This projection provides an initial example of the projection modelling that living lab data can support in developing plausible future scenarios. MBSE tools can help track the underlying assumptions and their relationship to the living lab households. For example, it is quite possible that a quantitative model would include only a limited number of the most materially relevant appliances, while the MBSE representation could explicitly represent a more complete set. By comparing the MBSE representation of the model to that of the energy system itself, the simplifying assumptions made for the quantitative model relative to the more complete model become explicit. Similarly, it would be common for a lumped parameter in a given quantitative model to have a more detailed interpretation that can be described in an energy system MBSE representation. This then also becomes a visual representation of otherwise implicit modelling assumptions. The same approach can be extended to other demographic variables and technologies.

4: DISCUSSION: EXPANDING THE FRONTIER OF ENERGY DEMAND FORECASTING

This section discusses how MBSE could support the integration and scaling of household-scale data into broader models of future energy demand. The case study explored here is based on data obtained from WP7's Living Lab households, but household attributes gathered from diverse sources can also be incorporated. These include equivalent demographic, building-attribute, technology-ownership and purchase-intention data from the Australia-wide WP1 survey, as well as placeholders for future technology-ownership trends identified in WP2, such as hydrogen appliances for space or water heating. The main value of MBSE here is not that it produces forecasts directly, but that it provides a structured way to represent the relationships among households, technologies, behaviours, and the wider multi-energy system on which forecasting depends.

Scaling knowledge is a priority for Work Package 7. One objective is to scale data from the WP7 Living Lab to explore the wider energy-system impacts of technology, business-model, and behavioural change. This aligns directly with the WP7 research question of: "*How can the knowledge generated in WP1-6 be scaled up to address national energy challenges?*"

MBSE supports these objectives by providing precise representations of key elements within both the WP7 Living Lab and the wider energy system, including technologies, service providers, and consumers. These SysML representations clarify the relationships among relevant system elements and support the design, communication, and justification of analytical methods for scaling from sample observations to broader inferences. This includes the impacts arising from modern technologies, changes in energy-service-provider business and operational models, and shifts in consumer behaviour. The extensible structure of MBSE is likewise capable of integrating aspects of other work packages, including attributes of WP1's surveyed households and emerging technology trends (WP2).

Previous approaches to population-scale energy-demand forecasting include developing probabilistic energy-use profiles for demographic groups and combining them with projected demographic change. However, this implicitly assumes that household energy-use behaviour remains statistically stationary once demographic characteristics are specified. This assumption is unlikely to hold during the energy transition as customers adopt new technologies, tariffs, and everyday practices.

More realistically, forecasting future energy demand requires modelling the evolution of:

(i) population demographics and housing stock;

(ii) the uptake and mix of end-use technologies, such as air conditioners, solar panels, electric vehicles, pool pumps, and alternative water-heating systems; and

(iii) the operating behaviour of installed technologies.

Future diurnal electricity-demand patterns therefore cannot be projected accurately by simple extrapolation of historical trends. More sophisticated models are needed to represent not only circuit-scale demand, but also changes in technology mixes and operating patterns over time. Modelling work already underway in SFL provides household-scale nuance to demand modelling. WP4 seeks to make different futures of CER uptake accessible to system planners and industry by providing a sandbox for understanding the effect of different types of CER adoption and usage behaviour on load signatures. Our separate work in WP7 utilises probabilistic modelling to predict air-conditioning use based on climatic, demographic and behavioural variables, as shown in Figure 1 (Project Background).

MBSE does not provide modelling in itself; rather, it provides a structured, machine-readable way to describe complex systems and to integrate models based on different sources of information and resolution detail. For any given model of some aspect of the Australian energy system, MBSE tools can rigorously describe the energy components the model represents, and the boundaries of the model's scope. Consequently, given several models, it can rigorously represent common elements, distinguish distinct elements, and identify possible relevant interfaces among them.

MBSE's ability to communicate across models relies on its formal representation of fundamental modelling structural assumptions such as part-whole decompositions, boundaries of representation and analysis, component elements and interfaces; its support for alternative views of a common underlying structure; and its (delimited) ability to make explicit the distinction between models and the things that they represent. Many studies have examined how Australian energy end-use technologies affect aggregate electricity demand (including rooftop photovoltaics[26],[27], electric vehicles[28], batteries[29], flexible demand devices[30], residential[31], and commercial[32] building energy

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[26] Graham, P. and Mediwaththe, C. 2024, *Small-scale solar PV and battery projections 2024*. CSIRO, Australia. https://www.aemo.com.au/-/media/files/major-publications/isp/2025/CSIRO-2024-Solar-PV-and-Battery-Projections-Report.pdf

[27] Paul Nidras, Isabel Neilson, Hana Ramli, Jacobs (2025), *Mid-scale Solar PV System Projections*, Clean Energy Regulator RFQ ID 23652 , https://cer.gov.au/document/mid-scale-solar-pv-modelling-report-jacobs-july-2025

[28] Graham, P., Mediwaththe, C. and Green, D. 2025, *Electric vehicle projections 2024*. CSIRO, Australia. https://www.aemo.com.au/-/media/files/major-publications/isp/2025/stage-2/electric-vehicle-projections-2024.pdf

[29] Brinsmead, T.S., Graham, P., Hayward, J., Ratnam, E.L., and Reedman, L. (2015). *Future Energy Storage Trends: An Assessment of the Economic Viability, Potential Uptake and Impacts of Electrical Energy Storage on the NEM 2015–2035*. CSIRO, Australia. Report No. EP155039.
https://www.aemc.gov.au/sites/default/files/content/fa7a8ca4-5912-4fa9-8d51-2f291f7b9621/CSIRO-Future-Trends-Report.pdf

[30] CSIRO and Energy Networks Australia 2017, *Electricity Network Transformation Roadmap: Final Report*. https://www.energynetworks.com.au/assets/uploads/entr_final_report_web.pdf

[31] Energy Consult (2020) *RBS2.0 Methodology Report*
Department of Industry, Science, Energy and Resources (2021), *2021 Residential Baseline Study for Australia and New Zealand for 2000 to 2040,* https://www.energyrating.gov.au/news-and-stories/2021-residential-energy-baseline-study-australia-and-new-zealand

[32] *Commercial Building Baseline Study 2024 – Summary Report* (February 2025 Update) Prepared for: Australian Government Department of Climate Change, Energy, the Environment and Water February Date: 2025 https://www.dcceew.gov.au/sites/default/files/documents/commercial-building-baseline-study-2024-update-revised-feb-2025.pdf

uses, and energy-efficiency measures[33]). However, these studies do not always make their structural assumptions obvious. Compared with an MBSE approach, relationships among sectors, component technologies, and modelling assumptions are commonly represented less formally. This can make it harder to test consistency across studies or to identify where important assumptions remain unexamined.

A sophisticated multi-scale energy demand forecast does not strictly require MBSE. However, systems engineering methods encourage explicit representation of relationships among economic growth, population demographics, housing stock, household technologies, energy-use behaviours, and energy demand. They also make it easier to relate partial models to one another—for example, linking aggregate forecasts of solar PV and battery uptake to household-scale models of investment decisions.

In practical terms, a shared systems framework is expected to:

- improve communication of forecasting methods within analysis teams and with external audiences;
- support tracking of assumptions across modelling scales;
- highlight gaps, overlaps, and inconsistencies between subsystem models; and
- encourage explicit documentation of simplifications and approximations.

A flexible, standardised approach to system representation also supports mutual analytical consistency between broad exploratory studies, which typically arise earlier in a long-term research program, and the more detailed quantitative modelling exercises undertaken later.

This case study of representing the WP7 Living Lab as a small subsystem within the residential sector provides a pathway for scaling observations to the wider population. This requires identifying household characteristics and technologies that are both strongly correlated with energy use and observable, or at least inferable, across the broader population. Examples include bedroom count (Mo and Zhao, 2021, see footnote 25), solar PV and electric vehicle ownership, and behavioural predictors identified in the literature[34]. A focus on a scaling application points toward market segmentation approaches for representing the residential sector (see[35], or the energy demand forecasting approach in Section B.2 of[36]). This, in turn, suggests that the WP7 Living Lab should include adequate representation from all major segments to support broader inference.

[33] Strategy. Policy. Research. (2025) *2025 Energy Efficiency Forecasts Final Report*, Prepared for: Australian Energy Market Operator, https://www.aemo.com.au/-/media/files/major-publications/isp/2025/stage-2/2025-energy-efficiency-forecasts-final-report.pdf

[34] Steph Johnson Zawadzki, Leonie Vrieling, Robert Görsch, Georgios Michelakis, Nieke Lemmen, Nadja Zeiske, Mark Verschoor, Linda Steg, A meta-analytic review of why people save energy at home, Cell Reports Sustainability, Volume 2, Issue 10, 2025, 100493

[35] Tim Maiden, Emma Jones and Toby Bridgeman (2020), *Domestic energy consumer types: Review of existing segmentation approaches*, ClimateXChange

[36] Ausgrid (2025), *Distribution and Transmission Annual Planning Report,* https://www.ausgrid.com.au/about-us/regulation-and-compliance/network-planning/dtapr

5: SUMMARY, CONCLUSION, SUBSEQUENT WORK

Lessons learnt from activities

MBSE shows promise for “knowledge generated in WP1-6 [to] be scaled up to address national energy challenges” because it provides structured methods for documenting its key subsystems and their relationships to the broader Australian energy economy, and for scaling results from discrete studies to complex systems. This facilitates extrapolation of analysis and results from discrete investigations of smaller-scale aspects of the energy system to its more complex larger-scale context. It also supports explicit representation of the logical and informational relationships among those subsystems. The modelling exercise described here helps clarify the distinctions and interactions among: Living Lab measurement instruments; participant household environments; the national residential sector; the national multi-energy system; and potential future Living Lab data storage and processing.

Documenting these subsystems supports the systematic development of shared conceptual and quantitative models that can aid mutual understanding among diverse stakeholders, disciplinary perspectives and sectoral expertise. It also helps track decisions about what is included, excluded, or simplified — which is particularly valuable when models are developed collaboratively or integrated with other frameworks. Explicitly representing models in forms that can be critiqued is an important aspect of the scientific method.

The study shows that MBSE tools are highly flexible and broadly applicable, so that informed judgment is required to determine where they add most value. For simple systems, the overhead of formality may outweigh the benefits. MBSE is likely to become more useful for SFL as participant numbers grow, data volume and heterogeneity increase, and dataset interrelationships become more complex.

The greatest practical value of MBSE in the Living Lab remains to be demonstrated. This preliminary investigation applied only basic methods — system identification, architectural representation, and illustrative elaboration —to participant households and the residential sector. A full MBSE-driven digital engineering[37] approach was not attempted. These representations may assist in designing downstream probabilistic forecasting methods by visually representing the availability of relevant data sets, or they may prove more useful for retrospective documentation of already developed quantitative models.

Future possible MBSE related activities

Additional future activities and outputs may include:

- Further developing a prototype energy-demand forecasting model sensitive to changes in demographics, technology adoption, and resident behaviour, drawing on the system representations and sensor data developed to date.
- Given a description of specific quantitative forecasting methods using energy-behavioural data acquired as part of the Scenarios for Future Living research program (such as those under development in WP4 or as reported in Snow et al. 2025, footnote 1, for WP7), develop structural models of those forecasting methods that make explicit their relationship to the broader multi-energy system and to each other.

[37] D. Verma. Systems engineering for the digital age: practitioner perspectives. John Wiley & Sons, 2023.

- Development of a general mathematical framework for inferring parameter distributions in national energy-system models using sensor and survey data collected from participant households with known characteristics.
- Identification of gaps in existing household information, and proposal of high-priority survey questions or monitoring instruments relevant to residential energy-use behaviour.
- Further elaboration of SysML representations of participant households and their local environments, the national multi-energy system, and the residential sector — with clearer links between participant household models and the broader national energy system.
- Identifying further applications of MBSE within the SFL program, including applying a systems engineering lifecycle process to already-represented subsystems or to the future design of the Living Lab itself.

Summary

This report examined how MBSE can represent measurement instruments, household characteristics, and selected relationships between household observations and the broader multi-energy system. The main finding is that MBSE can provide a clear, systematic framework for organising heterogeneous data and linking household-scale observations to wider system models.

The WP7 Living Lab monitors electricity consumption and broader energy use in an initial cohort of several dozen NSW and Queensland households, supporting investigation into the human, social, and behavioural dimensions of the energy transition. This requires insight into attitudes, preferences, and behaviours of energy consumers, whose decisions shape both energy demand and expectations of system performance, but who are highly heterogeneous and do not behave as economically rational agents.

As an initial demonstration, this report applies SysML v2 to represent both the data-collection instruments in the Living Lab and the household elements those instruments monitor or explain. We show that SysML v2 can represent quantitative data — from indoor environmental sensors, weather stations, and electrical circuit monitors — and qualitative data from household surveys: demographics, dwelling characteristics, and appliance information. It explicitly represents logical relationships among these diverse datasets, helping to systematically identify, organise, and label Living Lab information.

The Living Lab can be seen as a small-scale emulation model of the residential sector. We used initially collected data to forecast how electricity demand profiles may evolve over time in response to changes in population demographics and consumer technology adoption. The initial representations of participant households, the residential sector, and the multi-energy system could be further extended to support similar quantitative demand forecasting.

The same modelling language can situate the residential sector within a broader multi-energy system model, alongside other demand sectors — commercial and industrial — and systems including coal, oil, gas, electricity, hydrogen, water, and wastewater. When compatible digital representations already exist using formal schemas, it is easier to infer logical relationships between datasets. This provides a minimum conceptual foundation for scaling Living Lab observations into quantitative models of the wider energy system and its future demand patterns.

Appendix

The following provides methodological details for the example in Section 3, electric-vehicle and consumption-profile projections.

We first create a sample set of 150 households to represent a feeder in a single suburb and assign a randomised distribution of bedroom counts as a static variable, assuming that this remains fixed over the representative period from 2025 to 2060 (that is, assuming no renovations as a convenient approximation). In this example, we developed a sample distribution based on the mean and standard deviation of the number of bedrooms in a typical Australian house, using data from the Australian Bureau of Statistics Household Census. Figure 11 shows this distribution and notes that the initial bedroom-count distribution of EV-owning households in the simulation, shown in the right-hand chart, differs from the full sample because it was selected to match the observed bedroom-count distribution of EV-owning households in the WP7 Living Lab.

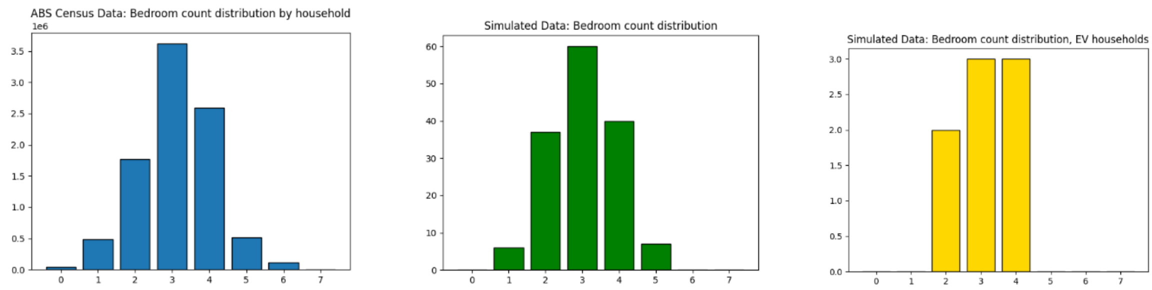

Figure 11: Bedroom count — ABS data and simulated data (150 samples)

We then build a randomised projection of changes in tenancy. Where particular parameter values are unsourced, they are not based on observational data; rather, they are simply plausible placeholders for illustration purposes. In any given year, it is assumed that there is a 1-in-7 chance that residents will move out for tenancies that have lasted up to seven years. For tenancies lasting beyond seven years, the likelihood of the tenancy continuing another year is assumed to be inversely proportional to its current length. It is assumed that about 50% of new residents own their homes in 2025, rising to 70% by 2060. When the simulation projects a change in residency, ownership status is randomly selected based on the year. It is further assumed that the average length of residency is about seven years, so every year there is a 0.5/7/7, that is, approximately 1%, chance that ownership status changes from unowned to owned.

It is also assumed that the number of children, pre-retirement-age adults, and retired adults starts in 2025 at the SFL Living Lab average and standard deviation. By 2060 the average number of children declines by one, the average number of pre-retirement adults decreases by 0.5 persons per household, and the average number of retired adults increases by one, while the standard deviation of retired adults decreases by one. When the simulation projects a change of residency, the household composition is changed according to these assumptions over time. For simplicity, this does not change over the course of the residency until the residency changes, and the number of residents in the three categories is represented as independent. Again, for simplicity, though unrealistically, no correlation with bedroom count is assumed.

The next step is to simulate a hypothetical projection of EV ownership over time. To this end, we first compute a similarity measure between each household in the fictitious sample and each household in the WP7 Living Lab, using a distance metric based on the demographic parameters: bedroom count, household ownership status, and resident count by age category (see Figure 6 and Figure 7). This enables calculation of the average distance from each sample household to each household in the WP7 Living Lab with an EV, and to households in the Living Lab without an EV. It is possible to randomly associate the sample households with EV ownership in such a way that:

- The total expected number of EVs in the simulated sample corresponds to projected EV uptake over time, based on data from the cited reference[38].
- The likelihood of an EV being purchased is greater if the sample household is more similar to a household with an EV in the WP7 Living Lab.
- Once a household obtains an EV, it keeps it unless the residency of the house changes.

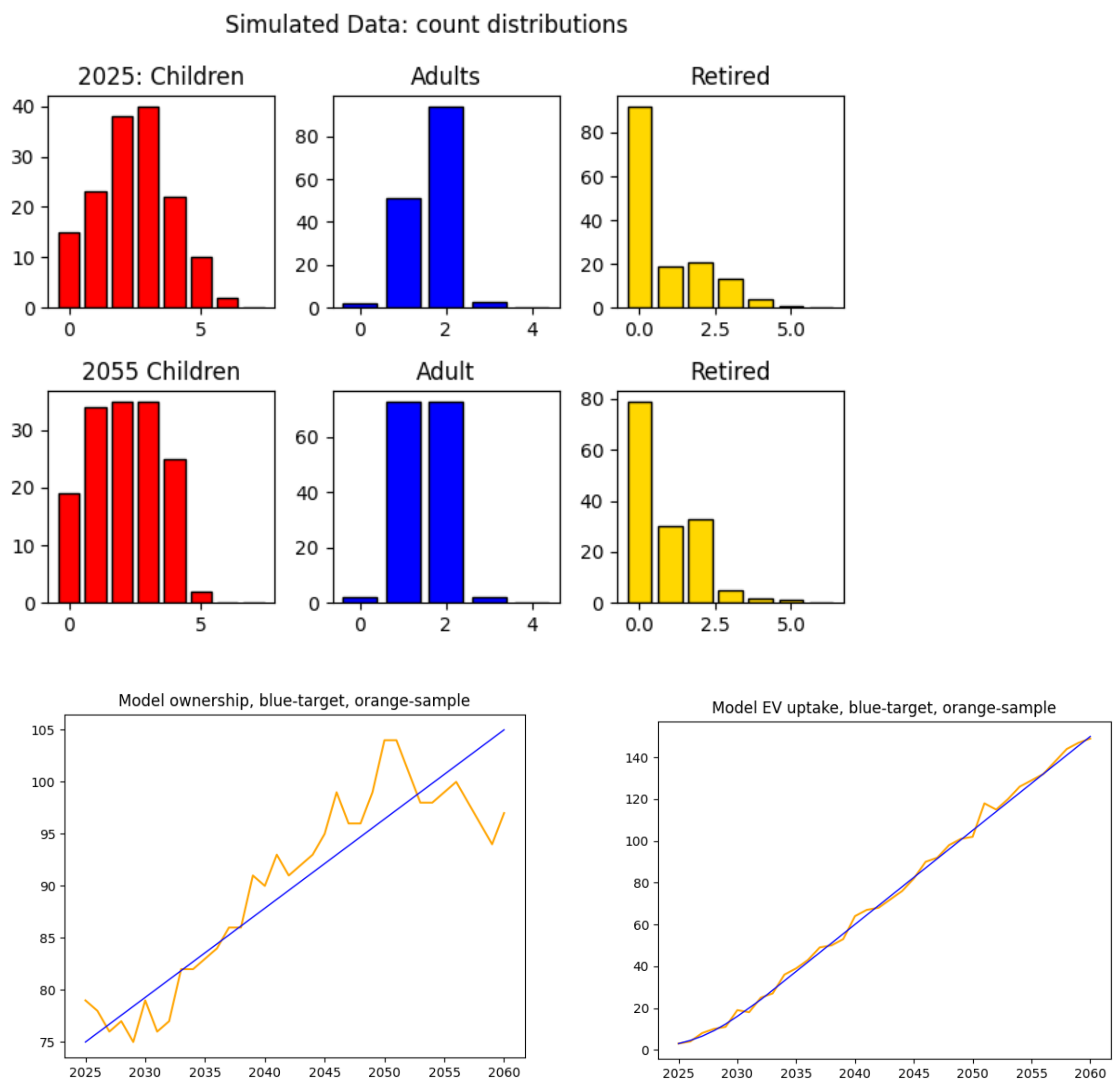

Figure 12: Target and simulated family age distributions, home ownership and electric vehicle count

38 https://agdatashop.csiro.au/ev-uptake-projections , from Graham, P.W. and Havas, L. 2021, Electric vehicle projections 2021, CSIRO, Australia. https://www.aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/csiro-ev-forecast-report.pdf

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