RACE for 2030

RELIABLE AFFORDABLE CLEAN ENERGY

Consumer Energy Unleashed

Mapping Australia's CER/DER priorities to unlock billions in customer, societal and whole-system value.

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Prepared for:

RACE for 2030
RELIABLE AFFORDABLE CLEAN ENERGY

What is RACE for 2030?

The Reliable Affordable Clean Energy for 2030 Cooperative Research Centre (RACE for 2030) is a 10-year, $350 million Australian research collaboration involving industry, research, government and other stakeholders. Its mission is to drive innovation for a secure, affordable, clean energy future.

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Energy Catalyst

Dedication

This report primarily examines ***what*** is required to unleash Australia's Consumer Energy revolution from a range of technological, regulatory, system and other perspectives.

It is dedicated to the diversity of Australian energy consumers who provide the fundamental ***why*** our power systems exist and ***how*** they will need to transform to meet consumers' future needs and aspirations and provide an equitable platform for their beneficial participation.

Executive Summary

Australia's power systems are experiencing the largest scale of transformation in their 100-year history. In the context of global decarbonisation efforts, a distinguishing feature of Australia's grid transformation is the scale and pace at which millions of Australian households and businesses are investing in Consumer Energy Resources (CER/DER).[1]

This analysis maps almost 200 CER/DER studies, trials and demonstration projects in Australia over the last 5 - 7 years, informed by the following strategic objective:

> Examine Australia's portfolio of CER/DER studies, trials and demonstration projects to map the priority gaps that must be addressed to unleash their full potential in enabling efficient, low carbon and self-balancing future power systems that serve the long-term interests of all consumers.

High-level Findings

While such a wide-ranging review will never be exhaustive, the study found that Australia's first major phase of CER/DER research has:

1. Provided an ***extensive body of knowledge*** on foundational CER/DER technologies and enablers, with over 60% of all research focus being on distribution network capabilities, operations and end-use devices;

2. Been conducted largely ***within the historical segments*** of the legacy supply-chain and placed primary emphasis on the ***mitigation of negative operational impacts*** that may arise with the integration of CER/DER technologies;

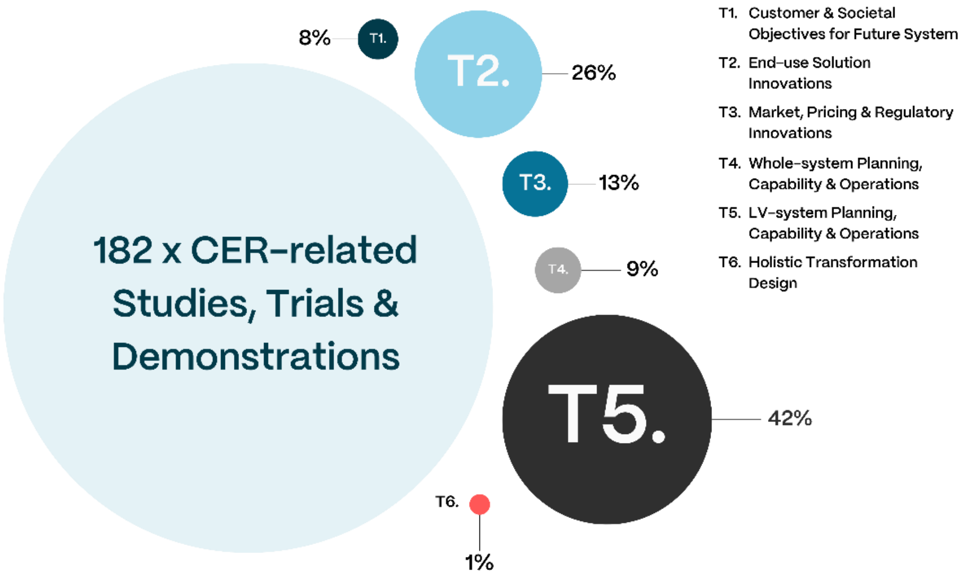

Figure 1 - Comparative Proportions of Research Focus across 6 x Themes (T)

[1] The combined acronym 'CER/DER' is used throughout this report to recognise that distributed resources may be located either behind-the-meter or front-of-meter.

3. Had limited focus on examining ***where*** Australia's power systems are heading in the medium to long term, ***what*** comprehensive range of functions CER/DER may serve to enable our future grids, and ***how*** these ultra-complex grids may be holistically transitioned to fully unleash this value with consumer benefits as a core objective;

4. Beyond the mitigation of potential negative impacts, not had the advantage of an *authoritative, positive vision for CER/DER* as a beneficial part of Australia's future power systems, nor a mandate for *unlocking its full customer, societal and system value* through a whole-system approach to integration;

5. Generally assumed and/or had no mandate to examine whether Australia's *legacy structural and market arrangements* are capable of scaling to Operationally Coordinate the extremely high levels of CER/DER envisaged by plausible future scenarios such as AEMO's Step Change scenario; and,

6. Been impeded by the *lack of a systems-based approach to CER/DER integration* and the *deferral of several foundational matters* key to the holistic integration of CER/DER, including Distribution System Operator (DSO) and Transmission-Distribution Interface (TDI) models, underpinning cyber-physical architectures, evolving functional roles, etc.

While recognising the above findings, it is also noted that initiatives such as Project EDGE, Project Symphony and Project Edith have made significant efforts to advance CER/DER research from a more whole-system perspective.

Report Structure

Chapter 1 of the report explores the contours of Australia's grid transformation and the distinctive focus of the report which aims at unlocking $-billions of economic benefits for customers, society and the wider system through the holistic integration of CER/DER.

> *Customers are playing a key role in the shaping the future of electric power systems, and Australia is leading the way globally*

Chapter 2 then provides an overview of the innovative methodology employed to develop this report and outlines the development of Australia's largest and most detailed database of CER/DER studies, trials and demonstrations. It describes the analytical framework developed to explore pathways for the whole-system integration of CER/DER informed by Systems Engineering-based methodologies. Given the wide-ranging scope of the analysis, guidance is also provided for interpreting the report and comprehending its limitations.

Leveraging the detailed project database and analytical framework, Chapter 3 then provides a high-level graphical view of the CER/DER initiatives studied. Presented under the 6 x Themes and 15 x Domains provided by the analytical framework, this provides a comparative sense of the areas where most research has been targeted. Chapter 4 then provides a deeper dive into each of the individual Themes to consider the research focus relevant to the 61 x Research Topics clustered under the Themes and Domains.

Chapter 5 then provides a high-level view of Australia's entire portfolio of CER/DER research to identify both the high-focus areas and those that have received only moderate or limited research attention. A selection of summary observations are provided, including the recognition that over 60% of the first generation CER/DER-related research has been primarily focused on two of the six Themes.

Looking forward, Chapter 6 explores a range of opportunities for delivering enhanced outcomes from the next generation of Australian CER/DER-related research. Aware of Australia's unique transformational context, it explores a set of key risks and opportunities before highlighting three strategic enhancements that would be universally beneficial to all future CER/DER research and action. While the report does not specify research priorities, the remainder of the chapter highlights numerous Research Topics that warrant greater focus in the next phases of research to deliver a whole-system approach to CER/DER integration that is key to unleashing its full customer and system value.

Finally, Chapter 7 takes a step back from the above detail to propose three target objectives together with twelve recommended actions for enhancing Australia's next phase of CER/DER research. These are:

1. Aligned Vision and Enablement: CER/DER research efforts are closely aligned with, and seen as an integral and beneficial part of, transitioning Australia's GW-scale power systems to achieve emission reduction goals in a manner that is secure, cost-efficient and focused on the long-term interests of all consumers.
2. Maximum Societal Benefits Targeted: Research is undertaken as a balanced and holistic portfolio designed to unlock the full system value of CER/DER and informed by in-depth social and consumer research to ensure benefits for individual consumers and enhanced outcomes for society that align with consumer expectations.
3. Efficient and Accelerated Progress: CER/DER research projects, and related funding mechanisms, are configured to support efficient and accelerated progress by addressing critical gaps, reducing the potential for unintended duplication and leveraging collaborative, scale economies.

These three objectives provide a framework for twelve recommended actions which are set out in Table 1 below.

Proposed Objectives & Recommended Actions

Target Objective	Recommended Actions
1. Aligned Vision and Enablement: CER/DER research efforts are closely aligned with, and seen as an integral and beneficial part of, transitioning Australia's GW-scale power systems to achieve emission reduction goals in a manner that is secure, cost-efficient and focused on the long-term interests of all consumers.	1.1. Representative working group. Establish a representative working group to review and expand the national CER/DER research database, analytical framework/taxonomy and gap analyses through recurring annual cycles, giving priority to holistic consumer outcomes and directly informing policy and regulatory evolution.
	1.2. Strategic vision and target outcomes. Collaboratively develop a set of *Guiding Principles* and a positive *Whole-system Vision for CER/DER* to inform a more integrated next phase of research and transformative action, together with a *Balanced Scorecard of Outcomes* to be achieved.
	1.3. Enabling system characteristics. Collaboratively examine and document the future power system characteristics and capabilities needed to enable the *Whole-system Vision for CER/DER*, presented in a form that supports collaboration across the end-to-end power system and involves a diversity of existing and emerging stakeholder representatives.
2. Target Maximum Societal Benefits: Research is undertaken as a balanced and holistic portfolio designed to unlock the full system value of CER/DER and informed by in-depth social and consumer research to ensure benefits for individual consumers and enhanced outcomes for society that align with consumer expectations.	2.1. Open research database. Develop and maintain an open, searchable public database of all CER/DER studies, trials and demonstrations that may be reviewed by research proponents to ensure priority gaps are targeted and duplication of effort avoided.
	2.2. Mapping of beneficial services. Collaboratively examine and document the full set of beneficial physics-based services that CER/DER can provide across the vertical tiers/layers of our future power systems as the basis for monetising and incentivising mass consumer participation.
	2.3. Enhanced research design. Expand power sector capability for designing research informed by a coherent theory of change, multi-time horizon analyses and formal systems-based tools that ensure solutions are considered in their whole-system environment as it transforms over time.
	2.4. Research priorities and collaboration. Strengthen early-stage project conception and design processes that ensure priority gaps are targeted and collaboration with upstream and downstream actors occurs from research concept to completion.

	2.5. Enhanced future resilience. Enhance Australia's focus on the 'future-proofing' of CER/DER systems-integration by developing formal mechanisms to validate the mass-scalability of solutions, from trial volumes in the hundreds/thousands to mass-deployment in the millions/tens of millions.
Target Objective	**Recommended Actions**
3. Efficient and Accelerated Progress: CER/DER research projects, and related funding mechanisms, are configured to support efficient and accelerated progress by addressing critical gaps, reducing the potential for unintended duplication and leveraging collaborative, scale economies.	3.1. Leverage global research. Increase international CER/DER scanning and collaboration to identify where research in other countries addresses specific gaps in Australia's research portfolio.
	3.2. Utilise research infrastructures. Strengthen the overall pace and effectiveness of Australia's CER/DER research by leveraging standing research infrastructures (e.g. Cooperative Research Centres, CSIRO, National Collaborative Research Infrastructure Strategy investments, etc).
	3.3. Strategically coherent research. Enhance CER/DER research project detailed design by ensuring that formal planning, approval and funding mechanisms that explicitly address: • How the proposed research targets identified gaps and will enable whole-system outcomes; • How current and future consumer needs and priorities are a substantive focus, including in-depth social and consumer research; • The current status of relevant Australian and international research and the potential for leveraging existing research infrastructures; • How the solution(s) researched will interface/interoperate with both upstream and downstream actors now and in the future; • How solution(s) are designed for scalability and extensibility across current, medium and long-term time horizons; and, • How the mass-scalability of solution(s), beyond trial and demonstration volumes, will be validated to ensure maximum customer and whole-system benefits when deployed at scale.
	3.4. Strategically coherent research funding. CER/DER research grant and funding mechanisms are aligned with and reinforce the above processes to accelerate Australia's achievement of maximum customer and whole-system benefits.

Table 1 – Key objectives and recommended actions for enhancing Australia's next phase of CER/DER research.

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1 Introduction

1.1 Background

Australia's GW-scale power systems are globally recognised as experiencing some of the world's fastest and most transformational change. The transformation is impacting all vertical layers of the system including bulk power, transmission, distribution and energy retail. And, the world is watching closely, intrigued by Australians' world-leading uptake of Consumer Energy Resources (CER/DER) – a trend that is reshaping the nature of power systems in real-time (Figure 2).

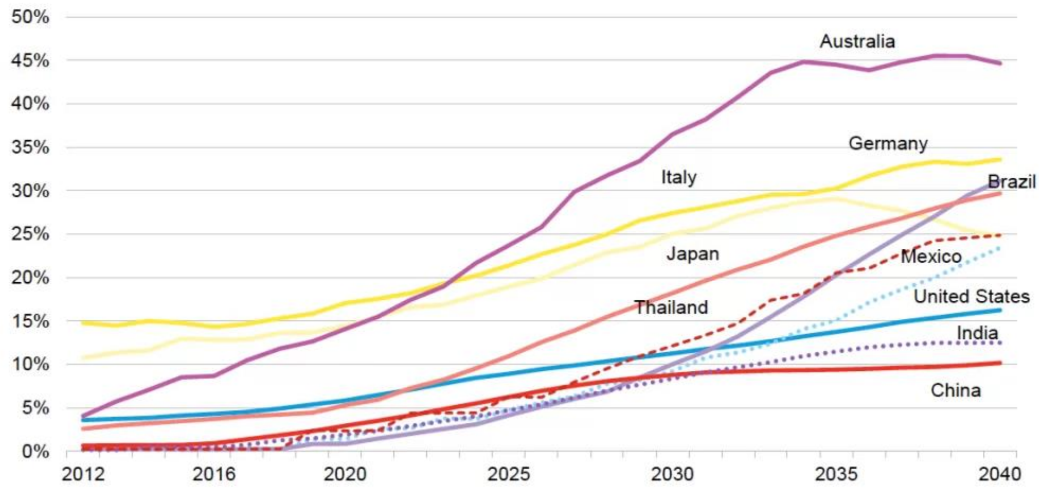

Figure 2 - Power system decentralisation ratio projections[2]

By comparison, 20th century power systems were largely centralised, one-directional bulk delivery systems. Almost all of the action occurred on the 'Supply-side' of the system.   A comparatively small fleet of large fossil fuel-based generators hundreds of kilometres upstream provided power to all major population centres. 'Consumers' were considered exactly that – passive recipients and consumers of energy, almost 100% of which was generated by others (Figure 3).[3]

[2] Image: Bloomberg New Energy Finance
[3] Refer Appendix C - Structural Shifts Relevant to Whole-system CER/DER Integration for more information.

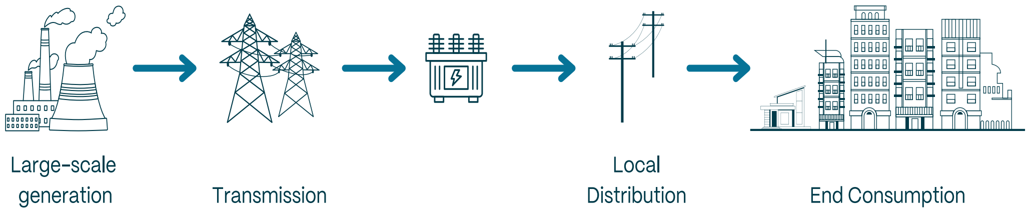

Figure 3 – 20th century power systems were designed as unidirectional bulk delivery systems, with almost all consumers having 100% of their electricity generated by others[4]

Today, most of Australia's large power systems are 'vertically disaggregated'. This is where the generation, transmission, distribution and energy retail functions are structurally separated from each other. Designed in the historical context of the one-directional power system described above, these structural arrangements have served Australia well for almost two decades.

Moving forward, Australia's large-scale power systems are transitioning from a past of tens or hundreds of large upstream resources to a future where millions of diverse energy resources participate across all vertical layers of the system.

As conventional sources of generation and flexibility are progressively withdrawn, there is global interest in whether and how Australia will successfully activate the massive volumes of new generation, storage and flexible resources that are emerging on what was traditionally called the 'Demand-side'[5] of the system.

Effectively unleashing the full potential of Australia's CER/DER revolution is estimated to be worth at least $20 – 30bn over the coming decades, and potentially up to $100bn.[6] Doing so, however, will require an increasing focus on integrative applied research in Australia that both leverages global best practice and avoids being unduly constrained by historical structural arrangements.

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[4] Image: Adapted from IRENA System Operation Collection (2020)

[5] While the term 'demand-side' is used in this report, it is becoming increasingly imprecise. While remaining the location of major load centres, distribution systems are now also hosting an ever-expanding proportion of Australia's fleet of energy resources. Many of these are highly relevant to the operational management and coordination of the entire power system in the form of generation, system buffering (storage), flexibility and the provision of essential system services. Given the physics-based nature of the system, this will need Australia's distribution system operators to more proactively coordinate with the wider power system as an increasingly hybridised location of demand, consumption, supply, storage, flexibility and essential system services.

[6] A growing body of Australian and international analysis is quantifying the massive scale of economic value at risk where 'whole-system' approaches to CER/DER integration are not applied. Effectively unleashing the full potential of Australia's distributed energy revolution is estimated to be worth at least $20 – 30bn over the coming decades, and potentially up to $100bn. For example:
https://www.iea-isgan.org/wp-content/uploads/2020/05/ISGAN_DiscussionPaper_Annex6_microVsMEGA_2020.pdf (pgs 73-74)
https://smarten.eu/wp-content/uploads/2022/09/SmartEN-DSF-benefits-2030-Report_DIGITAL.pdf
https://arena.gov.au/knowledge-bank/valuing-load-flexibility-in-the-nem/
https://www.datocms-assets.com/32572/1629948077-baringaesbpublishable-reportconsolidatedfinal-reportv5-0.pdf
https://www.energynetworks.com.au/resources/reports/electricity-network-transformation-roadmap-final-report/

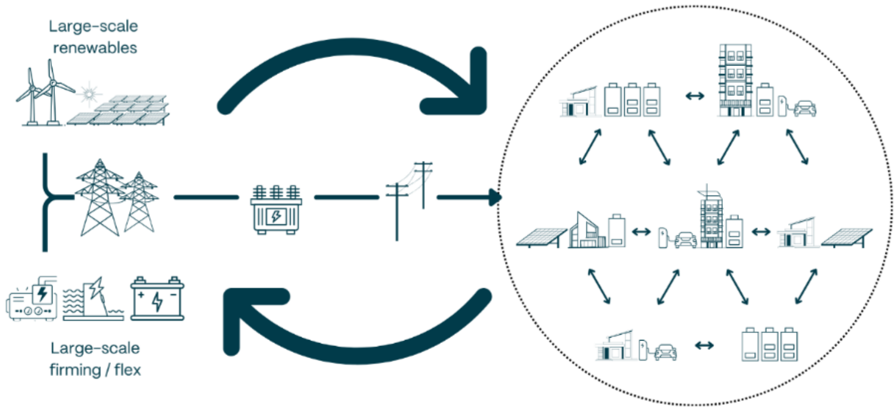
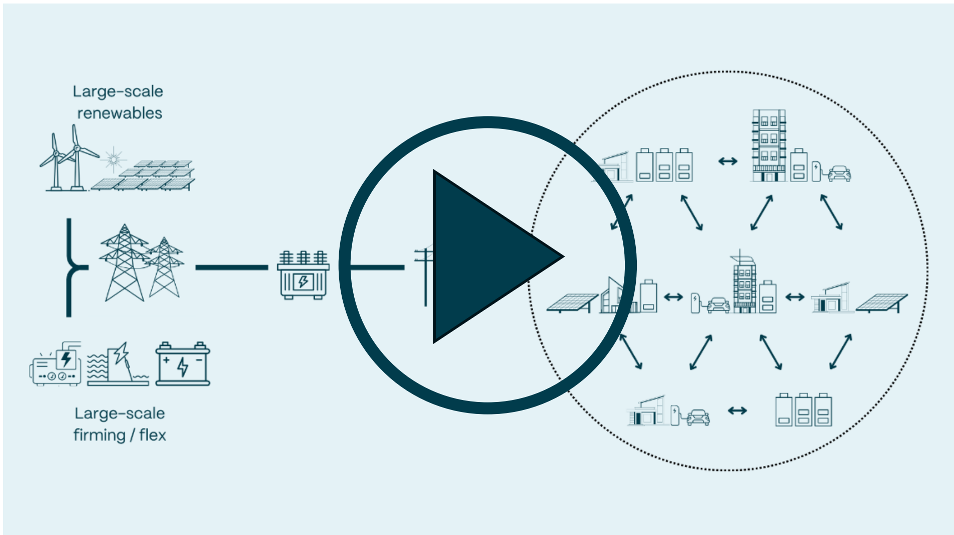


Figure 4 – 21st century power systems increasingly require millions of CER/DER to function as an integral part of a secure, efficient and self-balancing grid [7]

This is because the Laws of Physics interact with our grids as singular integrated systems, blind to conventional structural demarcations. The deliberate 'whole-system' approaches to grid transformation being pursued in other jurisdictions, such the United Kingdom, the European Union and the United States, simply mirror the physics-based realities of deeply integrating millions of CER/DER to become an integral part of a 21st century power system.

Given Australia's world-leading levels of rooftop solar PV, the NEM already has some regions experiencing close to 100% of instantaneous demand being served by CER/DER at midday on low load days. Later the same evening, these regions are almost 100% supplied by the centralised system. This results in a 24-hour operational profile that is essentially 'tidal' – certainly a dramatic departure from historical norms.



Animation 1 – Key grid transformation features that are broadly universal due to the physics-based realities of electricity systems and the deep integration of VRE and CER/DER.

[7] Image: Adapted from IRENA System Operation Collection (2020)

Looking out further to 2050, AEMO's Step Change scenario anticipates that the NEM will need to accommodate Variable Renewable Energy (VRE) and CER/DER at multipliers of 9x and 5x respectively! This is uncharted territory for GW-scale power systems anywhere, compounded further as the traditional sources of generation, flexibility and other services are withdrawn.

With the mass-deployment of VRE and CER/DER, our power systems become inherently more volatile and bi-directional. Jurisdictions such as Australia will need its end-to-end power systems and their rapidly expanding fleets of CER/DER to be made capable of functioning together in a far more dynamic, integrated, equitable and self-balancing manner. Holistic system design that harnesses the inherent physics-based properties of such a system is the only feasible way to achieve power systems that are simultaneously secure, cost-efficient and net zero emissions.

1.2 Report Objectives & Scope

This report and its supporting research activities was commissioned by the RACE for 2030 Cooperative Research Centre (CRC). RACE for 2030 is Australia's leading independent facilitator of integrative, whole-system and human-centred energy transformation research.

1.2.1 Strategic Objective

Australia has undertaken an extensive range of CER/DER related studies, trials and demonstration projects. To deliver maximum value to the nation, the approach to developing this report has focused on the following strategic objective:

> Examine Australia's portfolio of CER/DER studies, trials and demonstration projects to map the priority gaps that must be addressed to unleash their full potential in enabling efficient, low carbon and self-balancing future power systems that serve the long-term interests of all consumers.

As indicated earlier, such an integrative focus is required for Australia to realise the full potential of Australia's CER/DER revolution estimated to be worth many tens of $-billions over the coming decades. As AEMO has acknowledged, achieving this will require a step change in *whole-system* capability.

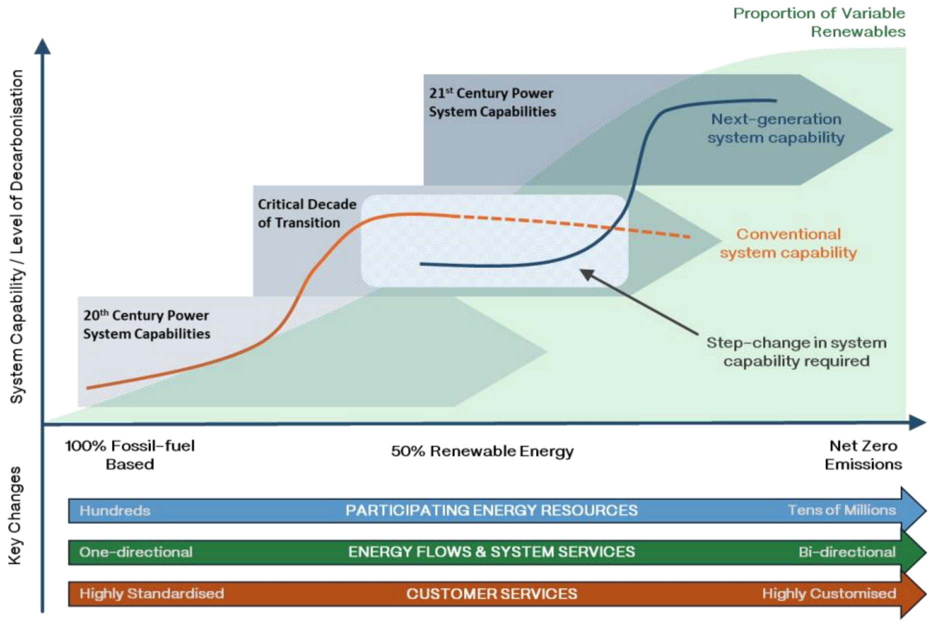


Figure 5 - Navigating Australia's transition to a high-VRE / high-CER/DER future power system requires a step change in whole-system capability.[8]

1.2.2 Development Objectives

Informed by the above strategic objective, the development objectives of this report have given priority to the following activities:

1. **Landscape Review.** Undertake a landscape review of Australia's CER/DER research projects and studies performed over the last five-years.
2. **Analytical Taxonomy.** Develop an analytical framework or 'taxonomy' for examining and categorising all CER/DER-related studies, trials and demonstrations; apply a holistic focus on technological, market and regulatory enablers, and the wider directional and social license considerations, needed to fully enable CER/DER benefits across end-to-end power systems.
3. **Focus Areas.** Identify the CER/DER research themes, domains and topics that have received significant attention and project focus; and, identify those that are important to unleashing CER/DER benefits across Australia's end-to-end power systems but have received comparatively limited research attention.
4. **Potential Enhancements.** Informed by the above analysis, highlight critical gaps and provide recommendations for enhancing Australia's program of CER/DER research in a manner that supports more collaborative, timely and cost-effective progress in unleashing the full benefits of CER/DER for Australian customers and end-to-end power systems.

[8] Image: Adapted from Engineering Framework – Interim Roadmap, AEMO, 2021 and A Gambit for Grid 2035 – A systemic look into the disruptive dynamics underway, Pacific Energy Institute, 2021

1.2.3 Report Scope

Given the diversity of topics relevant to the above strategic objective, and the tens of thousands of pages of related project information, it should be noted that the following are beyond the scope of the report:

- The report provides no commentary on, or validation of, the inherent value, completeness, functional veracity and/or transferability of any individual CER/DER-related initiative or combination thereof;
- The report contents are not exhaustive, and the findings should be understood as illustrative of overall CER/DER research trends rather than specific to any particular initiative; and,
- While a range of potential research priorities are examined, the report does not recommend specific priorities as they will evolve over time and should be considered on a case-by-case basis.

Please refer to Section 2.6 of this report for additional guidance on the interpretation of this report.

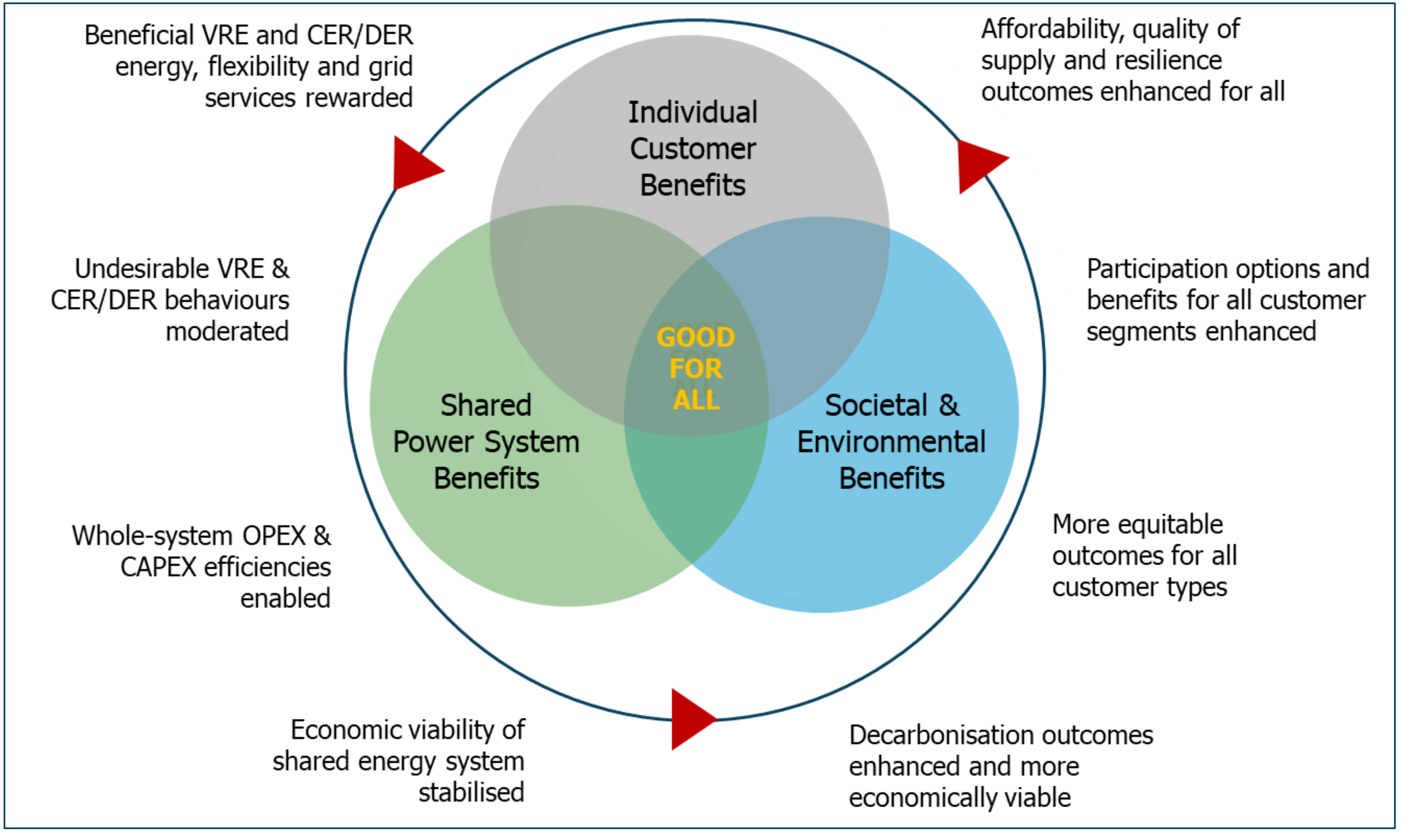


Figure 6 – A whole-system approach to CER/DER integration is key to ensuring a 'balanced scorecard' of customer, societal and system outcomes

1.3 Key Definitions

The following key concepts and definitions are provided to support both technical and non-technical readers in navigating the content provided in this report. And expanded set of definitions is also provided in Appendix A.

Term	Definition
Consumer Energy Resources (CER/DER)	A diverse range of small to medium scale energy resources located behind-the-meter at residential, commercial and industrial premises and owned and operated by the customer. CER include the following types of technologies: a) **Distributed Generation (DG):** including Distributed Photovoltaics (DPV) and embedded generators; b) **Battery Energy Storage Systems (BESS)**: including small and medium-scale batteries; c) **Electric Vehicles (EV)**; d) **Smart Inverters**; and, e) **Flexible Resources (Distributed)**. The term Distributed Energy Resources (DER) is commonly used of these technologies where they connected directly to the distribution system (i.e. front-of-meter). Active CER/DER can provide valuable Electric Products to the shared system, in exchange for some form of value or additional benefit, where they are highly correlated with the specific needs of the power system through Orchestration.
Customers	The human individuals, families, organisations, institutions and whole societies served by the power system and that are the fundamental reason it exists. Customers may choose only to receive, consume and pay for services from the power system. They may also elect to provide services to the power system, in the form of valuable Electric Products consistent with technical requirements, in exchange for some form of value or additional benefit.
Distributed Energy Resources (DER)	A diverse range of small to medium scale energy resources that are connected directly to the distribution system (i.e. front-of-meter). Refer to Consumer Energy Resources (CER/DER).
Distributed Photovoltaics (DPV)	Solar photovoltaic panel installations connected to the distribution network. In many cases, these resources are located behind-the-meter at residential and commercial customer properties.

Distributed Market Mechanisms	A general term reflecting a spectrum of approaches and mechanisms to value, incentivise, procure and coordinate energy, flexibility and/or essential system services from distribution-connected CER/DER. In basic form, this may include tariff-based incentives and/or bilateral contracts. In more advanced forms, it may include Network Services Markets and/or Flexibility Markets that are co-optimised with conventional wholesale market mechanisms.
Distribution System Operator (DSO)	A future-oriented set of capabilities required in a high-CER/DER power system where distribution-connected resources provide a growing proportion of energy, power and related grid services. While there are a range of different visions of DSO evolution, somewhat analogous to the activities of a conventional Market/System Operator (MSO), key functions may include: a) **Real-time distribution system operations:** to support local supply and demand balancing, manage network constraints and provide enhanced visibility to the MSO at the relevant Transmission-Distribution Interfaces (TDI); b) **Distribution Market Mechanisms:** to value, incentivise, procure and coordinate the local provision of energy, capacity, flexibility and/or ancillary services from diverse DER when and where required by the system; and, c) **Integrated distribution system planning:** including scenario analyses of CER/DER and EV adoption rates, to ensure efficient network investments over various time horizons.
Electric Products	The valuable physics-based services that may be provided to the power system by CER/DER in exchange for some form of value or additional benefit. All beneficial grid services are derivatives of the following '3Rs': a) **Real Power:** measured in MW, is the instantaneous rate at which electrical energy is generated, transmitted or consumed; b) **Reactive Power:** measured in MVAR, sustains the electrical field in AC systems while maintain voltage within the limits specified for safe operation (source or sink); and, a) **Reserves:** measured in MW, represent contracted commitments to deliver or reduce real power (MW) or energy (MWh) at a point of time in the future.

Interoperability	The capability of two or more systems, components or applications to share, transfer, and readily use energy, power, information and services securely and effectively with little or no inconvenience to the user. Future-ready approaches to interoperability recognise that is has an intrinsic relationship to the underpinning structure and Roles & Responsibilities of the wider system, both in their current state form and as they will plausibly need to evolve to enable an increasingly decarbonised future system.
Operational Coordination	The systematic operational alignment of utility and non-utility assets to support system security, adequacy, reliability, and economic efficiency in an increasingly variable high-VRE / high-CER/DER power system. (*Refer to Appendix A for a more comprehensive definition*)
Orchestration	The coordination of dispatchable energy resources, including but not limited to CER/DER, in a manner that moderates negative system impacts and may include facilitating the provision of Electric Products to various tiers/layers of the power system under a commercial arrangement. (*Orchestration is closely related to Operational Coordination*)
Power System	An essential system that, in the case of GW-scale grids, exists to provide safe, reliable, and efficient electricity services to millions of Customers. The supply chain of a conventional power system incorporates the Bulk Power System, Transmission Networks and Distribution Networks supported by the related Energy Retail functions. A GW-scale power system is best understood as a 'Super-system of Systems'.[9] This is because a modern grid consists of a complex web of seven distinct, inter-dependent structures as follows: a) **Electricity Infrastructure** (Power Flows); b) **Digital Infrastructure** (Information/Data Exchange, Storage and Processing); c) **Operational Coordination Structure**; d) **Transactional Structure**; e) **Industry / Market Structure**; f) **Governance / Regulatory Structure**; and, g) **Sector Coupling Structures** (Gas, Water, Transport, etc). Many of these cyber-physical-transactional structures are functionally interdependent, which means that changes to one structure will have both intended and unintended impacts on the function of other structures.

[9] Refer to Appendix D – Power Systems as a 'Super-system of Systems'.

Systems Architecture	A formal element of Systems Engineering, which enables objective, collective reasoning about the underpinning Structure of a complex System, together with its components, interfaces, feedback loops and other behaviours.
Systems Engineering	An established engineering discipline applied in numerous sectors focused on the development and operation of ultra-complex systems including aerospace, military, manufacturing, energy and electronics sectors. While many engineering disciplines are oriented toward individual component technologies or sub-systems, Systems Engineering is a transdisciplinary approach that brings a holistic or 'whole-system' approach to the realisation of successful Systems which consistently satisfy the needs of their Customers, users and other stakeholders.
Theory of Change	A structured framework that outlines the causal pathways through which interventions are expected to lead to desired outcomes. In a complex, multi-stakeholder context, this enables more efficient and effective interventions by making the assumptions underlying interventions explicit, identifying the necessary conditions for success, and describing the logical sequence of events that are expected to result in the intended changes. (*Refer to Appendix A for a more comprehensive definition*)
Transmission-Distribution Interface (TDI)	The physical point(s) at which the upstream Bulk Power / Transmission System and a downstream Distribution System interconnect, typically at one or several major substations. In a conventional, highly bifurcated Power System, these were traditionally known as the Supply-side and Demand-side respectively. Power Systems that host growing volumes of VRE and CER/DER will experience significantly greater levels of Volatility which can propagate upstream and downstream in a somewhat 'tidal' manner. In this context, simultaneously ensuring system Adequacy, Security, Reliability and Cost-efficiency will require a much greater level of dynamic interdependence across the Transmission-Distribution Interface (TDI) than in the past.
Variable Renewable Energy (VRE)	A generic term for intermittent forms of generation plant that are powered by renewable resources that are inherently variable such as wind and solar energy. While it is technically correct to also refer to Distributed Photovoltaics (DPV) as VRE, the term is mostly used to describe large, utility-scale applications of solar and wind generation.

Volatility	The propensity of rapid and/or unpredictable change, especially in a manner that is unfavourable and difficult to manage. Power systems served by growing levels of VRE and CER/DER experience significant growth in operational Volatility. This must be actively managed to ensure system security.
Whole-system	A systems-based approach to power system transformation that recognises the Laws of Physics interact with end-to-end system as one integrated whole, blind to historical structural separations.

Table 2: Key definitions employed in this analysis

2 Development Methodology

2.1 Development Overview

This analysis has been supported by the following three elements developed to provide a sufficiently objective basis for the review of CER/DER-related initiatives:

- National Database of Studies, Trials & Demonstrations (Section 2.2);
- Whole-system Analytical Framework / Taxonomy (Section 2.3);
- Overview of Themes, Domains & Research Topics (Section 2.4); and,
- Research Focus & Comparative Maturity Ratings (Section 2.5).

While recognising that such a wide-ranging analysis has several inherent limitations (Section 2.6), the key findings are set out as follows:

- Graphical Overview of CER/DER Research from a Whole-system Perspective (Section 3);
- Graphical Comparison of CER/DER Research by Domain & Research Topic (Section 4);
- Observations on Australia's Program of CER/DER Studies, Trials and Demonstrations (Section 5); and,
- Opportunities for Enhanced Outcomes from Australia's CER/DER Research (Section 6).

The three elements developed to enable a sufficiently objective basis for the review of CER/DER-related initiatives are now described in more detail followed by the consideration of limitations inherent in this type of analysis.

2.2 National Database of Studies, Trials & Demonstrations

A wide-ranging scan of Australia's CER/DER-related studies, trials and demonstration projects, sponsored and funded by multiple entities, was undertaken utilising the extensive materials available in the public domain.

The environmental scan applied a primary focus on initiatives completed in the last 5 – 7 years to develop an unprecedented view of the scale and diversity of CER/DER-related research activities recently undertaken in Australia. While involving many thousands of pages of project reports and supporting materials, key information on each of the individual initiatives was distilled from the published materials into the database. This included project context, scope and key research topics. Where available, the project budget and specific start and finish dates were also captured.

Given the dynamic nature of the topic, the database will continue to expand as new initiatives are identified and/or commenced. However, the current version upon which this report is based, includes 182 research initiatives across 46 lead project sponsors. While project expenditure is not universally available, the cost estimates for executing this portfolio of initiatives ranges between AUD $500 – 750M cash and AUD $250 – 500M of in-kind contributions.

Although Australia's largest such database, it is not exhaustive. A significant amount of relevant research has not been included where publicly available information is less readily available. Nevertheless, it does provide a representative view of the breadth and proportionality of CER/DER-related research undertaken. The table below provides an overview of the key project sponsors, and the number of CER/DER-related initiatives identified and analysed per sponsor.

Organisations	# Initiatives
Market & Regulatory Bodies	**26**
Australian Energy Market Commission (AEMC)	7
Australian Energy Market Operator (AEMO)	12
Australian Energy Regulator (AER)	1
Energy Security Board (ESB)	6
Universities, Research Agencies & Consortia	**81**
Australian National University (ANU)	15
Commonwealth Scientific Industrial Research Organisation (CSIRO)	10
Monash University	1
RACE for 2030	18
University of Melbourne	10
University of New South Wales (UNSW)	4
University of Tasmania	1
University of Technology Sydney (UTS)	2
Centre for New Energy Technologies (C4NET)	20

Network Service Providers	47
ActewAGL	1
Ausgrid	2
CitiPower & Powercor	1
Energy Queensland	9
Essential Energy	3
Evoenergy	1
Horizon Power	1
Jemena	1
SA Power Networks (SAPN)	18
TasNetworks	1
Western Power	9
Retailers & Aggregators	**7**
AGL	1
Enel X	1
EnergyAustralia	1
Flow Power	1
GreenSync	1
Pooled Energy	1
Simply Energy	1
Others	**21**
Climateworks	1
Department of Climate Change, Environment, Energy & Water (DCCEEW)	1
Distributed Energy Integration Program (DEIP)	2
DNV GL	1
Dynamic Limits	1
Energy Consumers Australia (Grants)	6
GridQube	1

Mondo	1
NOJA Power	1
Renew	1
Solar Analytics	2
Wattwatchers	1
Yurika	1
Zepben	1

Table 3 - The CER/DER-relevant studies by organisation type considered in this analysis

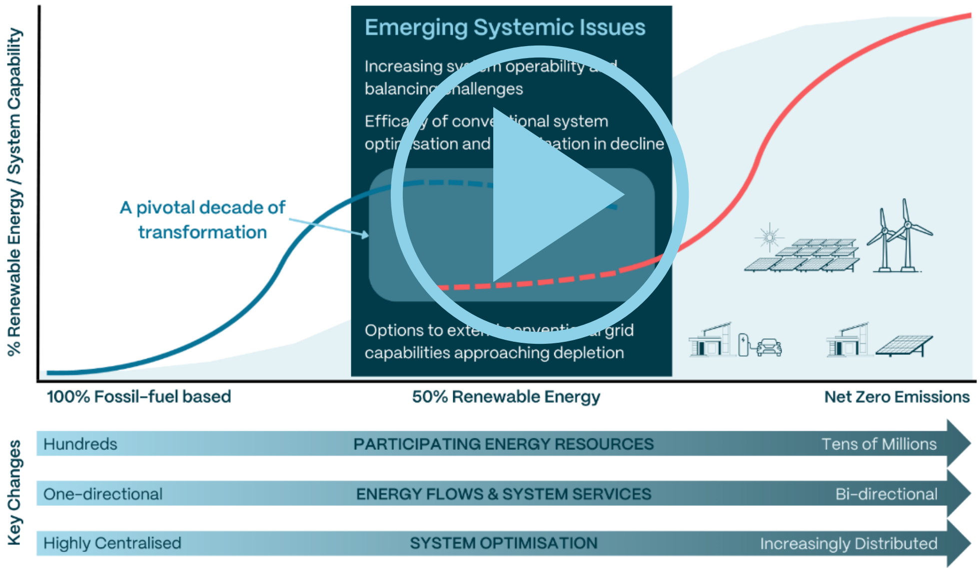
2.3 Whole-system Analytical Framework / Taxonomy

As noted earlier, the strategic objective of this report is to map critical gaps that must be addressed to unleash the full potential of millions of CER/DER as an integral part of Australia's 21st century power system. By definition, this is an undertaking that cannot be limited to any one individual segment of the power system as we have understood them for much of the last century. It is an inherently 'whole-system' challenge.

Whole-system approaches to grid transformation are now being actively pursued in the United Kingdom and the European Union. This is occurring in the context of accelerating decarbonisation efforts, more volatile system operations, an expanding diversity of energy resources and an awareness that the Laws of Physics interact with our grids as singular integrated systems, blind to traditional role boundaries.

Unfortunately, no relevant analytical framework existed for interrogating the whole-system integration of CER/DER across all vertical layers of Australia's GW-scale grids. Therefore, the taxonomy was subsequently developed, informed by a wide-ranging review of the Australian and global literature[10], via multiple development loops being cross-checked against the literature and stakeholder input. Key Systems Engineering and Systems Architecture techniques were applied to create a robust analytic framework of Australia's end-to-end GW-scale power systems and representing all major topics relevant to holistic systems-integration of CER/DER.

[10] Key documents that provided useful starting points included the ARENA State of Distributed Energy Resources Technology Integration Report, Farrier Swier (2021) and the IRENA Innovation Landscape for Smart Electrification (2023).



Animation 2 – A holistic approach to identifying the targeted structural interventions required to unleash the full value of VRE and CER/DER at massive scale.

The final taxonomy of the end-to-end power system employs a three-level hierarchy of classification. At the highest level, Australia's end-to-end grid transformation landscape is reflected under the 6 x Themes described in Table 4 below.

Strategic Question	Theme #	Theme Name	Theme Description
WHERE? *Where are Australia's GW-scale power systems heading?*	T1	Customer & Societal Objectives for Future System	Modern power systems are 'socio-technical' systems. Transformation initiatives must therefore be informed by a deep awareness of both current and emerging priorities of policy makers, customers and society. Focusing on the emerging context, T1 includes consideration of all plausible future scenarios, mapping of the emerging trends driving change with a focus on end-user needs and policy priorities, and the identification of key systemic issues that must be addressed to meet them. Modern power systems are 'socio-technical' systems.
WHAT? *What technological, market, regulatory and operational enablers are required to enable the most plausible futures?*	T2	End-use Solution Innovations	Technologies that provide beneficial end-user services, manage energy costs, enable decarbonisation, and enhance system integration and device interoperability. T2 includes consideration of each technology within the commercial / business model ecosystems critical to enabling at massive scale their secure integration with the wider power system.
	T3	Market, Pricing & Regulatory Innovations	New market structures, pricing models, digital platform innovations, evolving roles and responsibilities and transformative changes to the regulatory architecture. T3 includes incentivisation of the new capabilities required to leverage the diverse range of CER/DER services and effective value propositions to encourage and retain customer participation.
	T4	Whole-system Planning, Capability & Operations	Innovative approaches to forecasting, planning, upgrading and operating the conventional supply-side of the power system in a manner that securely and efficiently leverages the millions of diverse CER/DER emerging on the demand-side. T4 includes consideration of the structural settings required to ensure that the Market/System Operator (MSO) can work effectively with multiple Distribution System Operators (DSOs) across the Transmission-Distribution Interface (TDI) to ensure whole-system stability and efficiency.
	T5	LV-system Planning, Capability & Operations	Innovative approaches to forecasting, planning, upgrading and operating distribution systems in a manner that securely and efficiently leverages the CER/DER becoming ubiquitous across Australia's LV networks. T5 includes consideration of the structural settings required to ensure that individual DSOs can work effectively with the MSO across the TDI to ensure both whole-system and distribution-level stability and efficiency.

HOW? *How can holistic transformation be achieved at scale and pace?*	T6	Holistic Transformation Design	Activities designed to support and accelerate the holistic transformation of energy systems, markets and regulation to achieve enhanced societal and customer outcomes, in reduced timeframes and with greater cost and resource efficiency. T6 focuses on design of holistic transformation pathways that engender trust, proactively share data, prioritises sectoral and workforce skills development and enhances the social license for beneficial transformation.

Table 4 – Description of the 6 x Themes representing the end-to-end grid transformation landscape relevant to systemic CER/DER integration

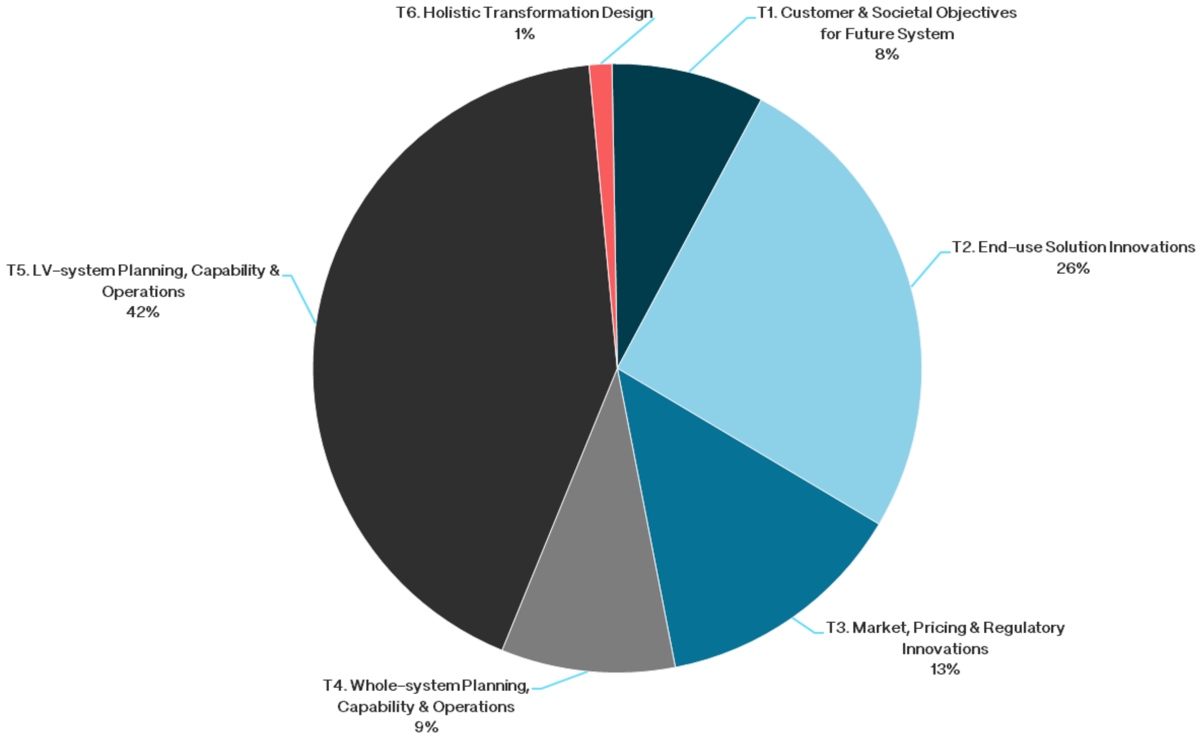


Figure 7 - Comparative proportions of research focus identified across 6 x Themes

The above 6 x Themes (T) provide the first of a three-level analytical hierarchy for analysing Australia's end-to-end grid transformation landscape. The second and third levels of the analytical hierarchy are 15 x Domains (D) and 61 x Research Topics (RT) respectively. This structure enabled each of the 182 x CER/DER-related initiatives to be analysed across almost 11,000 evaluation points.

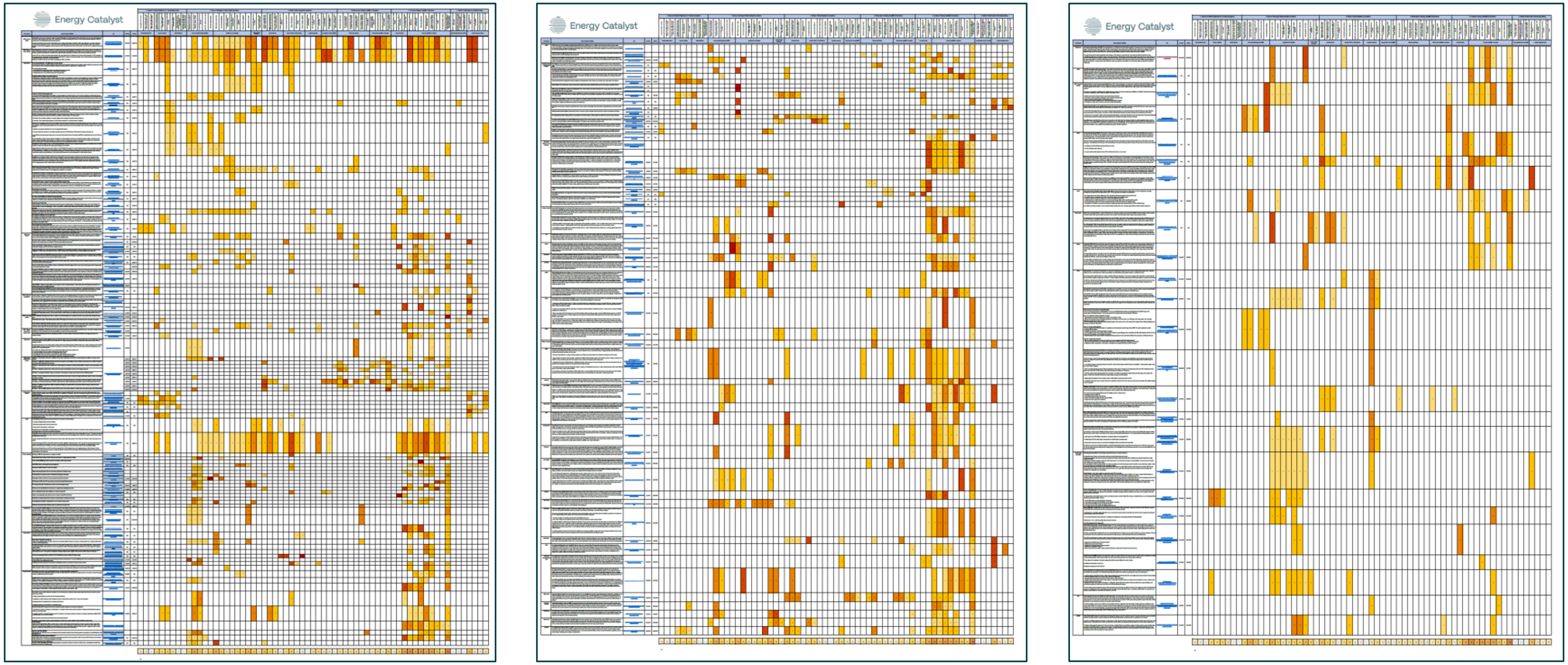


Figure 8 - The 182 x CER/DER-related initiatives were mapped (vertical axis) and evaluated against each of the 61 x Research Topics (horizontal axis) based on the publicly available information. The outcome shown here is the almost 11,000 evaluation points presented on three large A0 wall charts.

2.4 Overview of Themes, Domains & Research Topics

Following is an overview of each of the 6 x Themes (T) together with their respective 15 x Domains (D) and 61 x Research Topics (RT) that reflect Australia's end-to-end grid transformation landscape relevant to the systemic integration of CER/DER.

2.4.1 Theme 1: Customer & Societal Objectives for Future System

Modern power systems are 'socio-technical' systems. Transformation initiatives must therefore be informed by a deep awareness of both current and emerging priorities of policy makers, customers and society. [11] Focusing on the emerging context, T1 includes consideration of all plausible future scenarios, mapping of the emerging trends driving change with a focus on end-user needs and policy priorities, and the identification of key systemic issues that must be addressed to meet them.

Domain	Research Topic
D1.1 System Transformation Directions	RT1.1.1 Future power system scenarios and plausible alterative views
	RT1.1.2 Mapping of emerging trends / critical drivers of energy system change
	RT1.1.3 Mapping of cross-cutting issues that require structural interventions
D1.2 Policy/Customer Objectives	RT.1.2.1 Identifying the diversity of customer objectives for the future power system
	RT1.2.2 Development of evidence-based customer segmentation models
	RT1.2.3 Analysis of customer values and priorities per segment
D1.3 Societal Objectives	RT1.3.1 Identifying policy-maker objectives for the future power system
	RT1.3.2 Integrated approaches to the prioritisation of customer and policy maker objectives
	RT1.3.3 Approaches to converging on agreed future system objectives through structured trade-off processes

[11] Refer Appendix B – Customer & Societal Expectations of Future Power Systems for additional information.

2.4.2 Theme 2: End-use Solution Innovations

Technologies that provide beneficial end-user services, manage energy costs, enable decarbonisation, and enhance system integration and device interoperability. T2 includes consideration of each technology within the commercial / business model ecosystems critical to enabling at massive scale their secure integration with the wider power system.

Domain	Research Topic
D2.1 End-use Device/Technology Capabilities	RT2.1.1 Ability to withstand (and not disconnect during) power system disturbances
	RT2.1.2 Provide power system support (incl. voltage and frequency support)
	RT2.1.3 Coordinated device and network asset protection
	RT2.1.4 DER/D-Flex device-level cyber security
	RT2.1.5 Device standards compliance
D2.2 Specific End-use Technologies	RT2.2.1 BESS energy and power services
	RT2.2.2 DPV and inverter applications
	RT2.2.3 Process heating, cooling and water pumping applications
	RT2.2.4 Building heating, cooling and thermal storage applications
	RT2.2.5 Vehicle to Home/Building (V2H/B) applications
	RT2.2.6 Vehicle to Grid (V2G) applications
	RT2.2.7 DER Aggregation / VPP models
D2.3 Business Model Innovations	RT2.3.1 Technology-specific business model innovations
	RT2.3.2 Holistic customer outcome-based business model innovations

2.4.3 Theme 3: Market, Pricing & Regulatory Innovations

New market structures, pricing models, digital platform innovations, evolving roles and responsibilities and transformative changes to the regulatory architecture. T3 includes incentivisation of the new capabilities required to leverage the diverse range of CER/DER services and effective value propositions to encourage and retain customer participation.

Domain	Research Topic
D3.1 CER/DER Market Structures	RT3.1.1 Wholesale energy and ESS market integration of DER/D-Flex services
	RT3.1.2 Distribution-level valuation/markets for DER/D-Flex services and/or energy
	RT3.1.3 Integrated value-stacking of DER/D-Flex services across all vertical layers
	RT3.1.4 Distributed Ledger Technology (DLT) applications
D3.2 Advanced Tariffs & Trading	RT3.2.1 Advanced metering infrastructure
	RT3.2.2 Advanced tariff applications
	RT3.2.3 Tariffs to platform-based pricing transition
	RT3.2.4 Peer-to-peer trading applications
D3.3 Regulatory Innovation	RT3.3.1 Review of models for accelerating holistic regulatory transformation
	RT3.3.2 Review of DER/D-Flex regulatory innovation
	RT3.3.3 Valuation methodologies DER/D-Flex system services
D3.4 Emerging Roles & Responsibilities	RT3.4.1 Mapping of evolving power system roles and responsibilities
	RT3.4.2 Distribution System Operator (DSO) functional definitions
	RT3.4.3 Transmission – Distribution Interface (TDI) functional definitions

2.4.4 Theme 4: Whole-system Planning, Capability & Operations

Innovative approaches to forecasting, planning, upgrading and operating the conventional supply-side of the power system in a manner that securely and efficiently leverages the millions of diverse CER/DER emerging on the demand-side. T4 includes consideration of the structural settings required to ensure that the Market/System Operator (MSO) can work effectively with multiple Distribution System Operators (DSOs) across the Transmission-Distribution Interface (TDI) to ensure whole-system stability and efficiency.

Domain	Research Topic
D4.1 Whole-system Planning & Architecture	RT4.1.1 Whole-system planning models
	RT4.1.2 Whole-system cyber-physical and transactional-coordination architecture
	RT4.1.3 Economic analysis of whole-system coordination costs and benefits
	RT4.1.4 Sector coupling options analysis (i.e. transport, water, gas, etc)
	RT4.1.5 Grid modularisation to mitigate single-point-of-failure risks with increasing electrification
	RT4.1.6 Protection options in high-DER / low fault current systems
D4.2 Whole-system Capabilities & Operations & Data Exchange	RT4.2.1 Whole-system operational coordination and co-optimisation architecture
	RT4.2.2 Whole-system data exchange mechanisms
	RT4.2.3 System-level cyber security DER/D-Flex service integration
	RT4.2.4 Bulk power / transmission reliability and security processes for DER/D-Flex

2.4.5 Theme 5: LV-system Planning, Capability & Operations

Innovative approaches to forecasting, planning, upgrading and operating distribution systems in a manner that securely and efficiently leverages the CER/DER becoming ubiquitous across Australia's LV networks. T5 includes consideration of the structural settings required to ensure that individual DSOs can work effectively with the MSO across the TDI to ensure both whole-system and distribution-level stability and efficiency.

Domain	Research Topic
D5.1 LV-system Planning	RT5.1.1 Advanced/Integrated distribution system planning
	RT5.1.2 DER/EV adoption, usage, charging and network impacts
	RT5.1.3 Network DPV hosting capacity analysis and enhancement options
D5.2 LV-system Capabilities & Operations	RT5.2.1 DER/D-Flex integration with AEMO and/or DNSP systems
	RT5.2.2 DER/D-Flex operational forecasting and/or scheduling models
	RT5.2.3 DER/D-Flex visibility models
	RT5.2.4 DER/D-Flex provision of services to distribution network
	RT5.2.5 DER/D-Flex interoperability and capabilities for automated activation
	RT5.2.6 DPV dynamic export management models (DOE's)
	RT5.2.7 DPV emergency curtailment models
	RT5.2.8 Distribution system reliability, power quality and voltage management technologies and processes

2.4.6 Theme 6: Holistic Transformation Design

Activities designed to support and accelerate the holistic transformation of energy systems, markets and regulation to achieve enhanced societal and customer outcomes, in reduced timeframes and with greater cost and resource efficiency. T6 focuses on design of holistic transformation pathways that engender trust, proactively share data, prioritises sectoral and workforce skills development and enhances the social license for beneficial transformation.

Domain	Research Topic
D6.1 System Transformation Enablers	RT6.1.1 Integrated theories of large-scale systemic transformation of the power system
	RT6.1.2 Investigating 'social compact' evolutions required to underpin more participatory, low carbon energy systems
	RT6.1.3 Approaches for validating the stability and scalability of trial-volume solutions

2.5 Research Focus & Comparative Maturity Ratings

Given the diversity and complexity of the topics covered, and the tens of thousands of pages of relevant project information, the analytical method applied was necessarily qualitative and comparative, and the results illustrative of overall research trends.

While recognising the above, the rating scheme outlined in Table 4 (below) was developed to provide a basic level of objectivity for comparing the diversity of CER/DER-related initiatives spanning studies, trials and demonstrations (Ratings 1 – 4). Key progress steps from research to full deployment, including the rigorous validation of mass-scalability beyond what is possible with demonstration volumes, and the successful navigation of governance, regulatory and funding mechanisms, are also included (Ratings 5 – 7).

All 182 initiatives were rated across each of the 61 x Research Topics, totalling almost 11,000 points of comparative evaluation. No restriction was placed on the total sum of scores given per initiative, or number of categories scored, as the scale and scope of each CER/DER-related initiative varied significantly. Overall outcomes were holistically assessed for broad process consistency and a selection of the most significant initiatives were cross-checked with the project proponents where possible. The primary aim was to identify where the overall *focus* of CER/DER research has been more or less concentrated across all Research Topics.

Score	Study Index	Trial / Demonstration Index	Full Deployment Index
7	N/A	N/A	The final integrated solutions are formally approved and funded, and all supporting policy, regulatory, legal and related interventions are agreed and in train.
6	N/A	N/A	The most credible integrated solutions are shortlisted, evaluated, refined, finalised and approved by senior officials and all relevant stakeholders.
5	Integrated solutions verified and validated at a whole-system level as fully scalable and capable of supporting tens of millions of participating CER/DER in a secure, resilient and cost-effective manner. Leveraging the portfolio of relevant Level 4 studies and demonstrations, this will involve a combination of detailed model-based emulation and scalability analysis (particularly of computational complexity, latency stacking and communication bottleneck/congestion analyses) supported by an open, multi-stakeholder process of review and validation.		
4	Content development process recognised as providing a holistic treatment of the topic from the perspective of several elements of the system and with a focus on wider transferability.	Operationally credible and potentially scalable solution or intervention demonstrated in a localised context, with a specific community and with a focus on wider transferability.	N/A
3	Content development process accepted as providing a substantive approach to the topic, from the perspective of a part of the system.	Potentially viable solution / intervention designed and enhanced through incorporation of stakeholder review and feedback.	N/A
2	Topic researched and documented based on desktop analysis.	Topic researched and documented based on desktop analysis.	N/A
1	Topic broadly recognised as a relevant adjacency but not the key focus on research.	Topic broadly recognised as a relevant adjacency but not the key focus on research.	N/A

Table 5 – Rating scheme for CER/DER studies, trials and demonstrations (Ratings 1 – 4) and their transition to full deployment (Ratings 5 – 7)

2.6 Inherent Limitations

The following points highlight limitations that are inherent to such a wide-ranging analysis. They should be noted in the interpretation of this report.

1. The primary aim of this analysis was to identify where the *focus* of Australia's CER/DER research has been concentrated during the most recent 5 – 7 years.

2. The analysis was undertaken in a manner that also provides a secondary benefit of indicating the *relative maturity* of each Research Topic.

3. When considered together, both focus and relative maturity are referred to as *Research Focus*. Where maturity is distinguished in the analysis, it is referred to under *Comparative Maturity Index*, which reflects the average of the three highest ratings for that Research Topic.

4. Individual ratings are based solely on what the available public documents report. The analysis provides no comment on, or validation of, the inherent value, completeness, functional veracity and/or transferability of any individual initiative or combination thereof.

5. Given the diversity and complexity of the topics covered, and the tens of thousands of pages of relevant project information, stakeholders may differ on precise ratings assigned to any one of almost 11,000 evaluation points.

6. The analytical method was necessarily qualitative and comparative, and the results should be considered illustrative of overall research trends, not providing commentary on any individual initiative.

7. The primary value of the analysis is that for the first time, it enables stakeholders to 'zoom out' and see the broad patterns that emerge from Australia's significant portfolio of CER/DER-related research initiatives.

Related to the above, the development of the underpinning database and analytical framework provides Australia with a standing resource that can be collaboratively refined and expanded moving forward.

In summary, the findings of this report should be considered 'Release 1.0' of what could potentially become a multi-release process through which both completeness and accuracy continue to evolve.

3 Graphical Overview of CER/DER Research from a Whole-system Perspective

3.1 Summary of Content

The following charts provide a range of perspectives on the findings of the analysis when considered from a whole-system or end-to-end view of the electricity supply chain and transformation landscape.

- High-level Overview of 182 x CER/DER Initiatives (Section 3.2);
- Comparison of 6 x Themes (Section 3.3);
- Comparison of 15 x Domains (Section 3.4); and,
- Comparison of 61 x Research Topics (Section 3.5).

As noted earlier, the primary purpose of this analysis is to provide a set of indicative and comparative views of Australia's CER/DER research landscape.

3.2 High-level Overview of 182 x CER/DER Initiatives

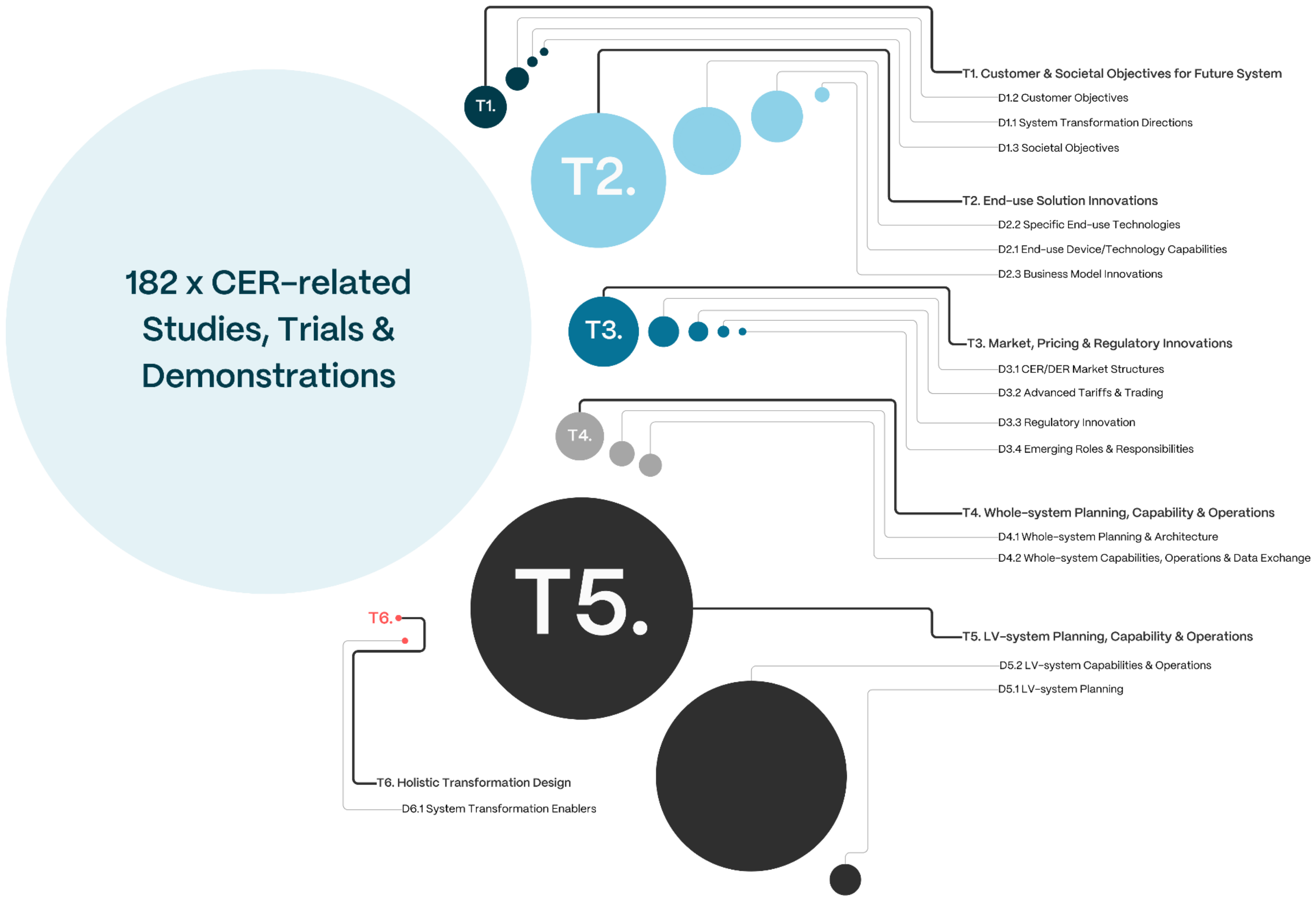


Figure 9 - Comparative Proportions of Research Focus: 6 x Themes and 15 x Domains

3.3 Comparison of 6 x Themes

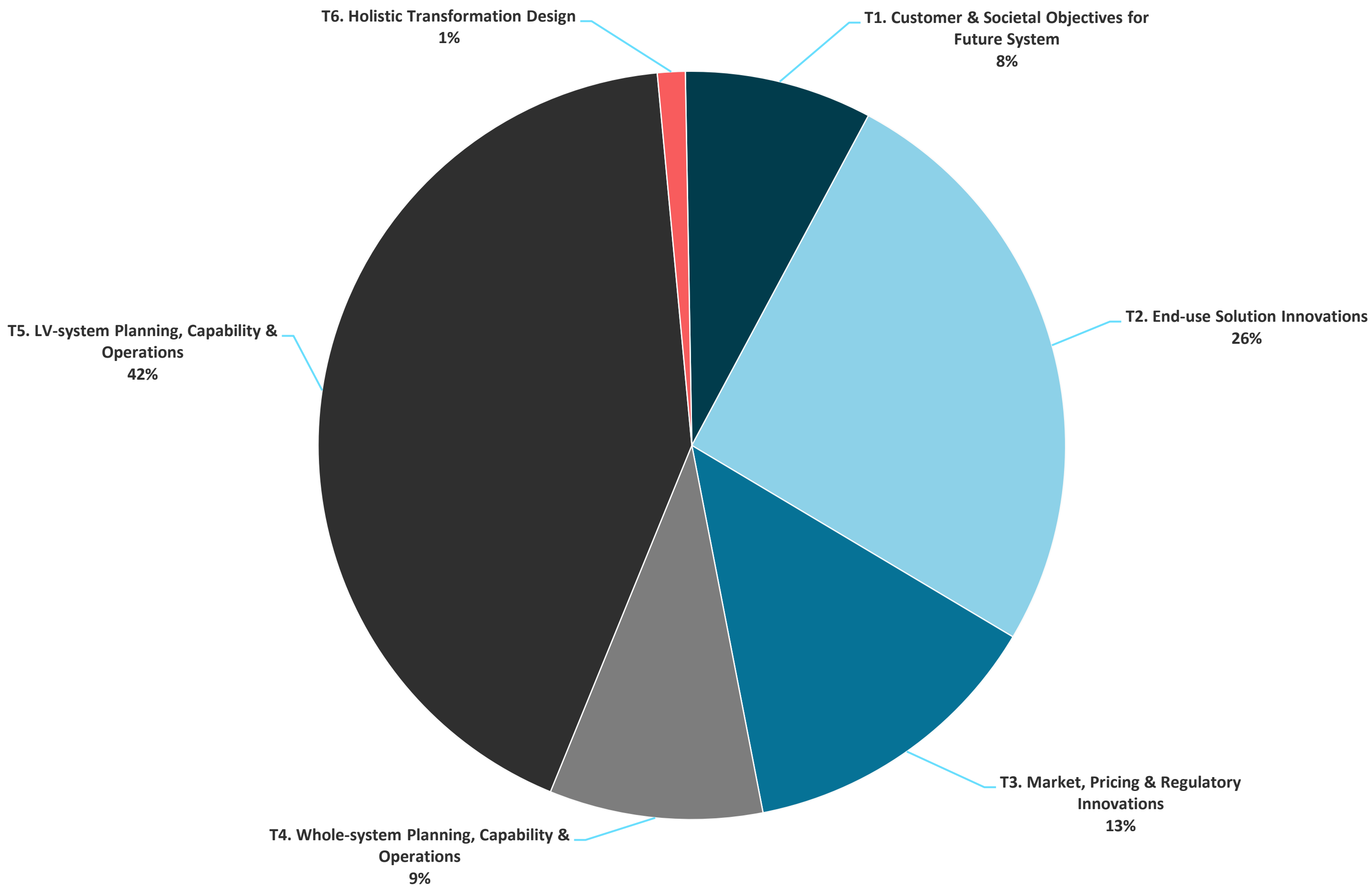


Figure 10 - Comparative % Proportions of Research Focus across 6 x Themes (Overall)

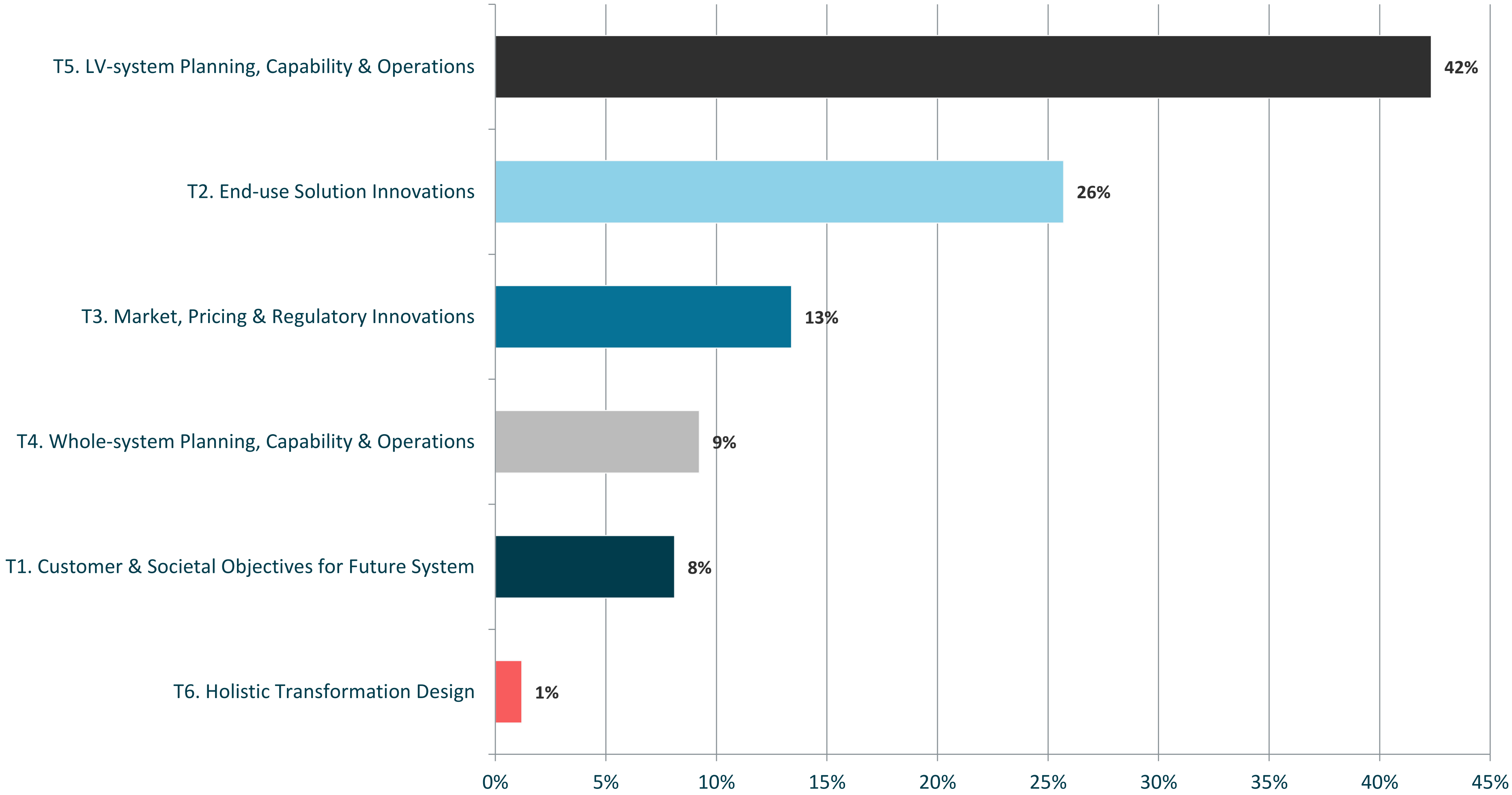


Figure 11 - Comparative % Proportions of Research Focus across 6 x Themes (Highest to Lowest)

3.4 Comparison of 15 x Research Domains

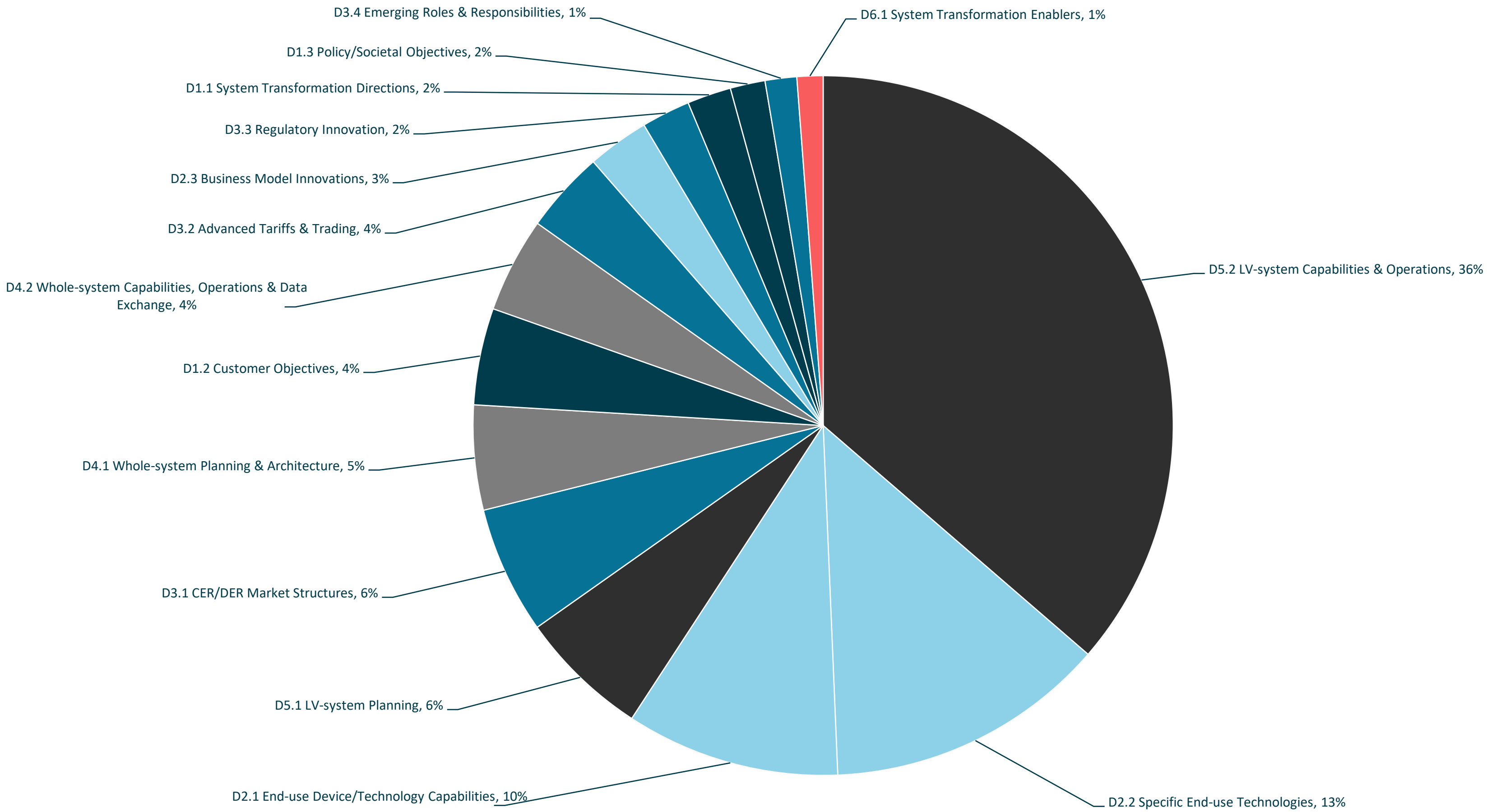


Figure 12 - Comparative % Proportions of Research Focus across 15 x Research Domains (Overall)

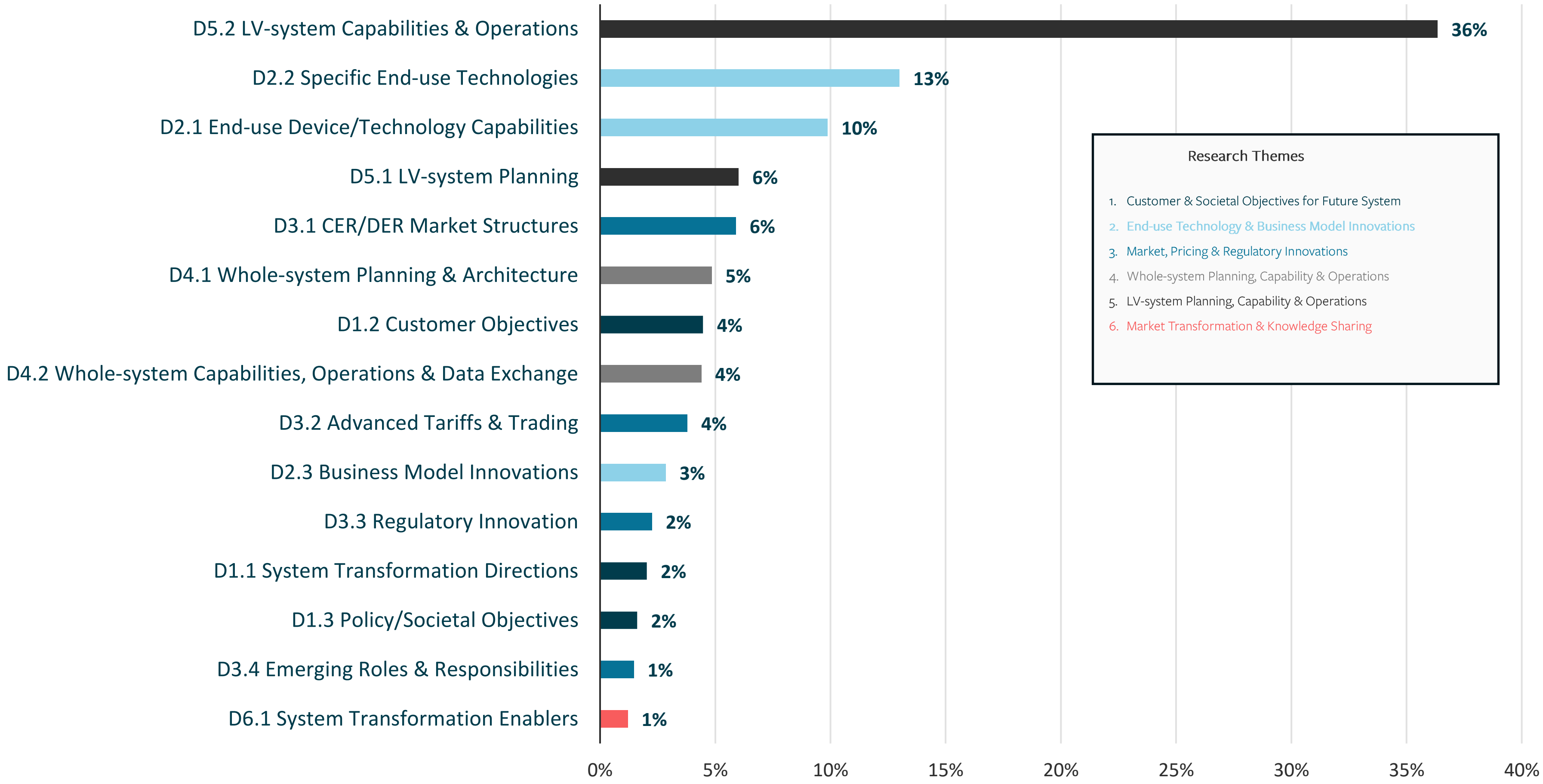


Figure 13 - Comparative Proportions of Research Focus across 15 x Research Domains (Highest to Lowest)

3.5 Comparison of 61 x Research Topics

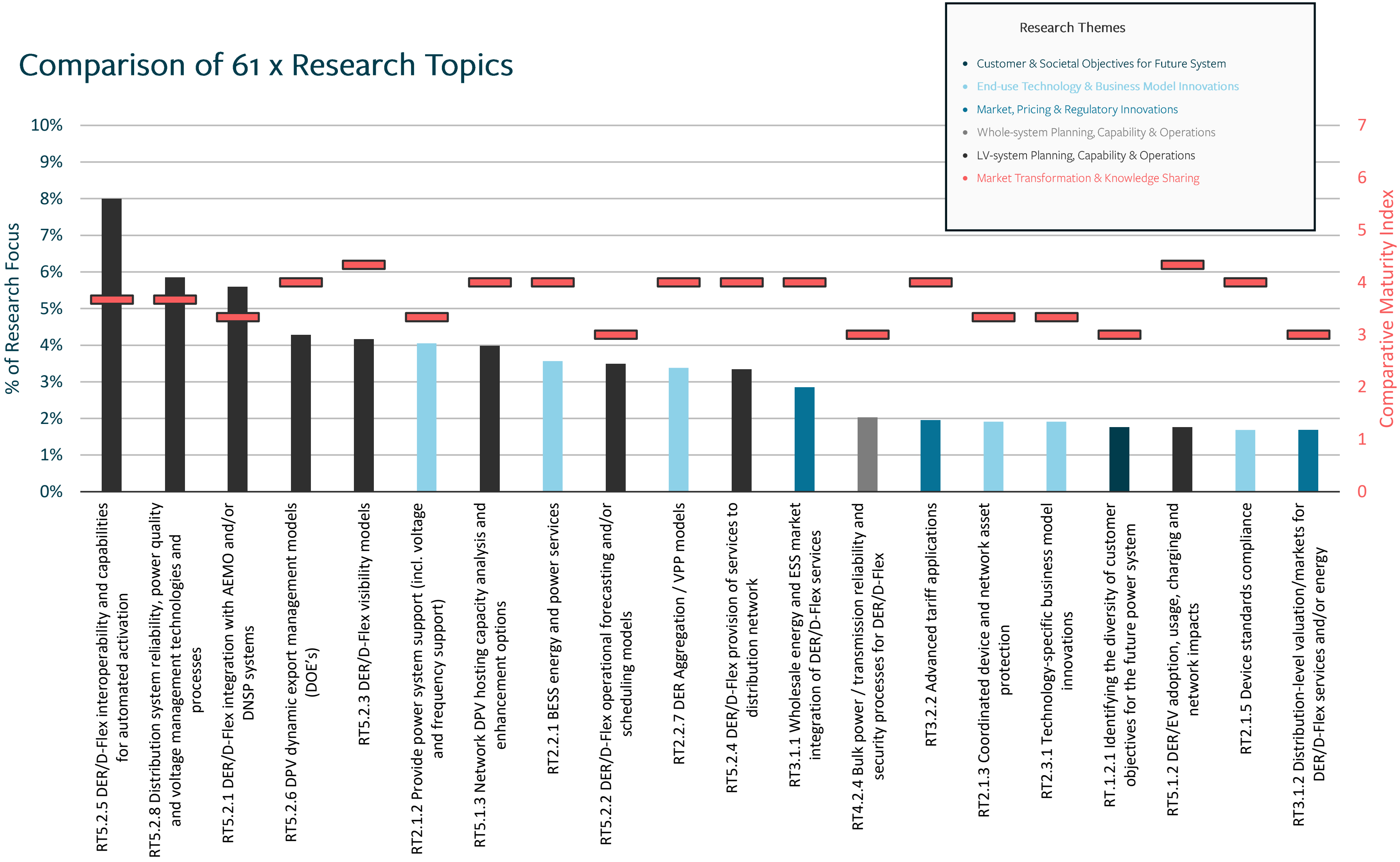


Figure 14 - Comparison of 61 x Research Topics (Top 20)

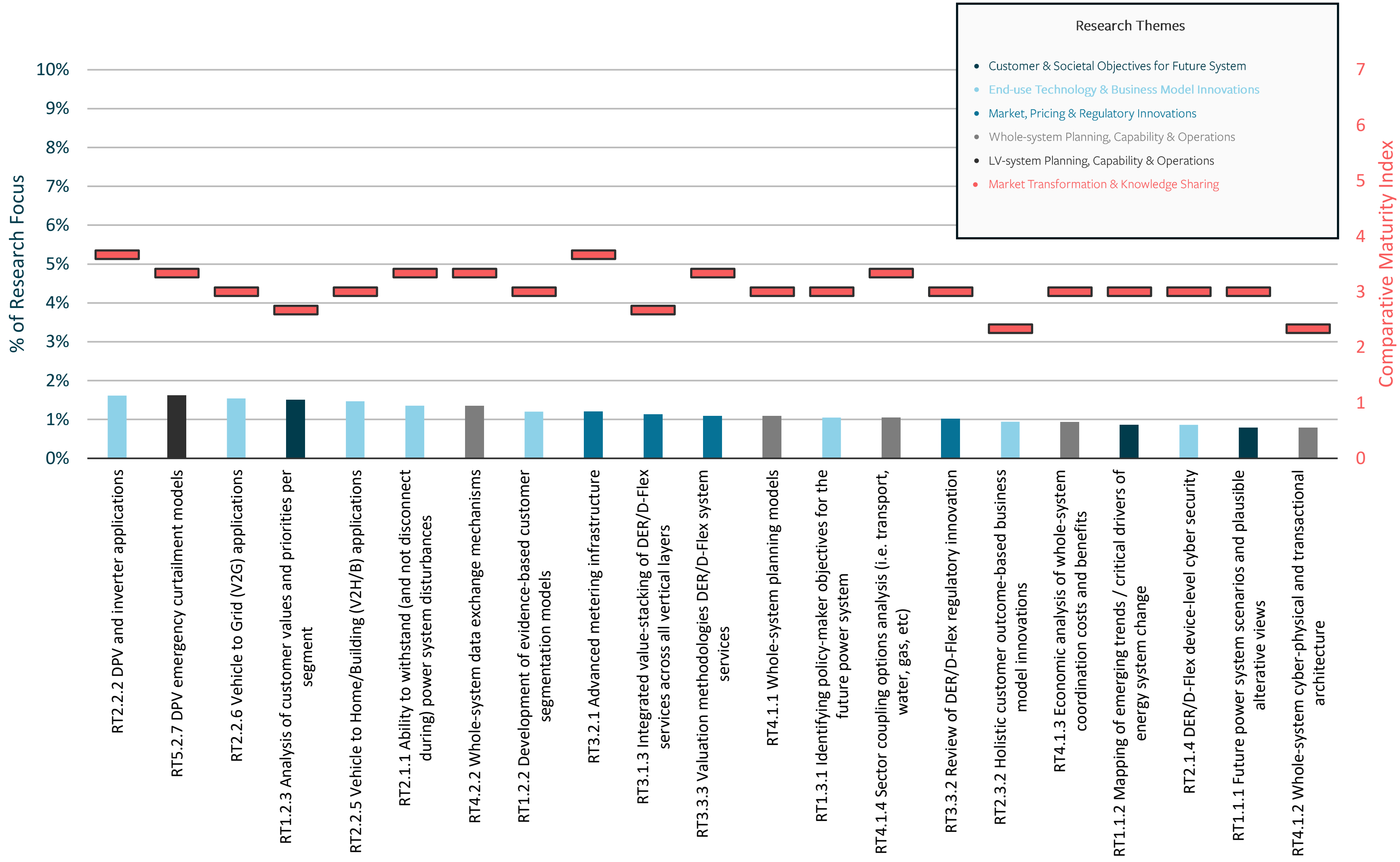


Figure 15 - Comparison of 61 x Research Topics (Middle 21)

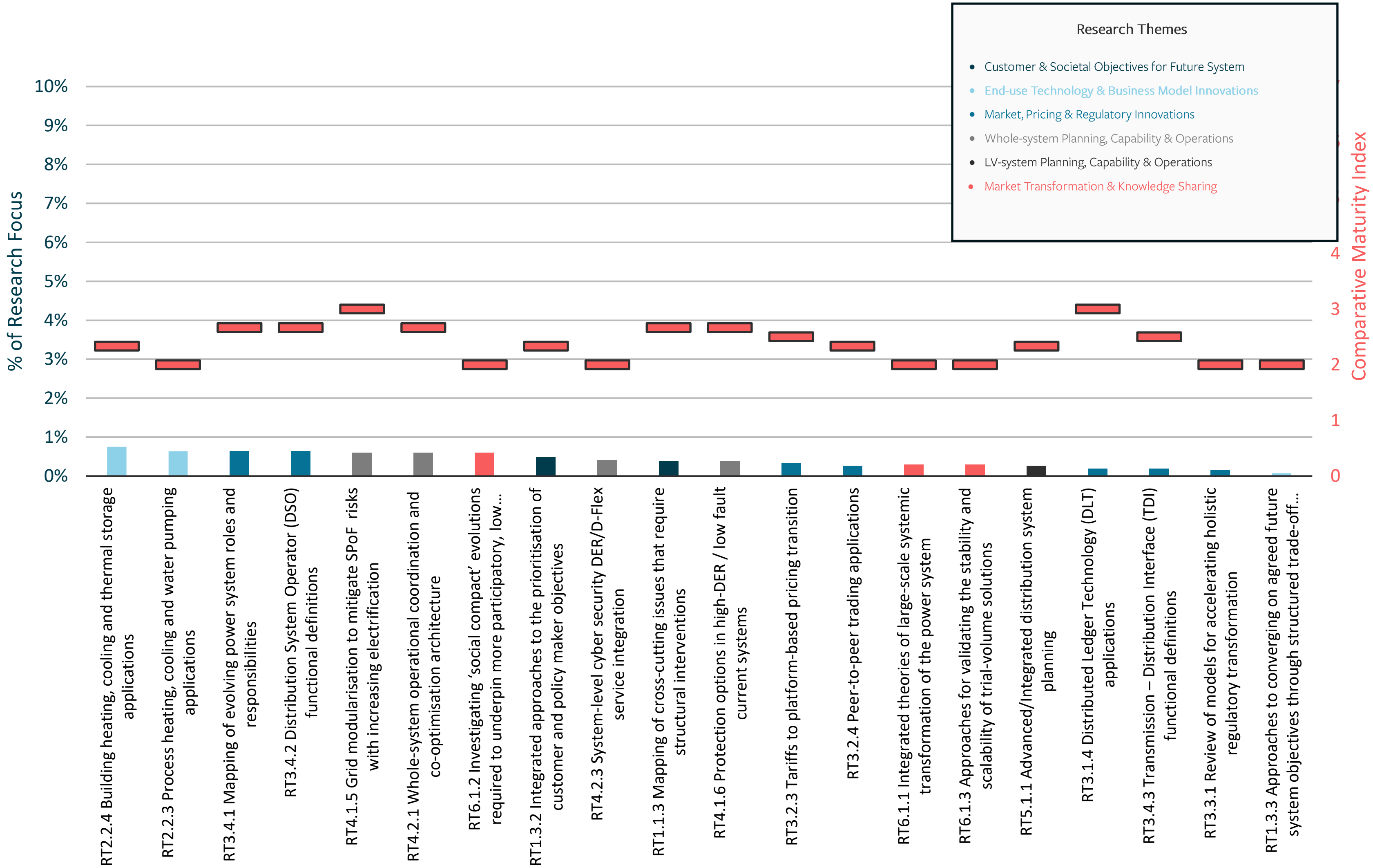


Figure 16 - Comparison of 61 x Research Topics (Bottom 20)

4 Graphical Comparison of CER/DER Research by Domain & Research Topic

4.1 Summary of Content

The following charts interrogate the 15 x Domains and the 61 x Research Topics that are clustered under the following structure of 6 x Themes.

- Theme 1: Customer & Societal Objectives for Future System (Section 4.2);
- Theme 2: End-use Solution Innovations (Section 4.3);
- Theme 3: Market, Pricing & Regulatory Innovations (Section 4.4);
- Theme 4: Whole-system Planning, Capability & Operations (Section 4.5);
- Theme 5: LV-system Planning, Capability & Operations (Section 4.6); and,
- Theme 6: Holistic Transformation Design (Section 4.7).

Please note that the previous chapter considered the proportionality of focus *between* the 6 x Themes. This chapter now considers the proportionality of focus *within* each Theme by Domain and Research Topic.

4.2 Theme 1: Customer & Societal Objectives for Future System

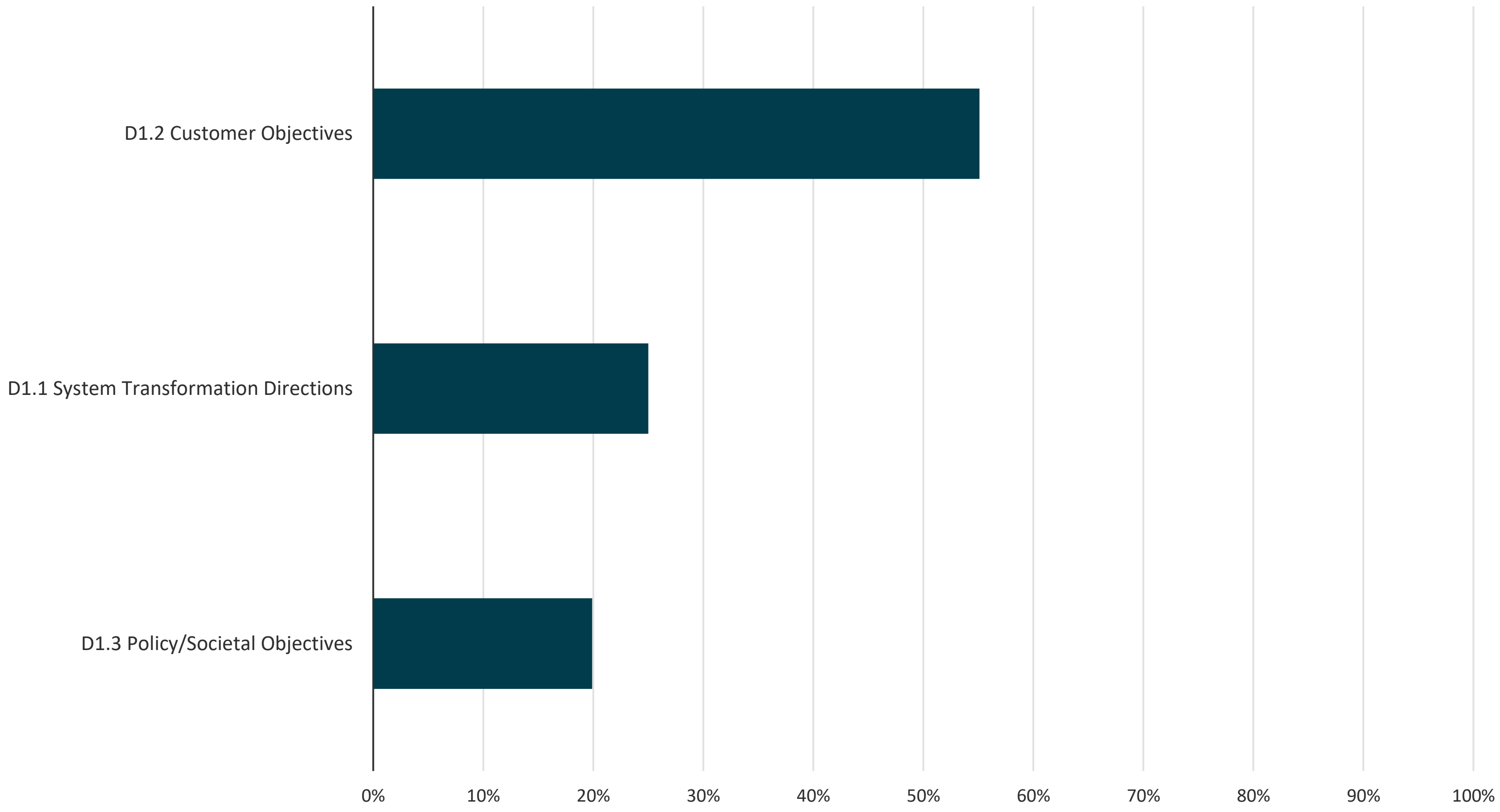


Figure 17 - Theme T1: Comparative Proportions of Research Focus x Domains (Highest to Lowest)

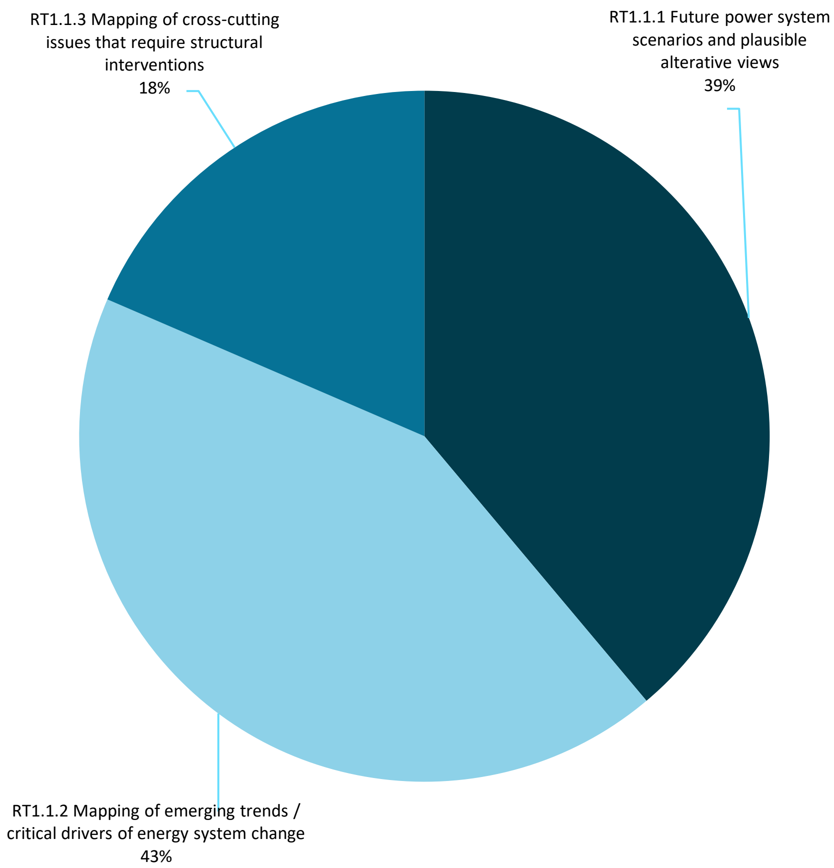


Figure 18 - Domain D1.1: System Transformation Directions (Research Topics as % of Domain Focus)

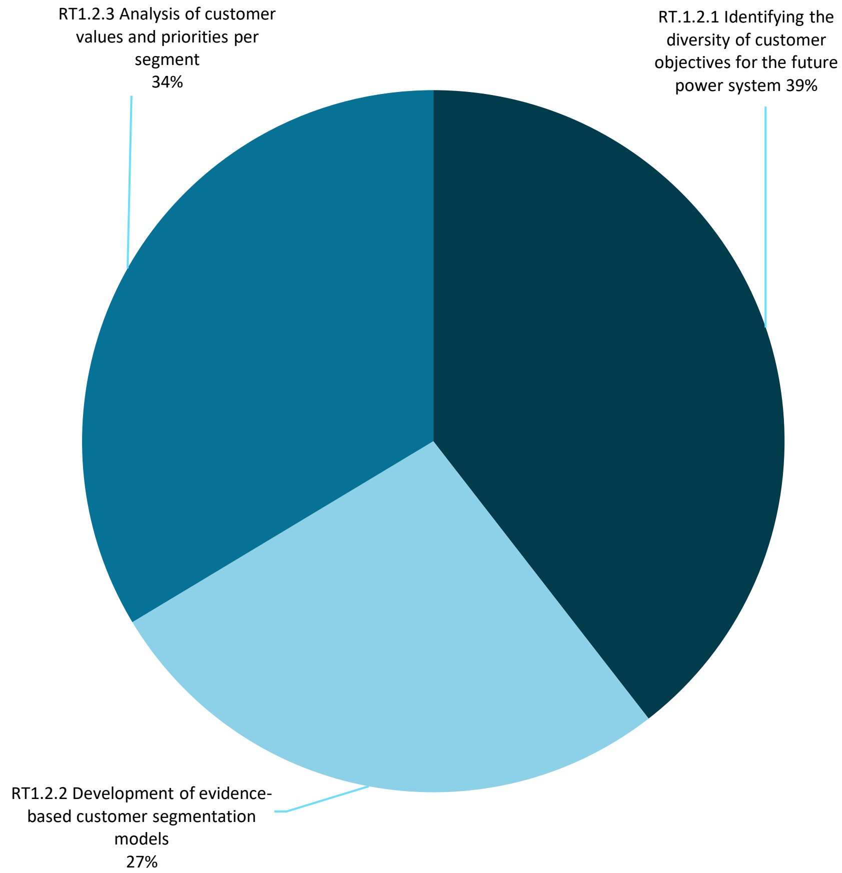


Figure 19 - Domain D1.2: Customer Objectives (Research Topics as % of Domain Focus)

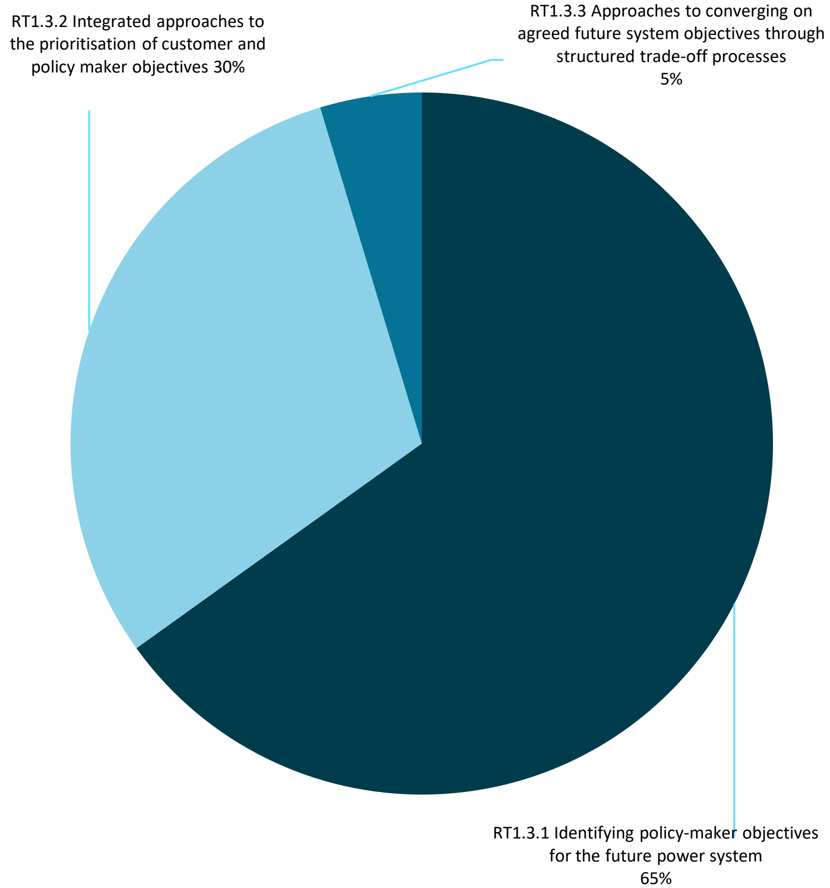


Figure 20 - Domain D1.3: Societal Objectives (Research Topics as % of Domain Focus)

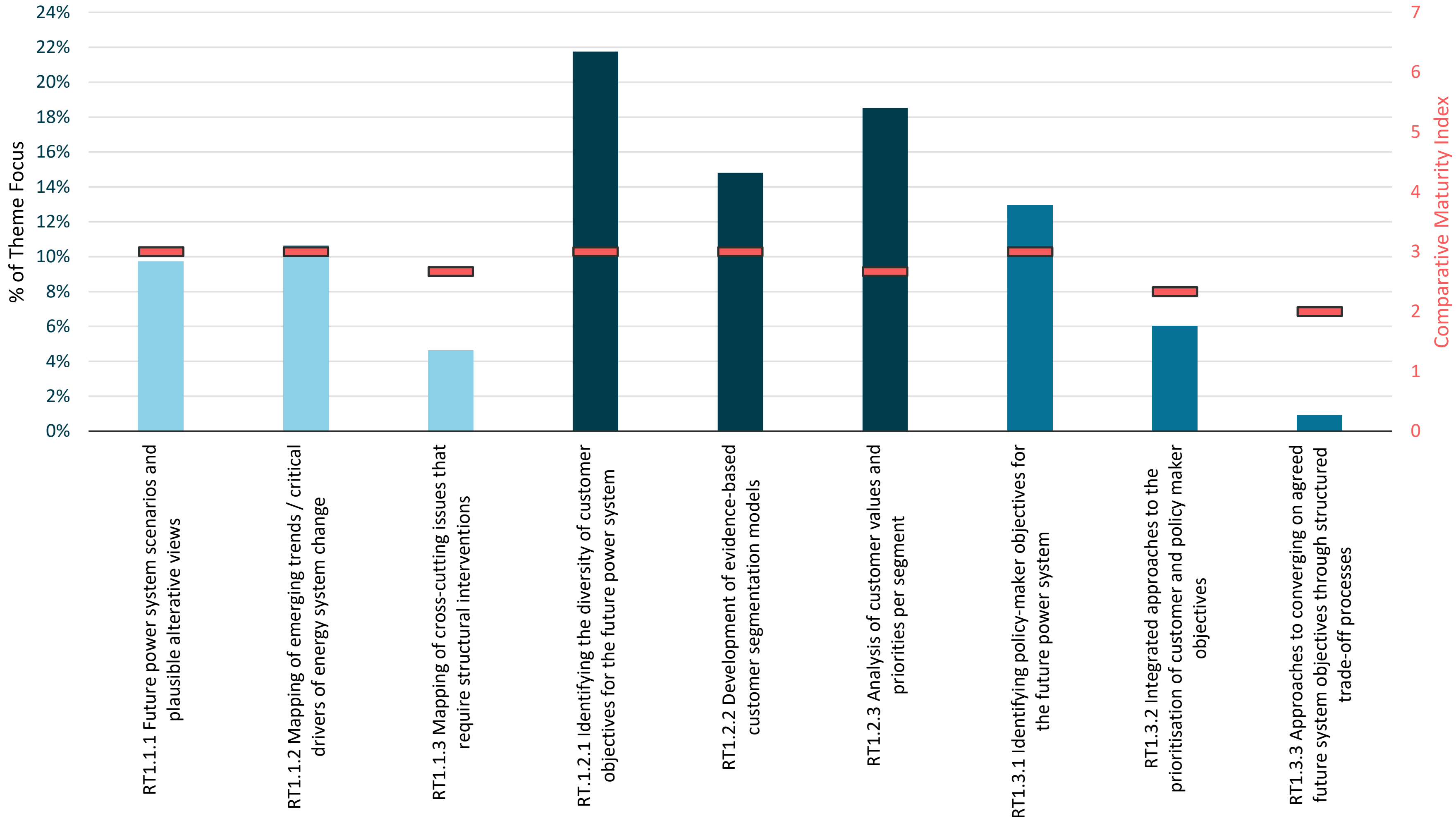


Figure 21 - Theme T1: Research Topics as % of Theme Focus and Comparative Maturity

4.3 Theme 2: End-use Solution Innovations

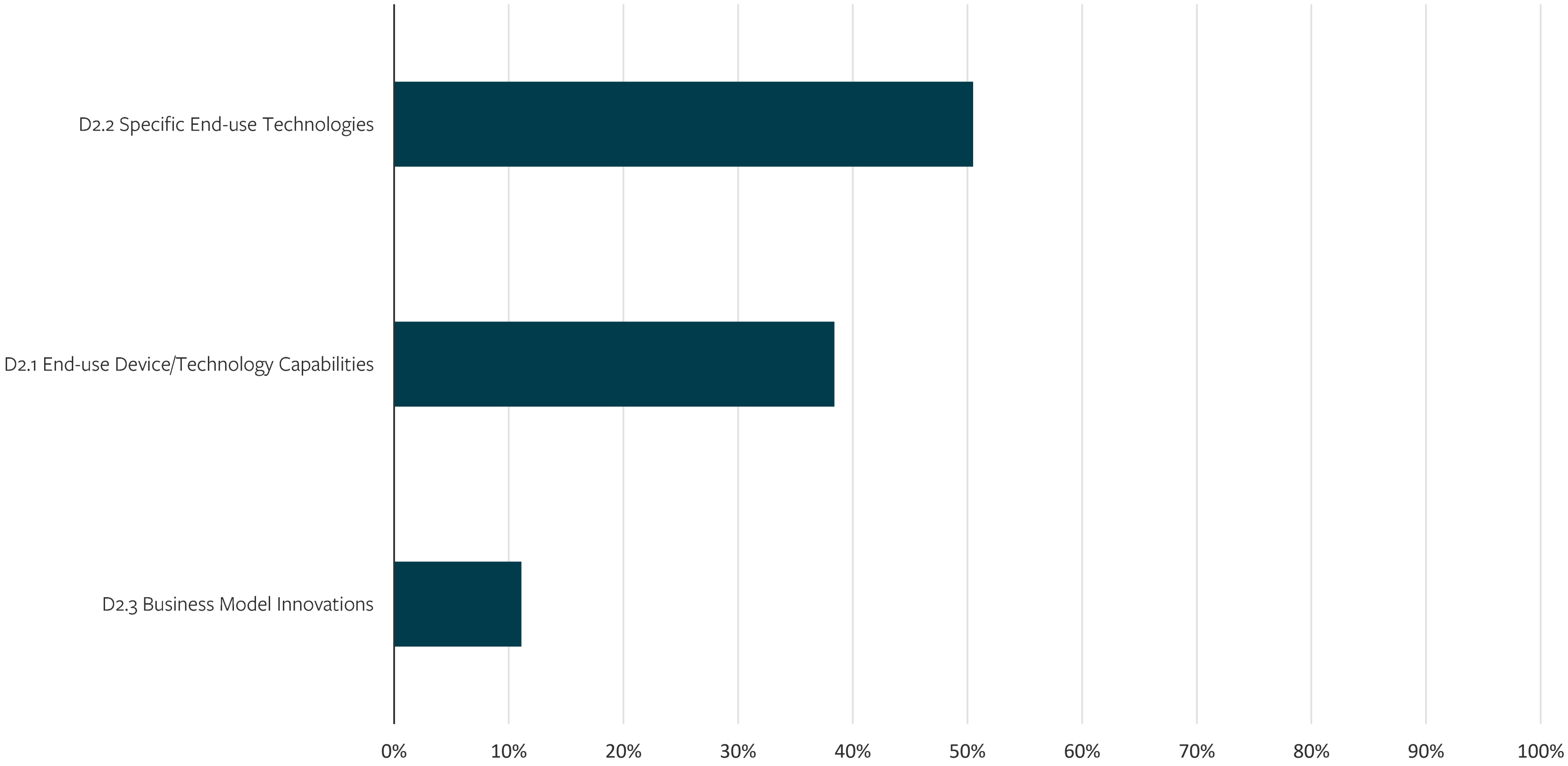


Figure 22 - Theme T2: Comparative Proportions of Research Focus x Domains (Highest to Lowest)

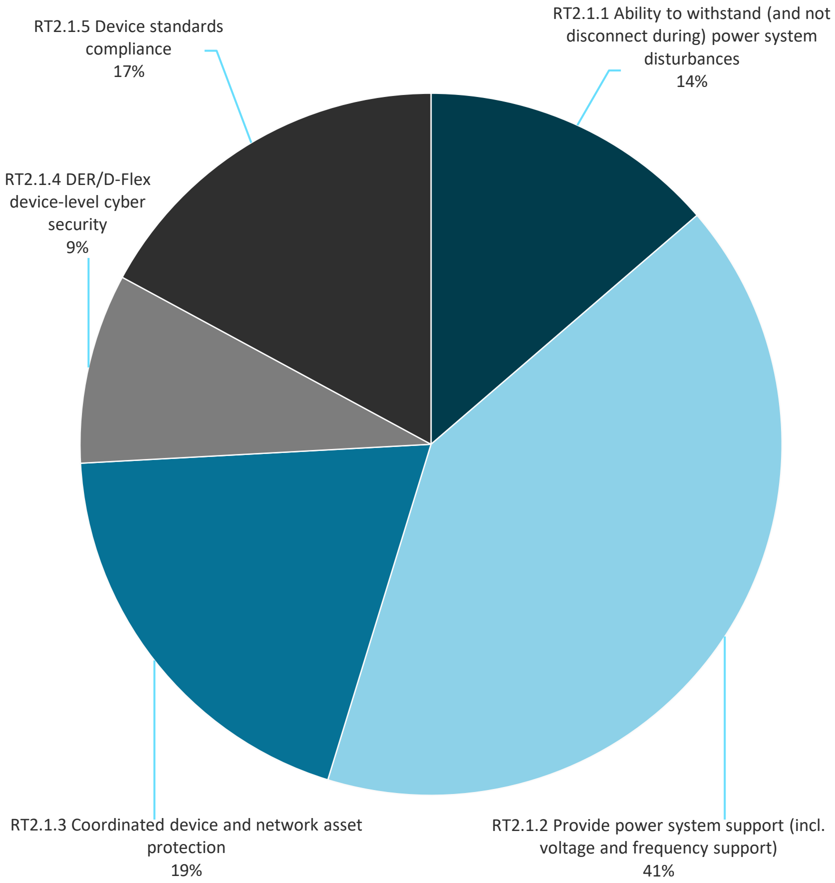


Figure 23 - Domain D2.1: End-use Device/Technology Capabilities (Research Topics as % of Domain Focus)

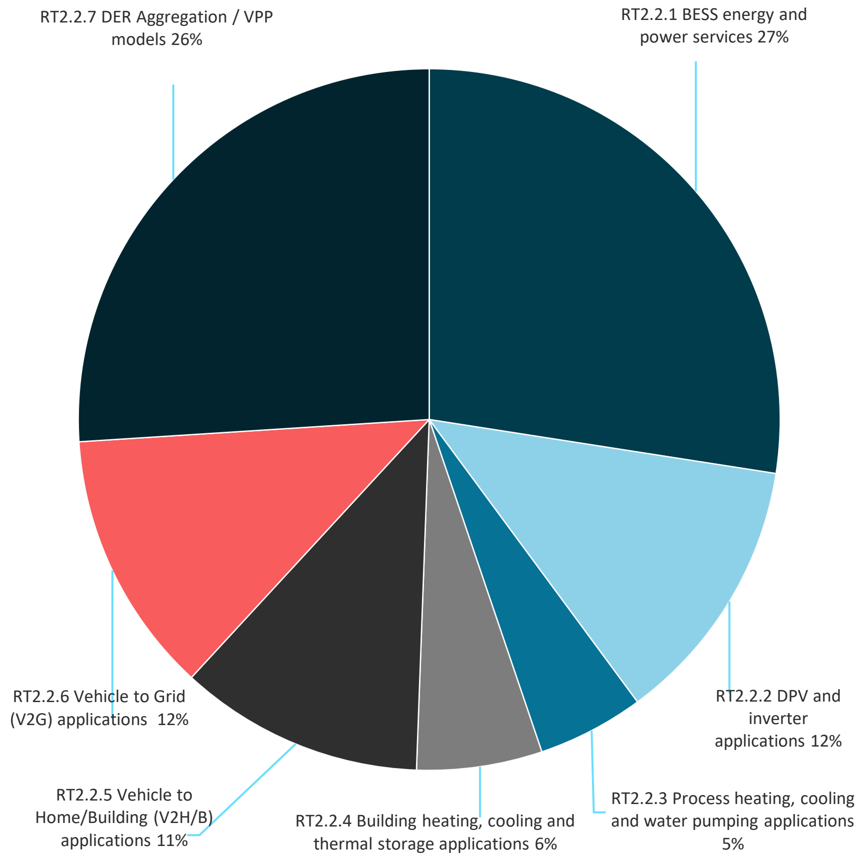


Figure 24 - Domain D2.1: End-use Device/Technology Capabilities (Research Topics as % of Domain Focus)

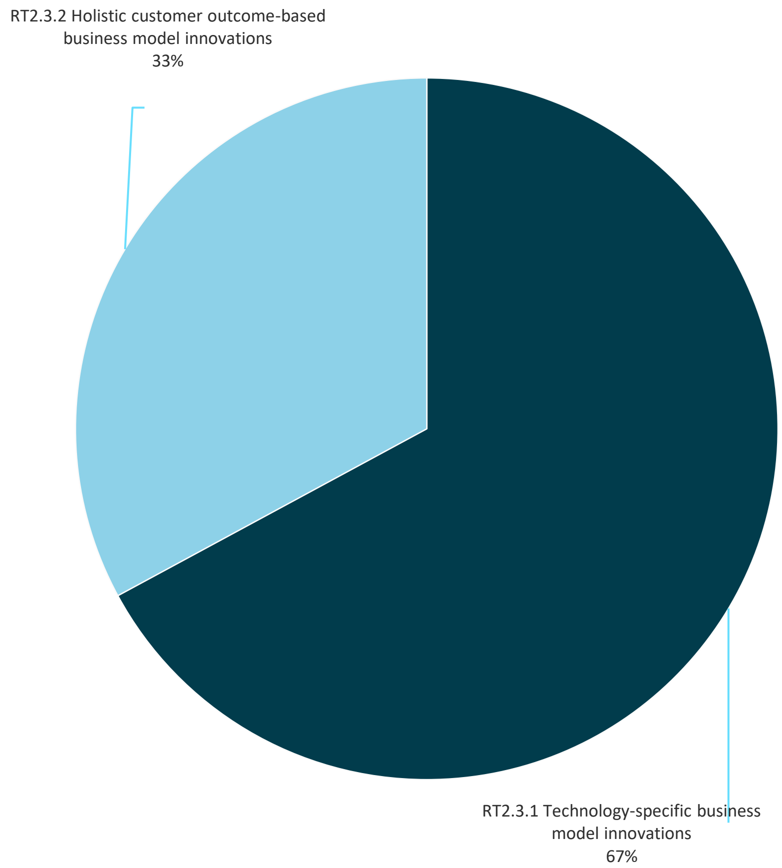


Figure 25 - Domain D2.3: Business Model Innovations (Research Topics as % of Domain Focus)

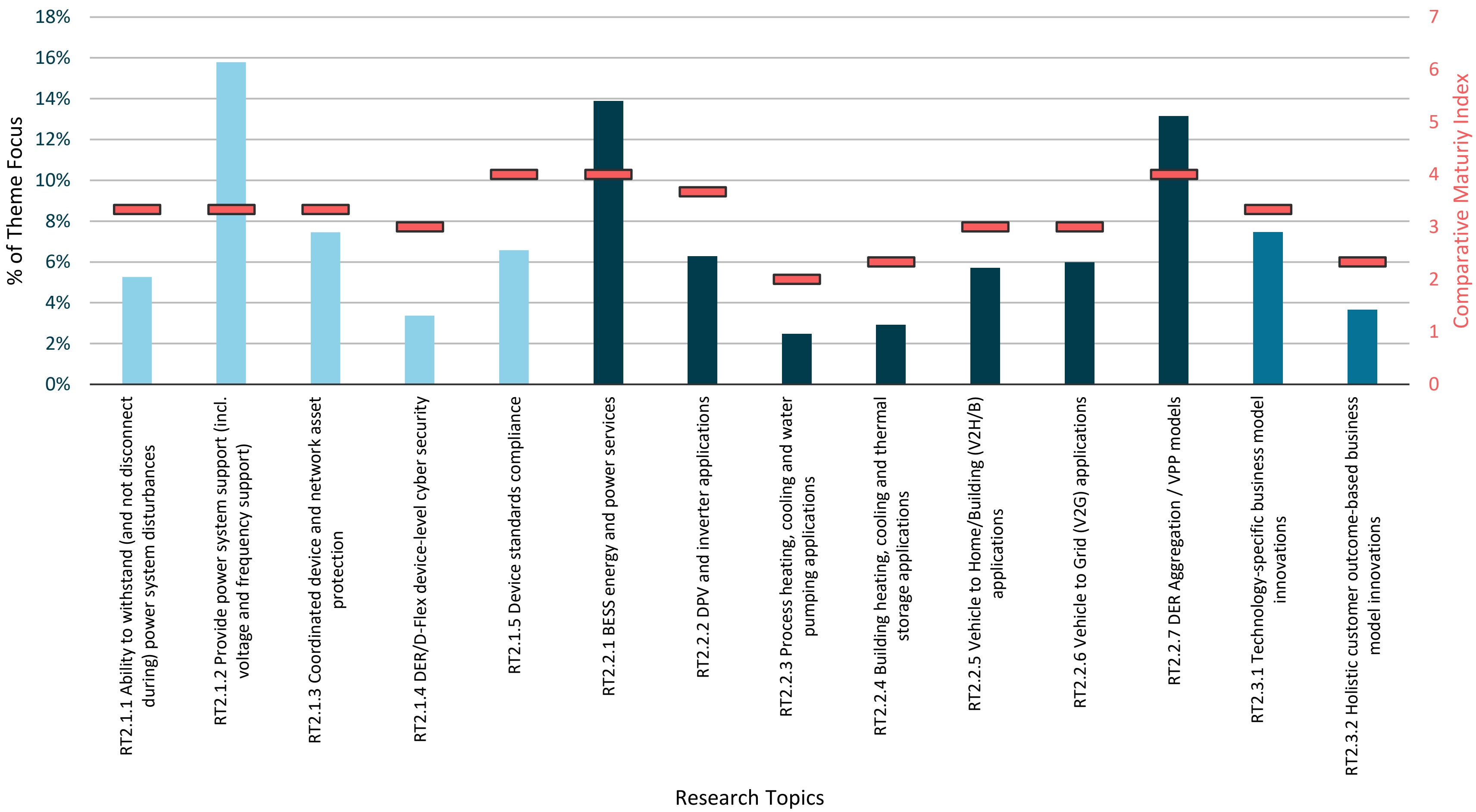


Figure 26 - Theme T2: Research Topics as % of Theme Focus and Comparative Maturity

4.4 Theme 3: Market, Pricing & Regulatory Innovations

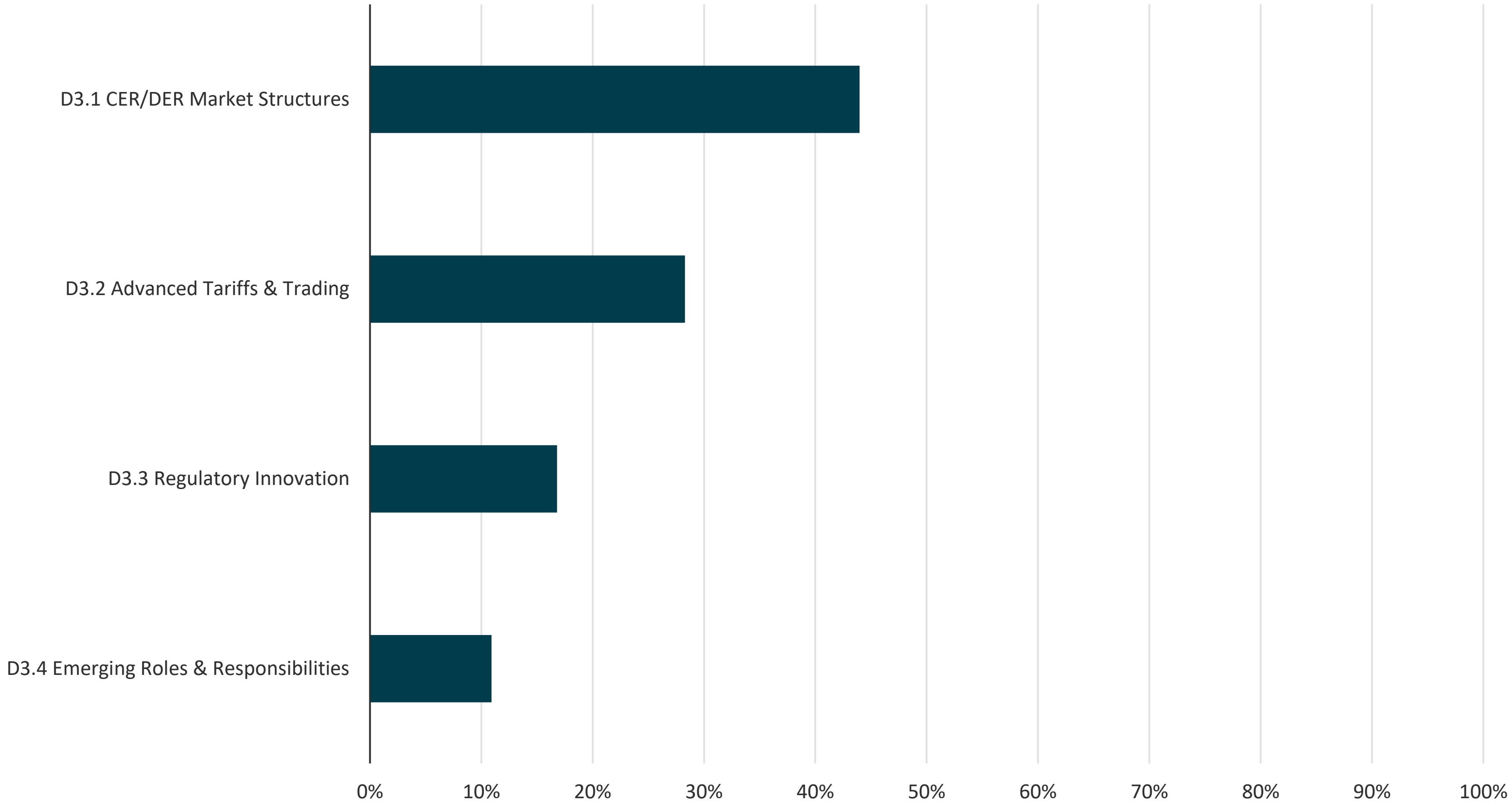


Figure 27 - Theme T3: Comparative Proportions of Research Focus x Domains (Highest to Lowest)

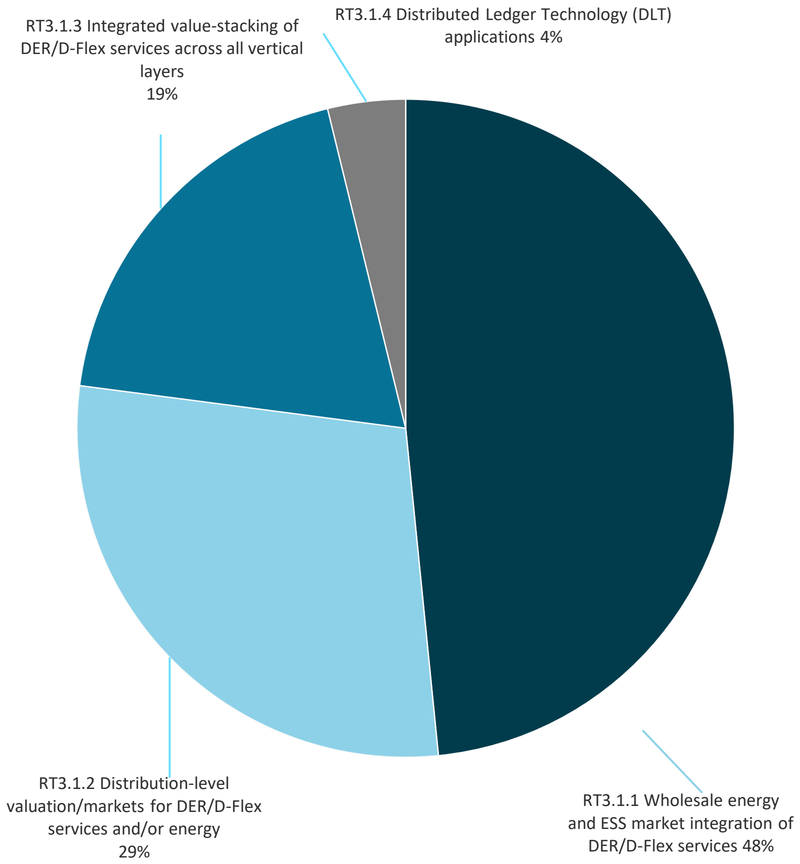


Figure 28 - Domain D3.1: Market Structures (Research Topics as % of Domain Focus)

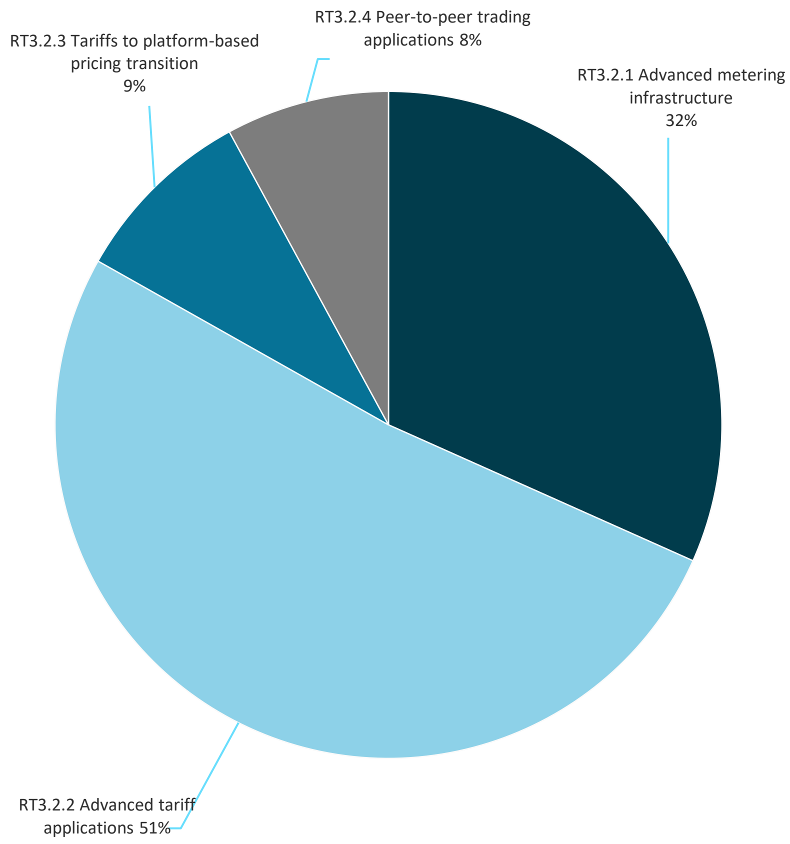


Figure 29 - Domain D3.2: Advanced Tariffs & Trading Platforms (Research Topics as % of Domain Focus)

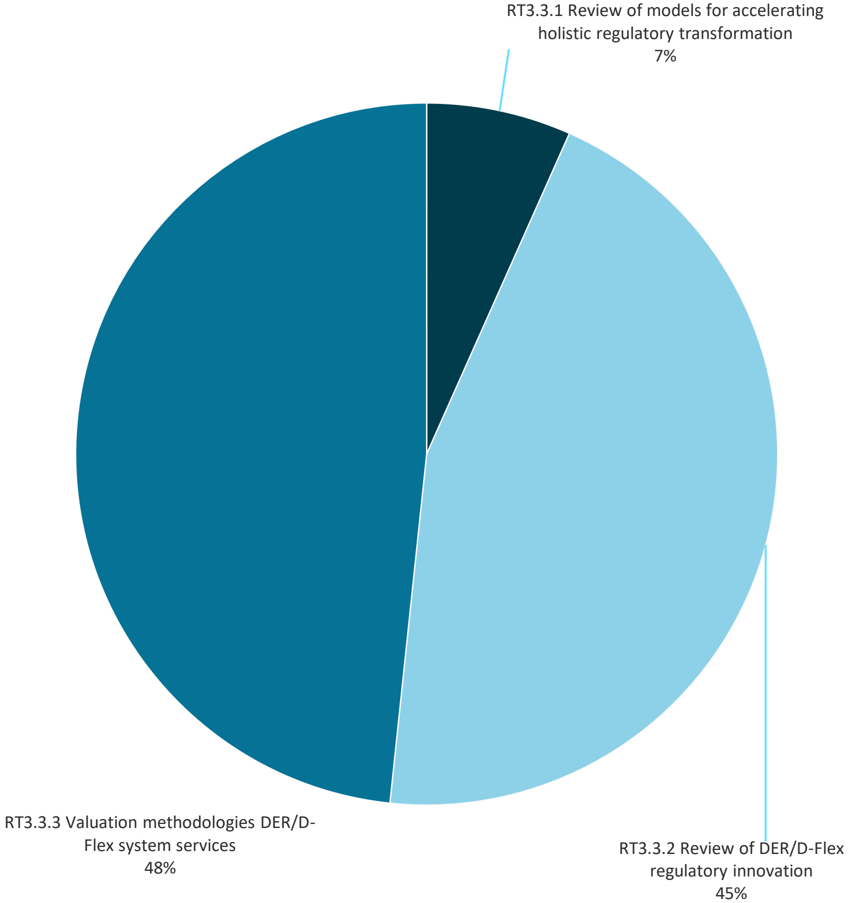


Figure 30 - Domain D3.3: Regulatory Innovation (Research Topics as % of Domain Focus)

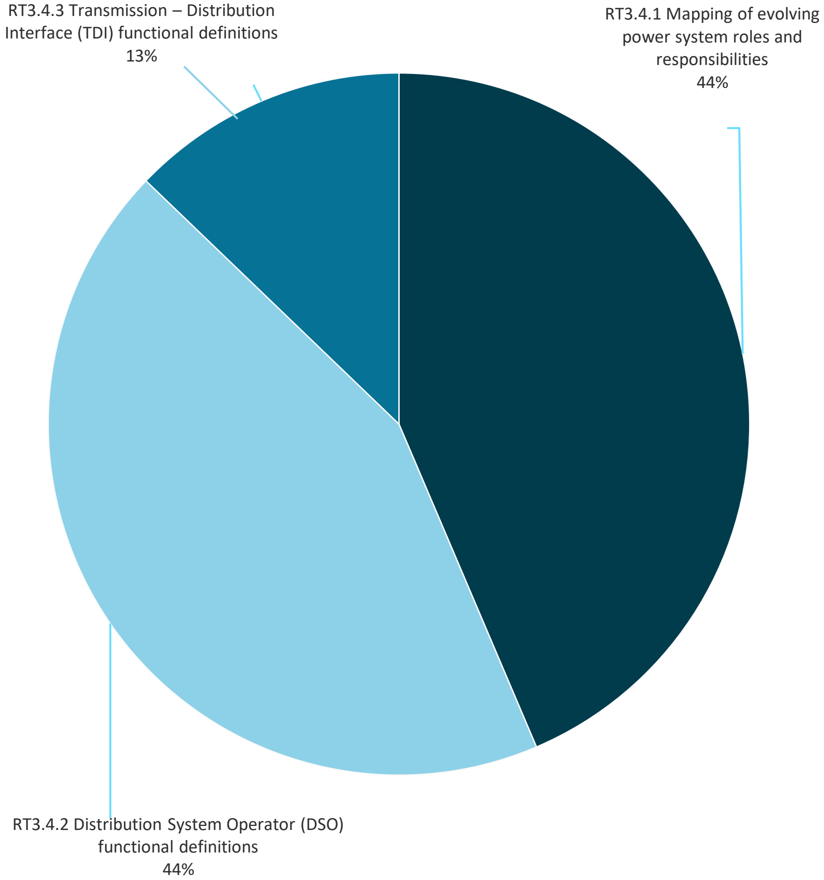


Figure 31 - Domain D3.4: Emerging Roles & Responsibilities (Research Topics as % of Domain Focus)

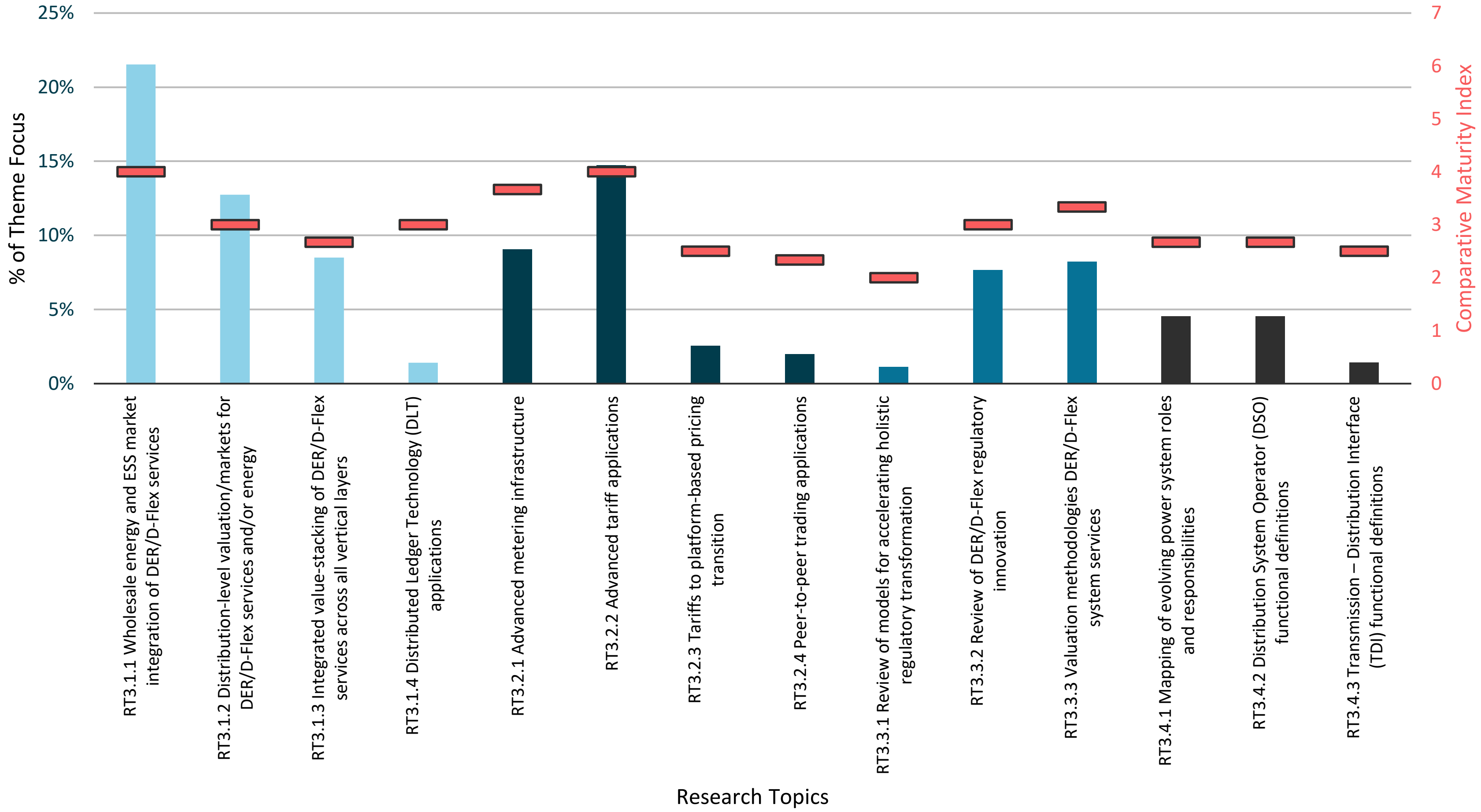


Figure 32 - Theme T3: Research Topics as % of Theme Focus and Comparative Maturity

4.5 Theme 4: Whole-system Planning, Capability & Operations

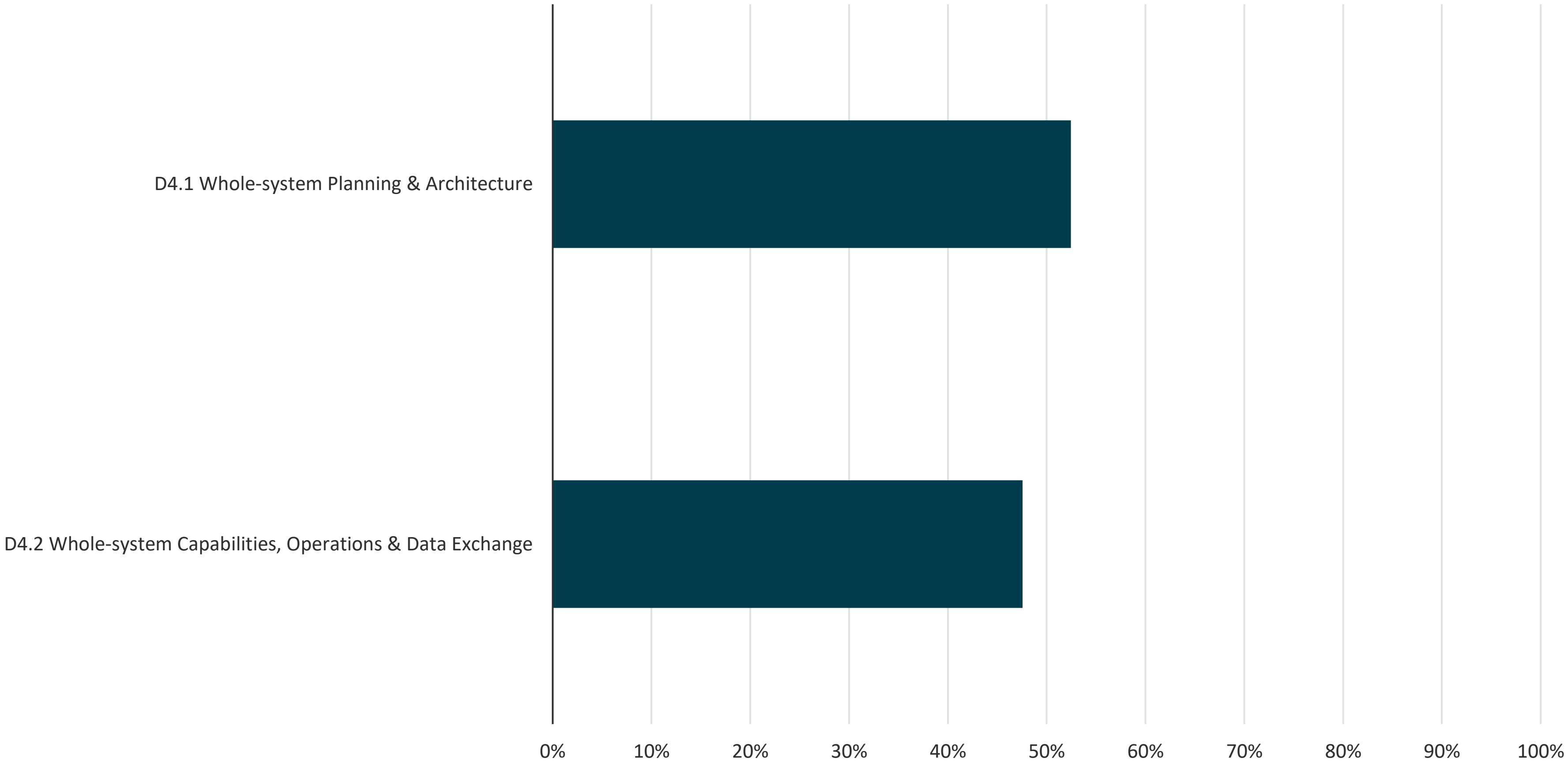


Figure 33 - Theme T4: Comparative Proportions of Research Focus x Domains (Highest to Lowest)

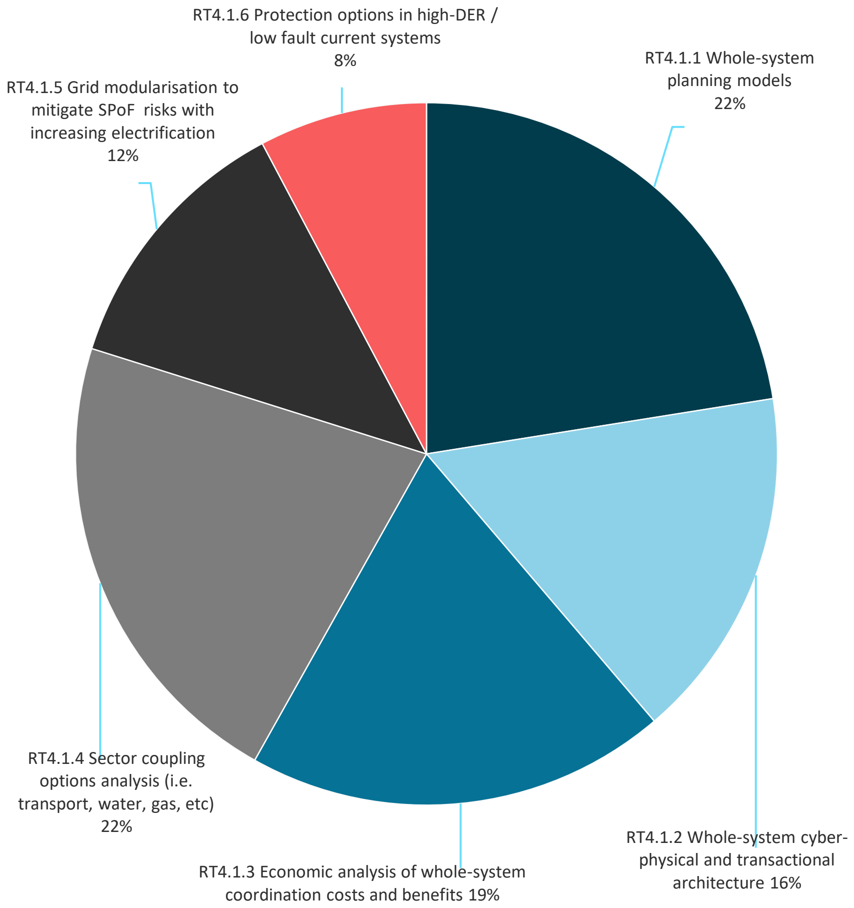


Figure 34 - Domain D4.1: Whole-system Planning (Research Topics as % of Domain Focus)

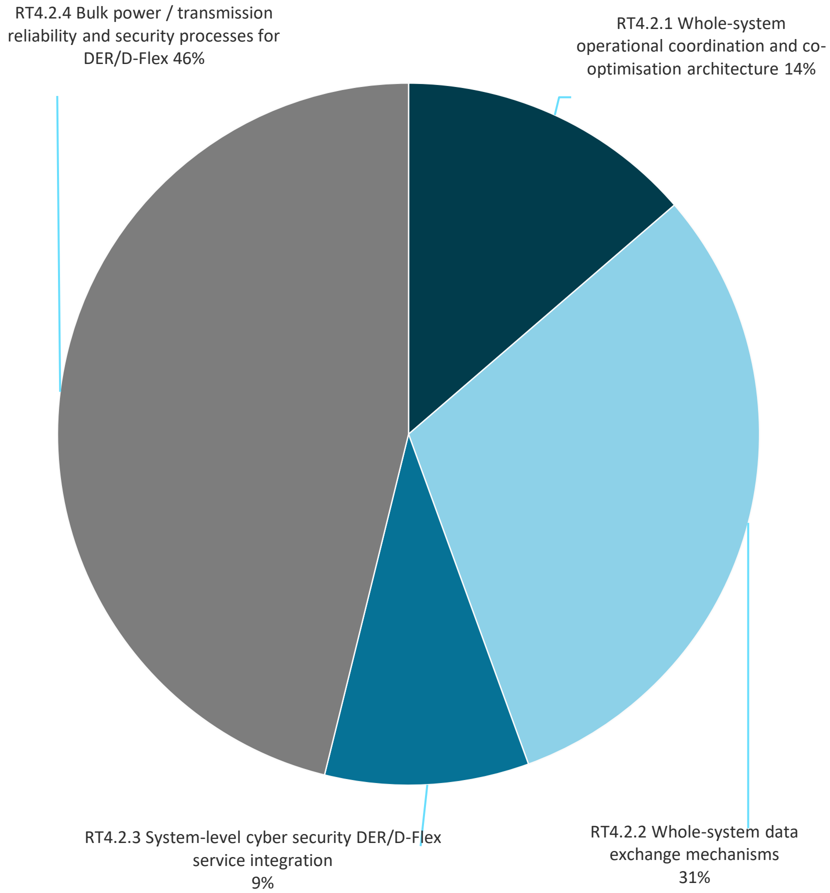


Figure 35 - Domain D4.2: Whole-system Capabilities & Operations (Research Topics as % of Domain Focus)

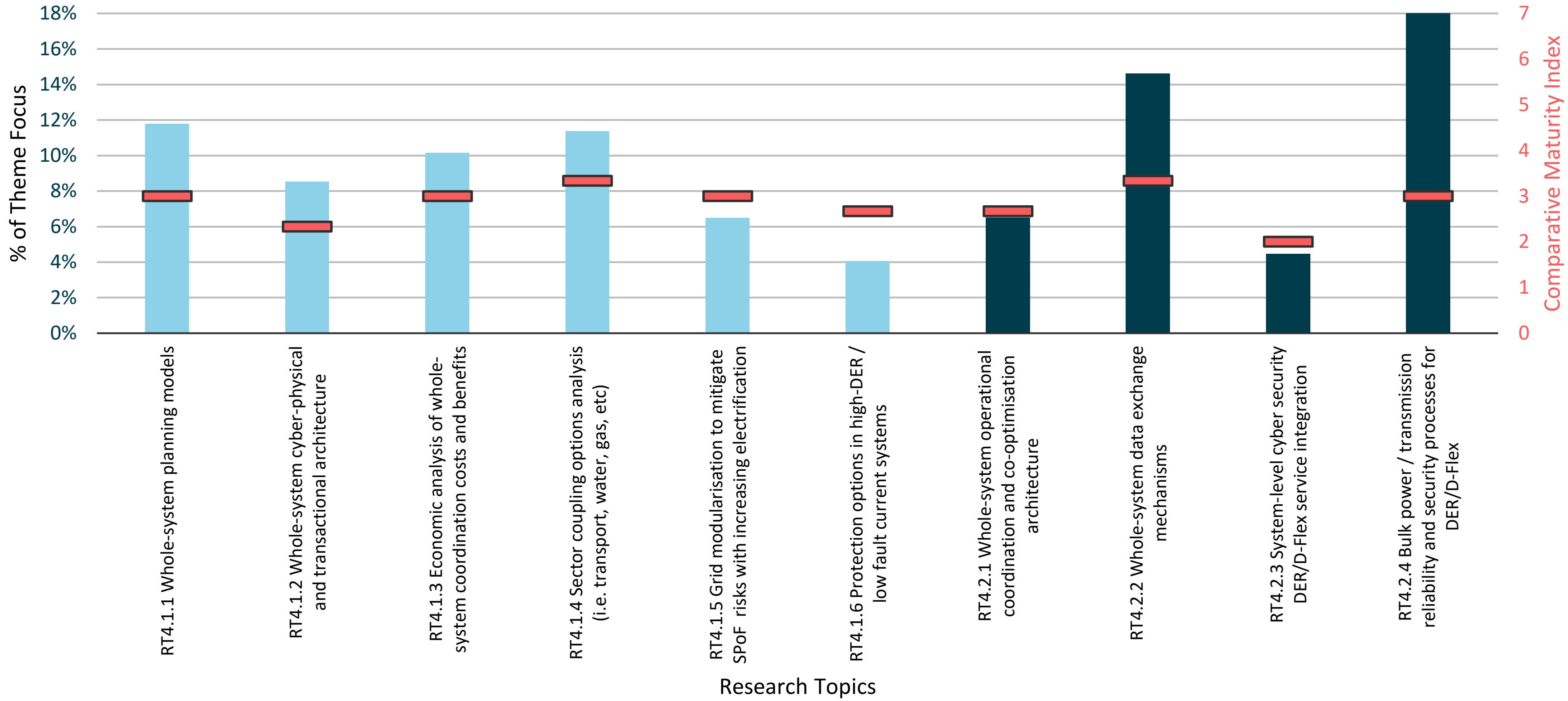


Figure 36 - Theme T4: Research Topics as % of Theme Focus and Comparative Maturity

4.6 Theme 5: LV-system Planning, Capability & Operations

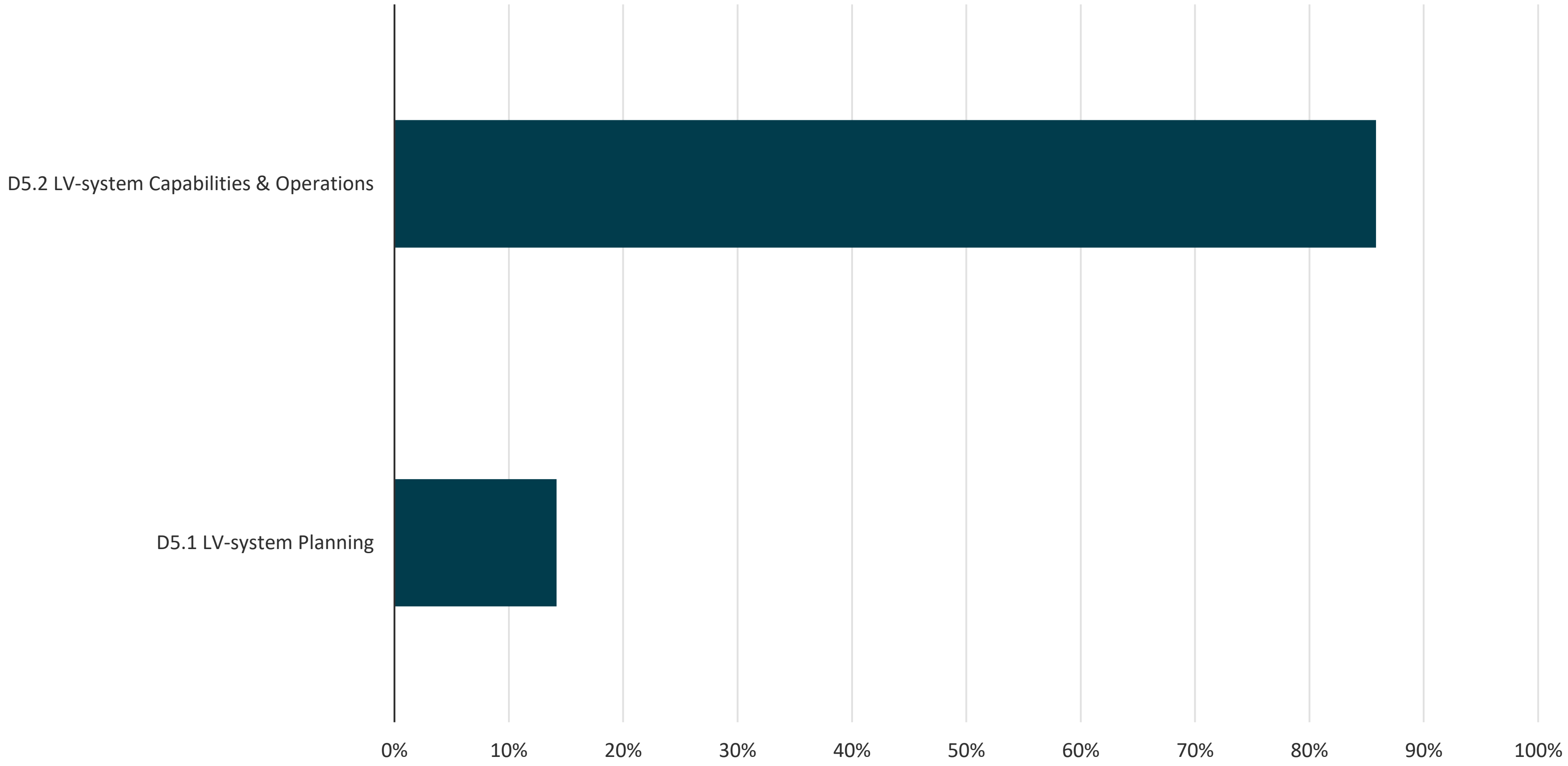


Figure 37 - Theme T5: Comparative Proportions of Research Focus x Domains (Highest to Lowest)

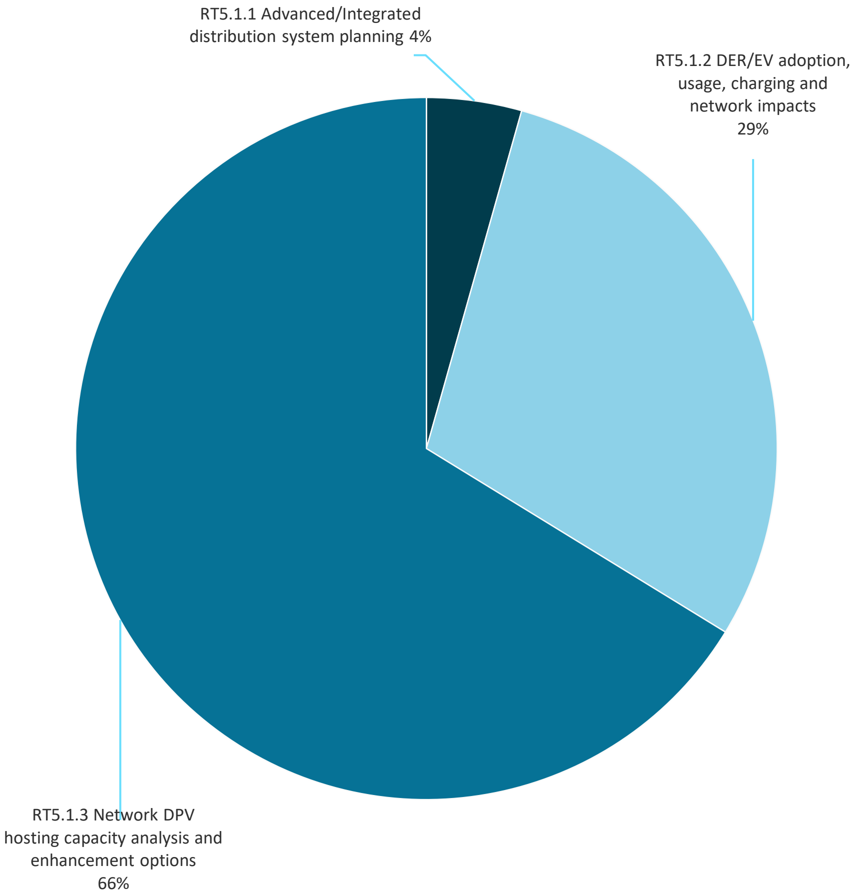


Figure 38 - Domain D5.1: LV-system Planning (Research Topics as % of Domain Focus)

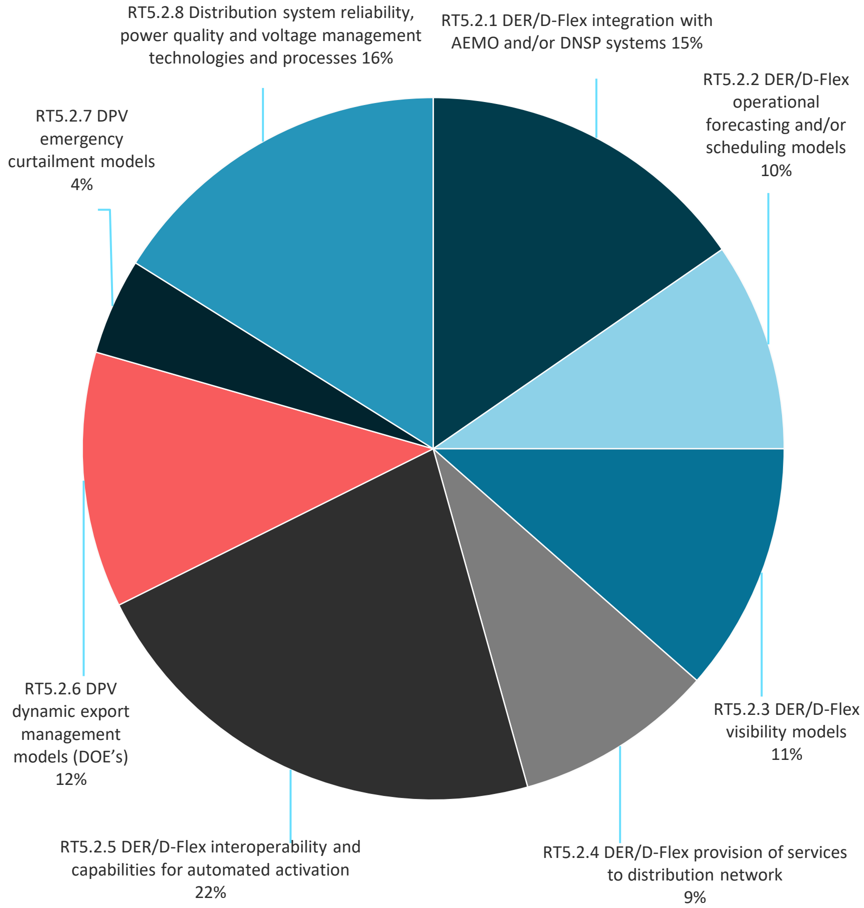


Figure 39 - Domain D5.2: LV-system Capabilities & Operations (Research Topics as % of Domain Focus)

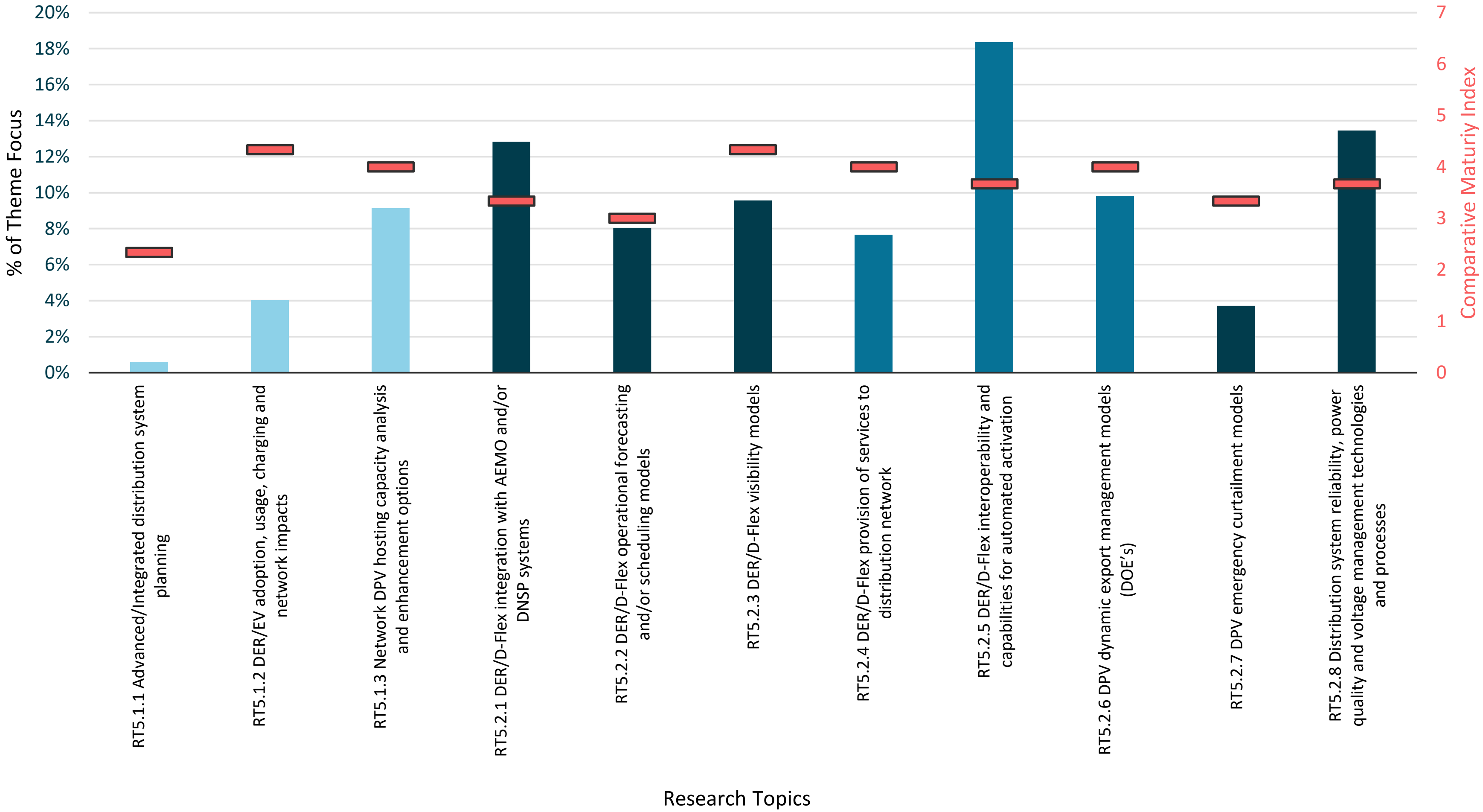


Figure 40 - Theme T5: Research Topics as % of Theme Focus and Comparative Maturity

4.7 Theme 6: Holistic Transformation Design

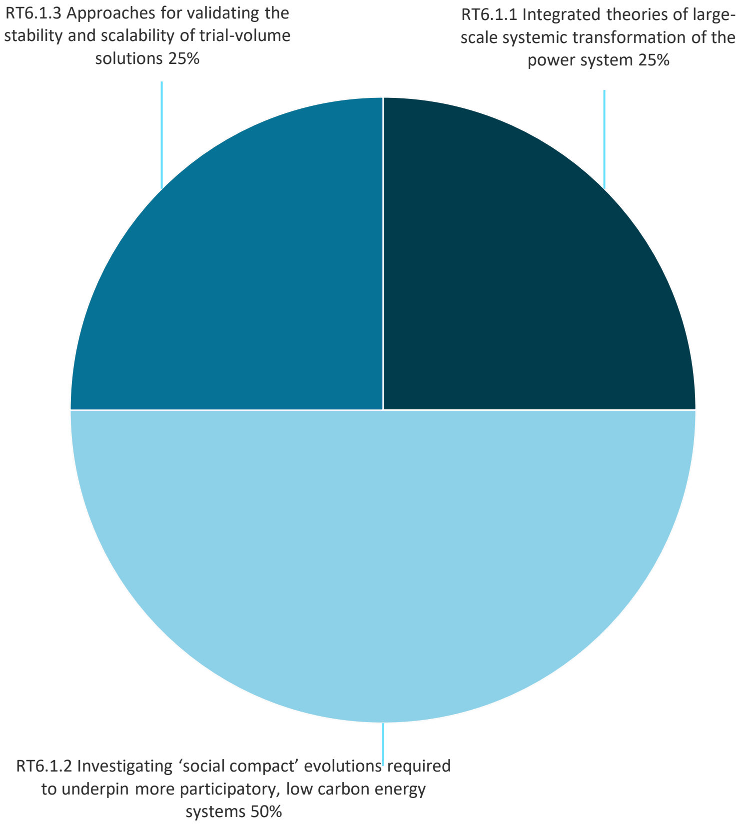


Figure 41 - Domain D6.1: System Transformation Enablers (% of Domain Focus)

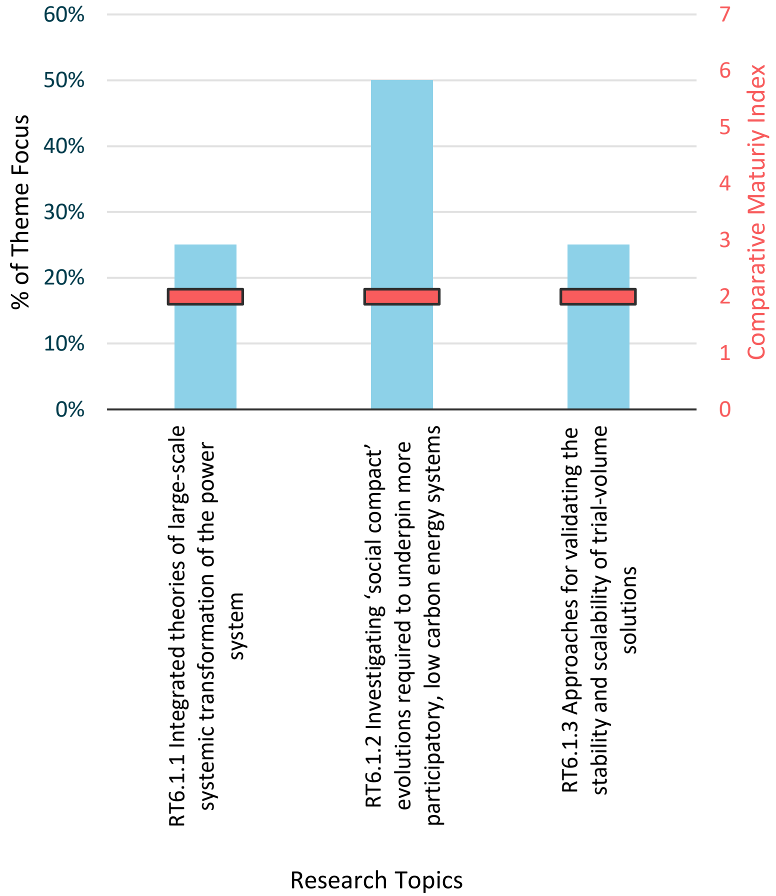


Figure 42 - Theme T6: Research Topics as % of Theme Focus and Comparative Maturity

5 Observations on Australia's Program of CER/DER Studies, Trials and Demonstrations

Australia is leading the world in the per capita adoption of Distributed Solar Photovoltaics (DPV). This has resulted in well over 200 research initiatives being undertaken, 182 of which have been examined in this study where sufficient information was available in the public domain.

The 182 x CER/DER initiatives were evaluated across the 61 x Research Topics that span Australia's end-to-end grid transformation landscape. As noted earlier, while research expenditure is not universally available, across the 182 initiatives examined it is estimated that Australia has invested in the order of AUD $500 – 750M cash and AUD $250 – 500M of in-kind contributions.

5.1 High-focus Areas

Given the scale and pace at which DPV has been adopted by Australians, it is perhaps unsurprising that the study found the primary focus of over two-thirds of the CER/DER research examined was concentrated in two out of the six Themes. As illustrated in Figures 9 - 11, these were:

- Theme 5: LV-system Planning, Capability & Operations (42%); and,
- Theme 2: End-use Solution Innovations (26%).

More specifically, the significant majority of CER/DER research over recent years has largely been:

- Targeted toward the segment of the power system closest to the DPV technology deployment, namely Low Voltage (LV) distribution networks;
- Overwhelmingly technology oriented, with the strongest areas of attention being LV-system capabilities and operations and end-use technologies; and,
- Primarily oriented toward mitigating the network impacts of CER/DER, with direct customer and wider societal benefits arguably being a secondary or tertiary consideration.

Further reinforcing the above finding, the study found that of all 61 x Research Topics considered, all of the top 10 x Research Topics were focused on LV-system capabilities, operations and end-use technologies (refer Figure 14).

5.2 Moderate-focus Areas

The study found that the following 2 x Themes important to the beneficial, whole-system integration of CER/DER received only a moderate level of focus, namely:

- Theme 3: Market, Pricing & Regulatory Innovations (13%); and,
- Theme 4: Whole-system Planning, Capability & Operations (9%).

In addition, while Theme 2 and Theme 5 both received the greatest focus, the study found this was primarily oriented toward discrete technologies. By contrast, other less tangible adjacencies of these technologies, critical to their ability to deliver overall societal benefits, received more limited attention. For example:

- Within Theme 2, the research focus on technology-based innovations surpassed the consideration of the business model innovations required for their mass-diffusion by a factor of 8 (refer Figure 22); and,
- Within Theme 5, the research focus on LV-system capabilities and operations surpassed the consideration of LV-system planning by a factor of 6 (refer Figure 37).

5.3 Limited-focus Areas

The unparalleled scale and pace of Australia's energy system transformation has become a recurring topic in the nation's electricity sector over recent years. It is also widely recognised that world-leading levels of CER/DER adoption provides one of the distinguishing features of Australia's grid transformation.

It is noteworthy, therefore, that the study found a comparatively small proportion of all research focus has been placed on topics that arguably have some of the most significant impact on the overall cost, effectiveness and future-readiness of all transformational efforts, namely:

- Theme 1: Customer & Societal Objectives for Future System (8%); and,
- Theme 6: Holistic Transformation Design (1%).

As highlighted in Table 4, within Australia's end-to-end grid transformation context, these 2 x Themes are key to informing such fundamental questions such as:

- Where are Australia's power systems most plausibly heading?
- What is the positive vision for the long-term, beneficial functions of CER/DER in Australia's power systems?

- How might Australia's grid transformation, including the participation of millions of CER/DER, be enabled at the necessary scale and pace?
- What structural interventions may be required to ensure the critical interfaces between all value-chain 'siloes' and subsystems function end-to-end to maximise whole-system benefits in a high-CER/DER future?
- How might considered structural interventions also enhance the overall operational resilience and cyber-security of Australia's power systems?
- What collaborative processes and transitionary phases should be considered support Australia's power system transformation?

In other words, beyond high-level emission reduction targets, explorative scenarios and aspirational statements, Australia has not developed a coherent vision (or visions) for systems such as the NEM that include a positive, actionable plan for unleashing the full societal value of CER/DER.

5.4 Summary Observations

While Australia has benefited from an enormous amount of activity and learning delivered by hundreds of CER/DER studies, trials and demonstrations, following are several general observations derived from the analysis above.

- The majority of Australia's CER/DER research activity has occurred within existing structural siloes. With a few exceptions, it has generally lacked a dedicated focus on the critical interfaces between structural siloes and subsystems that are essential to deliver whole-system outcomes.
- Research design generally appears to assume the infinite scalability of legacy structural arrangements that were historically developed in a unidirectional, supply-side oriented context.
- When considered across the entire grid transformation landscape represented by Research Themes 1 – 6, there has been a dominant focus on a few areas while other areas have received negligible attention. While this may be initially necessary, perpetuating such an approach will be problematic.
- Much of the research has applied an 'issue-in-isolation' focus which, while providing valuable learnings, cannot ultimately underpin a holistic and beneficial set of roles for CER/DER in Australia's power systems.

- Some areas of Australia's CER/DER research are world-leading whereas other areas significantly lag international best practice. These include:
    - Distribution System Operator (DSO) models;
    - Transmission-Distribution Interface (TDI) designs;
    - Distribution Market Mechanisms;
    - Cyber-physical System Architecture;
    - Data-sharing Infrastructures;
    - Integrated Distribution System Planning; and,
    - Advanced Operational Coordination models.
- While AEMO's future scenarios are widely referenced, there is limited practical relationship with the full implications of the future scenarios in the design of research (i.e. to ensure future resilience by design).
- Importantly, this also results in inadequate attention to the rigorous validation of the cyber-physical, structural and computational scalability of solutions beyond what can be validated by trial and demonstration participant volumes (i.e. from hundreds/thousands to millions/tens of millions).[12]

[12] The concept of Architectural Issues is critical for ensuring future whole-system scalability of solutions. Refer to the definitions provided in Section 1.3 for more information on this concept.

6 Opportunities for Enhanced Outcomes from Australia's CER/DER Research

A range of opportunities to enhance Australia's approach to CER/DER research are now considered. Based on the findings of Sections 3 – 5 (above) and informed by the transformational context in which power systems such as the NEM and WEM increasingly operate, several strategic and topical enhancements are now explored.

It is important to note that all of the following considerations are informed by the Strategic Objective of the analysis, namely:

> Examine Australia's portfolio of CER/DER studies, trials and demonstration projects to map the priority gaps that must be addressed to unleash their full potential in enabling efficient, low carbon and self-balancing future power systems that serve the long-term interests of all consumers.

6.1 Transformational Context

Australia is experiencing one of the fastest power system transformations on the planet, driven by the combined impacts of the '4 x Ds' – decarbonisation, decentralisation, democratisation and digitalisation. This complex and fast-moving environment is the context in which all CER/DER research is conducted.

These four drivers of change are themselves underpinned by a complex range of societal, technological, economic and commercial shifts, many of which are outside the direct control of traditional regulatory and governance mechanisms. The resulting transformational forces impacting Australia's power systems include:

- An escalating technological and locational diversity and quantity of energy resources connected to the grid (from tens/hundreds of broadly similar resources to thousands/millions of diverse resources);
- An increasing proportion of total generation output that is variable, inverter-based and asynchronous as conventional generation is progressively withdrawn;
- Increasing volatility and stochastic operational behaviours that far exceed those envisaged by the original system architects are being experienced across all layers/tiers of the power system;
- Structural shifts in customer demand and variability compounded with the mass deployment of distributed solar PV and growing levels of EV adoption;

- The **erosion of once-dominant paradigms**, such as the 'Supply-side/Demand-side' bifurcation and 'Load-following' operational paradigms, both of which were products of one-directional, fossil fuel-based power systems;

- A growing need for **new market models and sources of system flexibility, generation, buffering and ancillary services** that have traditionally been provided by conventional generation;

- Significant increase in dependence on **the end-to-end digitalization of the grid** to support operational efficiency, system stability and moderate the risk of capital infrastructure overbuild; and,

- The number and scale of **entities capable of influencing system operations** expands significantly as consumer participation is incentivised.

As these complex physics-based systems transform, they are experiencing levels of operational volatility unforeseen by their original architects. Compounded by the accelerating withdrawal of conventional generation, which provided the key sources of system flexibility, this is a context where…

> *Bulk power, transmission and distribution systems – and the rapidly expanding fleet of consumer resources – must be capable of operating far more* ***dynamically and holistically*** *end-to-end to underpin Australia's secure, cost-efficient and self-balancing future power systems.*

In other words, a massive scale of new dispatchable sources of flexibility is required as Australia's power systems become more volatile and dispatchable synchronous generation is progressively withdrawn. Much of this will need to be sourced from millions of diverse, participating CER/DER[13] that are effectively orchestrated through end-to-end Operational Coordination models.

[13] As noted in the Definitions, CER/DER are a multi-application resource that include the following types of technologies:

- Distributed Generation (DG): including Distributed Photovoltaics (DPV) and embedded generators;
- Battery Energy Storage Systems (BESS): including small and medium-scale batteries;
- Electric Vehicles (EV);
- Smart Inverters; and,
- Flexible Resources (Distributed).

6.2 Key Risks & Opportunities

The combined impacts of the '4 x Ds', many of which are driven by customer investments in new energy technologies, are influencing end-to-end power system operations and set the critical context for the next major phase of Australia's CER/DER research. This is essential as the Laws of Physics interact with our grids as singular integrated systems and are blind to the legacy structural separations embedded in the value chain.

Further, while historically AEMO's Integrated System Plan[14] process has most directly influenced the evolution of the east coast transmission system, it does note wider system risks and related opportunities that have relevance to CER/DER. Some key examples that have a bearing on the potential roles and importance of the millions of CER/DER for whole-system augmentation and operations follow.

6.2.1 Transmission Augmentation Risks/Opportunities

While the augmentation of Australia's transmission system to connect large volumes of new utility-scale wind and solar is advancing, challenges are being experienced. Planned projects are not progressing as expected due to several factors including approval processes, investment uncertainty, cost pressures, social licence issues, supply chain issues and workforce shortages. Unplanned coal generator outages are also becoming more common as the fleet ages. In this context, the potential importance of orchestrated CER/DER will become increasingly important for both supporting Australia's power system operations and meeting global emission reduction commitments.

6.2.2 CER/DER System Integration Risks/Opportunities

Where effectively integrated with wider power system operations, CER/DER assets offer significant system benefits and may defer or avoid the need for specific transmission and distribution system augmentations. Both CER/DER owners would need to realise benefits from participating and whole-system benefits would need to be guaranteed through huge volumes of devices being effectively orchestrated in response to current and new markets and network signals. Given the growing proportion of the generation fleet that CER/DER represents, a range of non-scalable features currently 'baked into' legacy grid structures will also need to be addressed. This is essential to avoid perpetuating issues that impact system resilience and ensure the effective Operational Coordination of tens of millions of CER/DER consistent with whole-system security and operational efficiency.

[14] Section 6.2 is adapted from the Integrated System Plan -Draft, AEMO (2024)

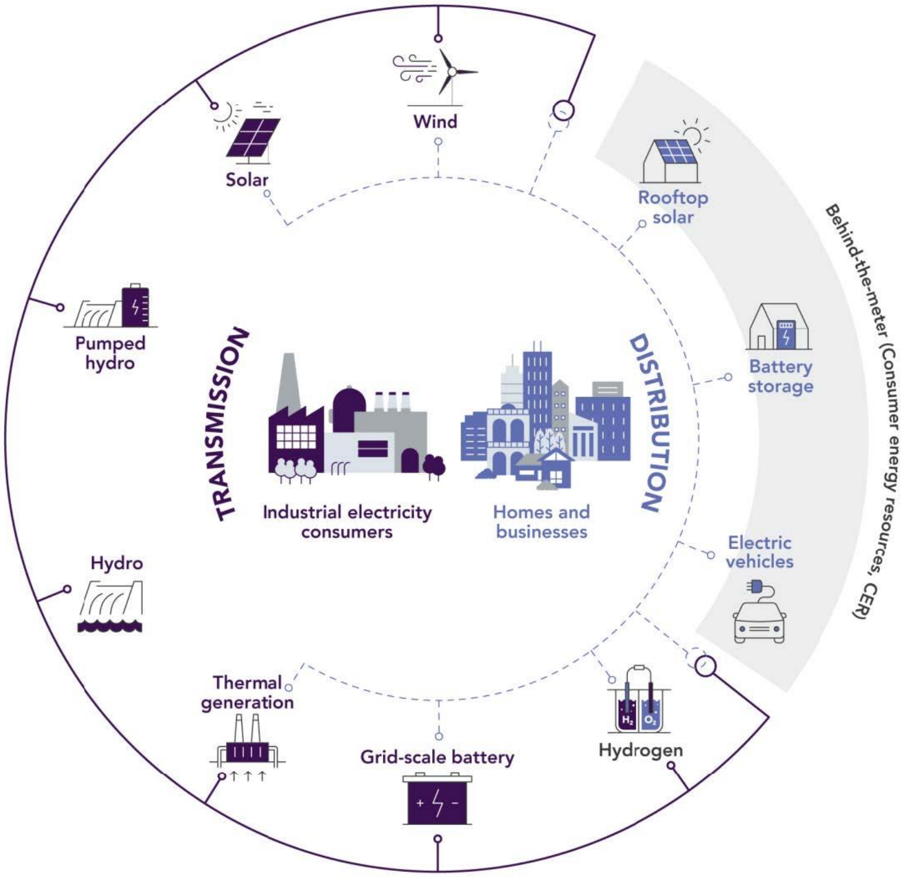


Figure 43: While AEMO's Integrated System Plan process most directly influences the NEM transmission system, it also recognises the increasingly important operational interdependencies between transmission and distribution systems.[15]

6.2.3 Market & System Operations Readiness Risks/Opportunities

As utility-scale and distributed sources of renewable energy are being installed at pace and scale, energy markets, networks and operations across the power system must evolve to be ready for very high levels of weather-dependant generation. Given the physics-based nature of the system, this requires collaborative processes that have a decided focus on whole-system solutions and that are not unduly constrained by legacy structural separations. As with addressing CER/DER system integration risks, this cannot be ultimately achieved without treating the non-scalable features embedded in legacy structures and focusing on the emerging new roles, functions and systemic interdependencies that are required.[16]

[15] Image: Integrated System Plan -Draft, AEMO (2024)
[16] For example, the consideration and detailed design of emerging roles and responsibilities and systemic interfaces, including Distribution System Operator (DSO) models, the Transmission-Distribution Interface (TDI), new market configurations, etc., all require a rigorous focus on the end-to-end Systems Architecture of the power system.

6.3 Strategic Enhancements

In recognising that Australia has benefited from an enormous amount of CER/DER research activity, Section 5.4 offered several summary observations that have a bearing on its ability to unleash the full potential of millions of CER/DER as a valuable part of Australia's future power systems.

Informed by both the Strategic Context and Key Risks & Opportunities outlined above, three Strategic Enhancements are now explored. Critical to underpinning a holistic, integrated and future-ready program of CER/DER research and related system transformation, they are:

- Development of a whole-system vision for CER/DER;
- Systems-based tools to 'tame' expanding grid complexity; and,
- Coherent processes to align and accelerate strategic transformation.

These three enhancements set the context and provide a transferrable set of tools for addressing the various Topical Enhancements (including potential research priorities) that are subsequently considered in Section 6.4.

6.3.1 Whole-system Vision for CER/DER.

Beyond high-level emission reduction targets and explorative scenarios, Australia lacks a positive and coherent whole-system vision for CER/DER to guide an integrated program of research and transformative action.

As noted above, Australia's power systems are already experiencing some of the world's fastest transformations, driven in significant part by the mass-adoption of CER by Australian consumers and further accelerated by the Commonwealth's Net Zero Emissions commitments.

In this transformational context, a valuable set of explorative plausible scenarios are periodically delivered through AEMO's Integrated System Plan development cycle. While the scenarios reflect a diversity of plausible futures, they all reflect a scale of transformation unparalleled since the dawn of electrification.

For example, AEMO's 2050 Step Change scenario[17] anticipated that the National Electricity Market (NEM) will need to accommodate order-of-magnitude transformative shifts, including:

- **9x Centralised VRE:** A nine-fold increase in the installed capacity of utility-scale Variable Renewable Energy generation (from 15GW to 140GW);

[17] Inputs, Assumptions & Scenarios Report, AEMO, 2021 (Comparison based on 2021 levels)

- **5x Distributed CER/DER:** Almost a five-fold increase in the installed capacity of Distributed Energy Resources, large volumes of which are customer owned (from 15GW to 70GW);
- **3x Dispatchable Firming Capacity:** A three-fold increase in installed Firming Capacity that can respond to a dispatch signal; and,
- **99% Electric Vehicles:** Almost the entire passenger vehicle fleet electrified.

Such futures represent a materially – if not radically – different operational environment for the end-to-end NEM from the past and present. For example, as the once-dominant 'Supply-side / Demand-side' bifurcation continues to erode, the proportion of synchronous generation declines, and the decarbonising system becomes more volatile, operational challenges are being experienced that are entirely new to GW-scale power systems anywhere.

In other words, from a unidirectional past, Australia's bulk power, transmission and distribution systems – and rapidly expanding fleets of CER/DER – must now be made capable of functioning in a far more dynamic, end-to-end manner to enable secure, cost-efficient and self-balancing future operation.

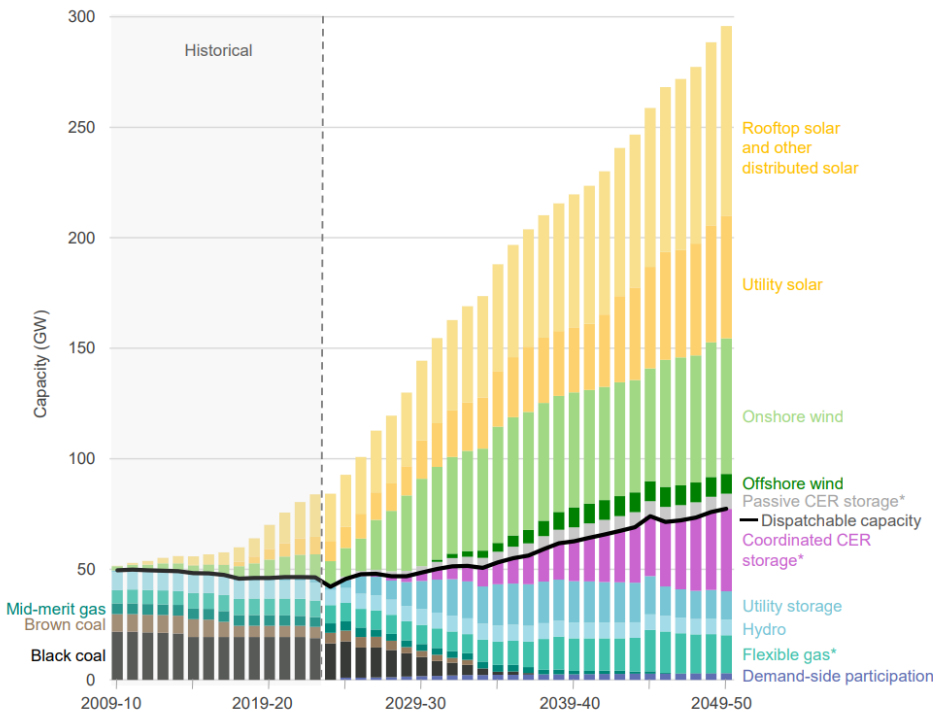


Figure 44 - AEMO's Step Change scenario for the NEM[18]

[18] Image: Integrated System Plan -Draft, AEMO (2024)

Beyond high-level emission reduction targets and explorative scenarios, however, Australia has not developed a coherent, positive future vision (or visions) for millions of CER/DER as a reliable, integral part of efficient, self-balancing power systems. In the absence of any sufficient level of alignment, the majority of activity continues to occur inside structural and disciplinary siloes, often with limited focus on the upstream and downstream interdependencies.

With few exceptions, this approach has resulted in limited attention to the interfaces between supply chain segments and negligible focus on the outcomes for the entire system. It certainly is not capable of unlocking the full economic value of systems-integrated CER/DER at massive scale.

The purpose of developing such a unifying vision, supported by a set of agreed Guiding Principles[19], is to enable convergence on an integrated set of matters that must be advanced to enable any/all of the plausible future scenarios. Guided by the inherent physics-based constraints, it would enable multi-stakeholder engagement on specific social, regulatory, technological and other matters that must be advanced over the next 5 – 10 years to establish the foundation of Australia's future power systems.

6.3.2 Systems-based Tools to Tame Complexity

As complex power systems experience profound transformation, they face increasing reliability, resiliency, cost-efficiency and scaling issues where the escalation of systemic complexity is not formally managed.

The power systems developed throughout the twentieth century are some of the largest and most sophisticated 'machines' created by humanity and are formally defined as Ultra Large-scale (ULS) complex systems.[20]

Given the scale of Australia's transformation, AEMO has highlighted that the NEM must be made capable of operating at 100% or more instantaneous renewable generation from both centralised and decentralised sources. [21] This is a feat without global parallel for GW-scale systems, further compounded by Australia's shift from hundreds to tens of millions of participating energy resources. Operating such a system will require vastly more functionality, more interoperability, more dynamic balancing, more participating entities, more technologies, more sector-couplings.

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[19] Refer Figure 45 for an example set of Guiding Principles.

[20] Feiler et al, Ultra-Large-Scale Systems: The Software Challenge of the Future, Carnegie Mellon, Software Engineering Institute, 2006.

[21] Engineering Roadmap to 100% Renewables, AEMO, 2022

Example Guiding Principles

A Balanced Approach to Value

- Focus on achieving an agreed 'Balanced Scorecard' of beneficial societal, customer and system outcomes.
- Target scalable, future-ready solutions capable of unlocking many tens of $-billions value in whole-system optimisation and customer savings.
- Optimise the utilisation of existing grid assets, complement and/or moderate the volume of system augmentation required, reduce the spill of unutilised renewable energy and efficiently accelerate emissions reductions.

A Reliable & Secure Power System

- Enable the secure orchestration of millions of participating CER as an integral part of Australia's secure, efficient and self-balancing power systems.
- CER grid services recognised as comparable to conventional solutions in delivering secure, optimised system operation, enabled by future-ready architecture, holistic technical standards, compliance and enforcement.

An Affordable & Equitable Power System

- Support equitable outcomes from new energy technologies for all Australians by maximising access options, reducing cross-subsidies and placing downward pressure on overall system costs.
- Enable customer energy bill reductions by mitigating negative system impacts, increasing the range of beneficial grid services CER can provide and simplifying participation options that customers find rewarding.
- Ensure a fair system that prioritises consumer protection that includes emerging energy products and services.

A Future-ready & World-leading Power System

- Enable Australia's 2030 emissions targets in a manner that is scalable to enabling Net Zero Emissions by 2050.
- Nationally consistent and integrated with other sectoral action plans, particularly built environment and transport, while adaptive to jurisdictional requirements.
- Capitalises on Australian and global research and demonstration investments to reflect global best practice in the whole-system integration and beneficial activation of CER.

Figure 45 – An example set of Guiding Principles relevant to developing a unifying shared vision for CER/DER as an important and beneficial part of Australia's future power systems.

As MIT's Crawley et al. note, however, additional complexity is unavoidably driven into an already complex system where additional functionality and interoperability are required of it. [22] This is especially the case where the underpinning structures of the system are inadequately interrogated and legacy structural constraints not resolved.

It is therefore vital to recognise that a modern power system is a 'Super-system of Systems' which must be holistically transformed to enable the systemic and beneficial integration of CER/DER at massive scale.

At a very practical level, GW-scale power systems consist of a complex web of the following seven inter-dependent structures:

1. Electricity Infrastructure (Power Flows);
2. Digital Infrastructure (Information/Data Exchange, Storage and Processing);
3. Operational Coordination Structure;
4. Transactional Structure;
5. Industry / Market Structure;
6. Regulatory Structure; and,
7. Sector Coupling Structures (Gas, Water, Transport, etc).

This 'Network of Structures' spans the vertical tiers/layers of the power system, impacts multiple system actors (e.g., bulk power, transmission and distribution systems, energy retailers, aggregators, customers, etc.) and must be transitioned holistically. Importantly, they provide the underlying 'DNA' of each power system and are directly involved in the systemic integration of CER/DER.[23]

Surprisingly, compared to other advanced sectors[24], the electric power sector has been slow to integrate contemporary Systems Engineering disciplines. Their absence tends to perpetuate research that is primarily focused on discipline-specific siloes. For example, there is a growing recognition of the need to address the 'data architecture' of Australia's power systems. While this is an important development, a cautionary note is that the data architecture cannot be artificially separated from three other 'functionally interdependent' structures, namely the electricity infrastructure, operational coordination structure and transactional structure. Together, these four structures are spatially and temporally inter-dependent, meaning that changes to one structure will always impact how the others function.

[22] System Architecture, Crawley, Cameron & Selva, 2016

[23] Refer to Appendix D – Power Systems as a 'Super-system of Systems' for more information.

[24] Including aerospace, defence, mining, advance manufacturing, rail systems, etc.

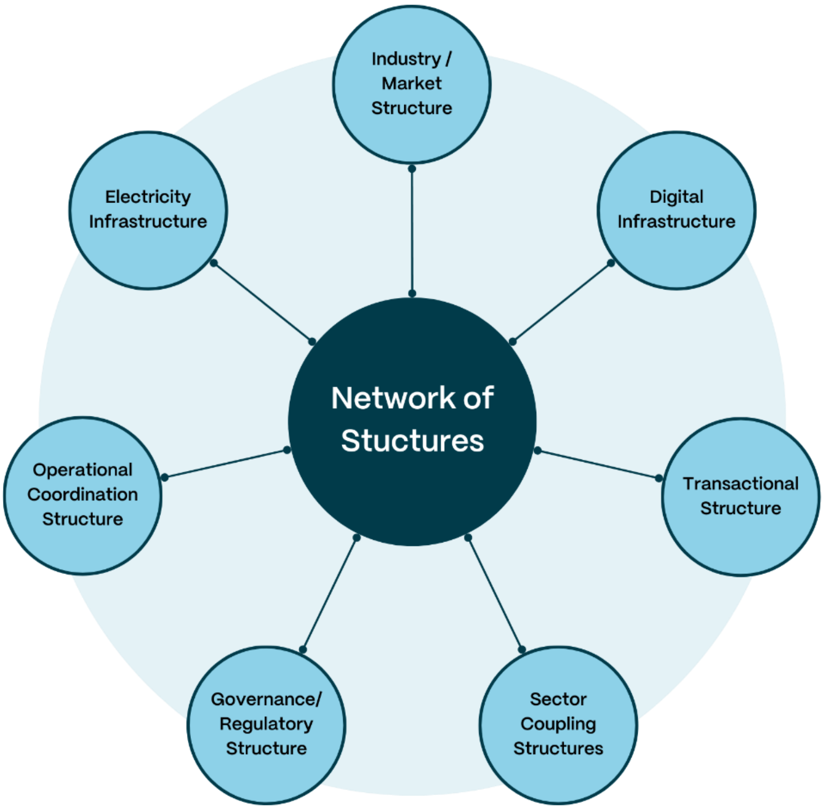

Figure 46 - Modern power systems are a 'Super-system' of interdependent structures'[25]

Particularly striking, in most jurisdictions it is also common to find that no complete and generally agreed set of documents exists that represent how all seven structures are currently configured and dynamically influence each other (as most legacy power systems have emerged and evolved over decades). It is also common to find that no single entity is responsible for ensuring these critical underpinning structures (or 'architecture') remain fit-for-purpose in a transformational environment.

This is a profoundly significant gap. Systems Science highlights that the underpinning architecture of any complex system – how all the elements and actors are formally linked together as an integrated system – will always have a disproportionate impact on what the system can safely, reliably, and cost-efficiently do. Like an intricate tapestry, changes to one structure will impact the functioning of the other structures in both intended and unintended ways and must therefore be managed carefully.

[25] Image: Adapted from Pacific Northwest National Laboratory, United States

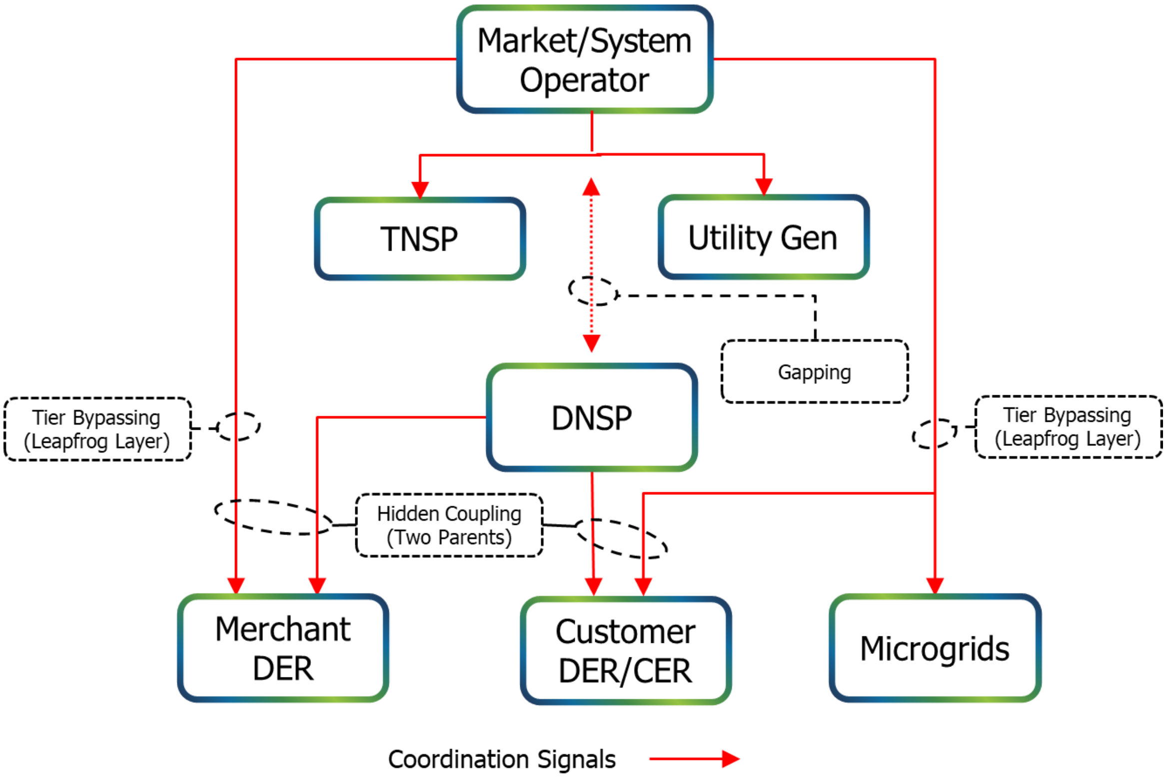

Figure 47 - Example Architectural Issues that negatively impact CER/DER orchestration[26]

Given the unparalleled cyber-physical interdependencies key to twenty-first century power systems, the ability to undertake formal, whole-system structural analysis of potential changes while they remain 'on paper' becomes critical. The failure to do so elevates the likelihood of unintended consequences, long-term scaling issues.[27], non-linear behaviours, runaway complexity and the propagation of structural fragility.

In summary, an already extremely complex system that is undergoing transformation will become intractably complex where the underpinning structural arrangements do not keep pace with the expanding expectations of the system.[28] In addition, the absence of a shared 'view of the whole' system results in poorly integrated change initiatives.

In this area, despite being ahead on the velocity of transformation, Australia significantly lags the United States, the United Kingdom and the European Union in the application of more advanced Systems Engineering-based tools for managing and 'taming' the related escalation of complexity. This complexity is only further compounded by Australian

[26] The concept of Architectural Issues is critical for ensuring future whole-system scalability of solutions. Refer to the definitions provided in Section 1.3 for more information on this concept.

[27] Many serious scaling issues will not become obvious during trial scale demonstrations. Systems Engineering-based tools enable the surfacing of scaling issues while proposals remain 'on paper'.

[28] Section 2.7 of the DER Market Integration Trials – Summary Report, ARENA, 2022 provides an early example of the complexity involved in developing holistic solutions.

consumers' world-leading levels of CER/DER adoption and the transition of our power systems from tens or hundreds to millions of participating energy resources.

EXAMPLE: Operational Coordination for the 21st Century

A critical question that requires a holistic, systems-based approach to resolve is: "How will a power system with millions of participating energy resources be 'Operationally Coordinated'?"

In the Australian context, this will require whole-system coordination of one of the world's longest power systems, as it transitions:

- *From* hundreds of large, dispatchable, synchronous machines *to* tens of millions of diverse and highly dynamic resources...
- *Which* are ubiquitous across all vertical layers of the grid, and blind to our historical bulk power, transmission and distribution boundaries...
- *In* a context where grid security will need growing levels of flexibility, balancing and ancillary services from what we once called the 'demand-side' of the system, and...
- *All* of which must be Operationally Coordinated in a manner that instantaneously balances supply and demand every millisecond of the year.

This is a challenge that spans bulk power, transmission, distribution and CER/DER aggregation. It requires a shared systems-based methodology to develop integrated solutions that benefit all.

Given the inseparable cyber-physical-economic nature of a GW-scale power system, close 'market-control' alignment is required to incentivise and activate service provision in a reliable and mutually reinforcing manner (across timescales of days to milliseconds).

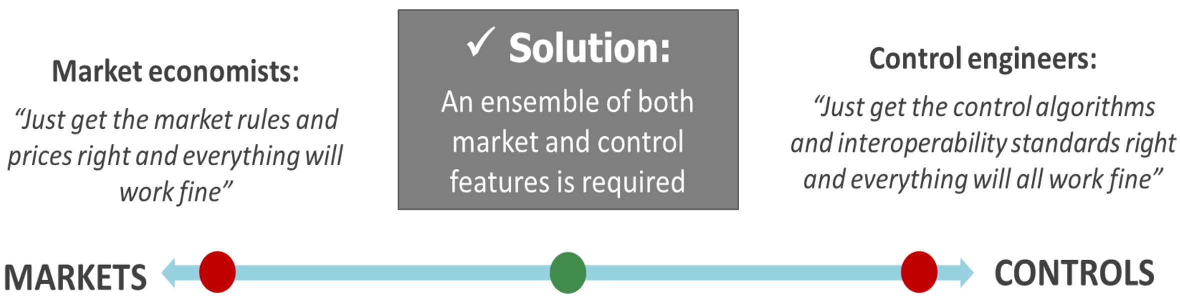

Figure 48 - The 'markets vs controls' false dichotomy[29]

6.3.3 Coherent Processes for Strategic Transformation

Despite a general recognition of the scale of transformation unfolding, the absence of a coherent and broadly agreed 'theory of change' commensurate with the scale and pace of change places the timely realisation of $-billions of whole-system optimisation benefits for customers and society at risk.

In contrast the unidirectional bulk delivery system of the 20th century, it is internationally recognised that decarbonising power systems require vastly greater levels of dynamic, bi-directional interdependence between the bulk power system and the various distribution systems served.[30]

As noted earlier, to enable secure, cost efficient and self-balancing operation in any future remotely similar to AEMO's Step Change scenario, the bulk power, transmission and distribution systems – and the rapidly expanding fleet of CER/DER – must be made capable of functioning together in a far more dynamic, end-to-end manner. Achieving this in practice will potentially be one of the most complex undertakings ever attempted in Australia's power sector.

The collaborative, multi-stakeholder development of an informed, coherent and shared 'theory of change' becomes essential at times of large-scale transformation that outpaces conventional change mechanisms. The process provides diverse actors, including consumer representatives, the opportunity to engage deeply with, and make collective sense of, the nature of the transformation that is unfolding. It builds shared awareness of the most plausible future directions and the range of trade-off choices[31] that may need to be made to successfully navigate it.

However, in a sector that prides itself on 'being practical', there is always a temptation to dismiss such concepts as overly academic or abstract. This overlooks the fact that the sector already has a long-established, albeit largely tacit, theory of change. Evolving in the far more stable historical context of the last century, the sector has tended to approach change in a compartmentalised, issue-in-isolation manner. In this context, historical structural arrangements are largely assumed to be infinitely scalable. Change initiatives tend to be framed within functional siloes and rigorous attention to whole-system outcomes is often lacking.

[29] Image: Adapted from Paul De Martini and Dr Jeffrey Taft. Refer to the definitions provided in Section 1.3 for more information on the topic of Operational Coordination.

[30] For example: System Operation Collection, International Renewable Energy Agency, 2020; Coordination of Distributed Energy Resources; International System Architecture Insights for Future Market Design, Newport Consortia, 2018; and, Evaluation of Combinations of Coordination Schemes and Products for Grid Services, EU CoordiNet Project, 2022.

[31] Refer Appendix B – Customer & Societal Expectations of Future Power Systems

Perhaps the most explicit recognition of the need for such a commensurate theory of change was published by AEMO. As illustrated in Figure 49 below, it highlighted that journey forward required both the augmenting of the existing system in parallel with designing and implementing step change capability for the future.

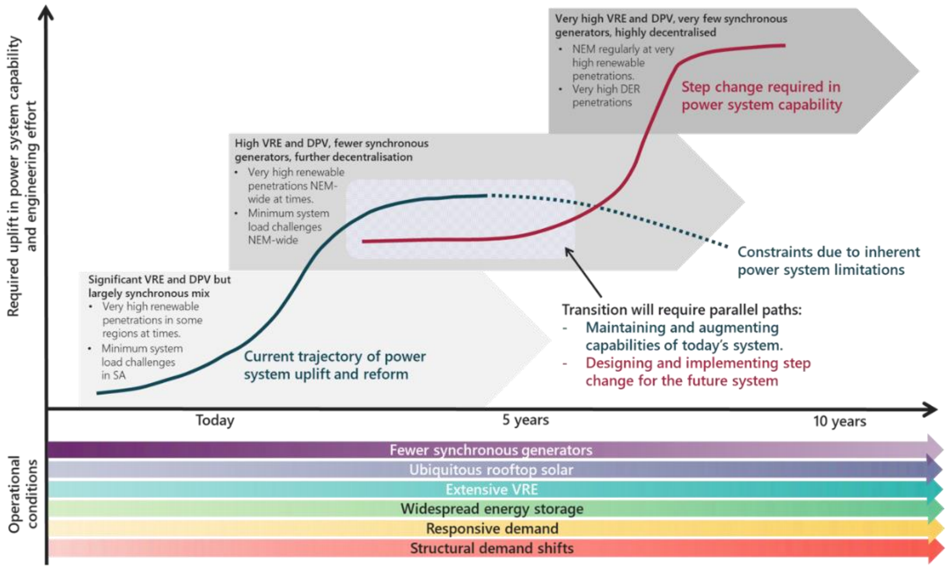

Figure 49 - AEMO has recognised the need for a transformative approach involving parallel paths of activity focused on different time horizons[32]

Despite the general recognition of the magnitude of transformation unfolding, the lack of any structured and documented approach to whole-system transformation significantly impacts Australia's capacity for integrated, collective action. As a high potential but still maturing set of technological solutions, achieving the full national benefits realisation of CER/DER is arguably particularly impeded by such a gap. This is further compounded by, and perhaps the reason for, the absence of an emerging whole-system vision for CER/DER and the limited application of systems-based tools despite the complexity of the challenge.

Rather than abstract or impractical, conscious sectoral engagement with how large-scale transformation may be effectively navigated is vital to ensure a secure, scalable and future-ready power systems capable of unlocking many tens of $-billions in customer savings.[33] Conversely, the absence of a level of shared coherence, formal transition methodologies and shared tools significantly elevates the risk of stakeholder and solution misalignment, and reduced whole-system optimisation benefits for customers and society.

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[32] Image: Engineering Framework – Interim Roadmap, AEMO, 2021; adapted from A Gambit for Grid 2035 – A systemic look into the disruptive dynamics underway, Pacific Energy Institute (2021)

[33] Refer Footnote 5.

6.4 Topical Enhancements

Informed by the above analysis, the following content seeks to highlight some of the potential research gaps and/or comparative research priorities going forward.

Once again, it is important to recognise that such a wide-ranging analysis has inherent limitations as are set out in Section 2.6. It is recognised that different stakeholders will necessarily bring different perspectives to any such process, meaning that it will always be something of an 'imperfect science'.

6.4.1 Methodology

Nevertheless, while this content should be considered indicative and capable of providing general guidance only, the following approach has been applied to provide a plausible basis for comparison.

Key Principles

1. Any gap analysis process necessarily requires and assumes at least a level of emerging clarity on the following three topics:

   - Where is the system now (current state)?
   - Where is the system most plausibly heading in the longer term (future state)?
   - What is needed to move from the current state to the future state (at least in terms of 'least regret' actions)?

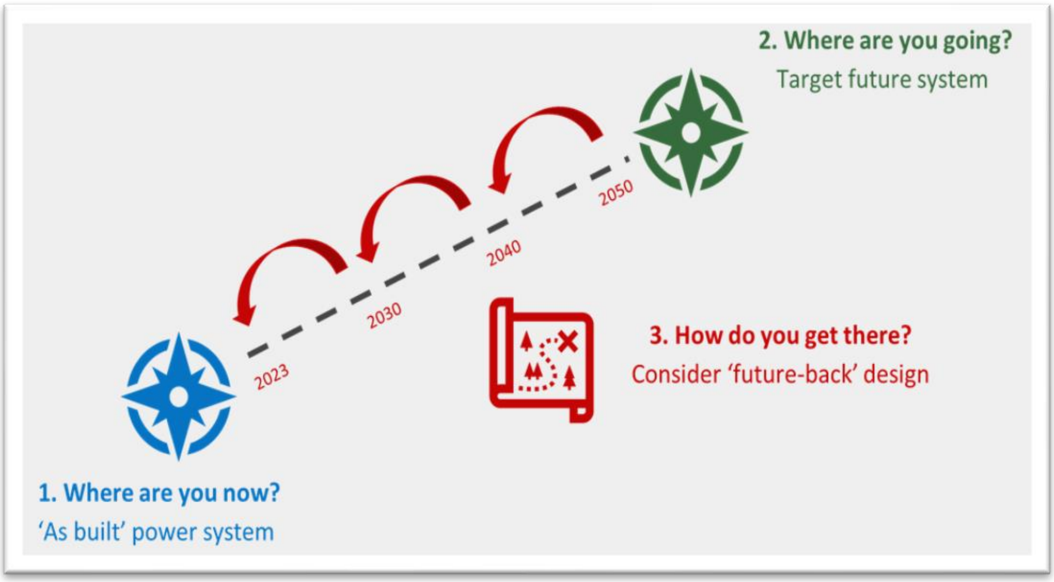


Figure 50 – Three key questions relevant to gap analysis processes

2. In the absence of a single, authoritative position on the above three points, the gap analysis and resulting indicative research priorities set out below are informed by the following inputs as discussed in this report:

   - Strategic Objective: Unleash the full potential of millions of distributed resources as an integral part of Australia's dynamic, efficient and self-balancing power systems.
   - Customer & Societal Expectations: Power systems are complex techno-economic systems that have a critical societal role. Any consideration of future options must be informed by what customers and policy makers expect of their future power systems and seek to deliver a 'balanced scorecard' of societal outcomes.[34]
   - Whole-system Perspective: The Laws of Physics interact with our grids as singular integrated systems and are blind to the legacy structural separations embedded in the value chain.
   - Operational Context: Australia already has some regions experiencing periods of almost 100% of instantaneous demand being served by CER/DER on low load days. Later the same evening, these regions are almost 100% supplied by the centralised system. This results in a 24-hour operational profile that is essentially 'tidal'.
   - Insights from Systems Science: By definition, a system is not the sum of its parts, but the product of the interactions of those parts. Therefore, the underpinning structure or 'architecture' of a system always has a disproportionate and irreducible influence on the essential limits of what the system can reliably and efficiently perform.
   - Guiding Principles: Recognising the above points, the example set of Guiding Principles[35] support convergence on the following generic statement of high-level capabilities that will be required by Australia's future power systems in a high-VRE and high-CER/DER future.
   - High-level System Capabilities: Bulk power, transmission and distribution systems – and the rapidly expanding fleet of consumer resources – must be made capable of operating far more dynamically and holistically end-to-end to underpin secure, cost-efficient and self-balancing future power systems.
   - Current Status of Research: The observations on Australia's program of CER/DER studies, trials and demonstrations as completed to date.[36]

[34] Refer Appendix B - Customer & Societal Expectations of Future Power Systems for more information.
[35] Refer Figure 44.
[36] Refer Section 5 of this report.

Indicative Rating System

Reflecting the above inputs, the rating system applied to highlight potential research priorities incorporates the following five elements:

Elements	Description	Rating Scale
Directional or/and Structural (DS)	Research Topics that directly influence the overall direction of strategic transformation or/and the core structural relationships that directly impact system scalability	0 – 10
Sequence (S)	Research Topics that are time critical or/and involve an extended development period.	0 - 5
Technical Complexity (TC)	Research Topics that involve comparatively high levels of technological complexity.	0 – 5
Stakeholder Complexity (SC)	Research Topics that involve comparatively high levels of stakeholder divergence of opinion.	0 – 5
Comparative Maturity Index (CMI)	The average of the three highest research ratings for each Research Topic.	1 – 7

Table 6 – Rating system to identify indicative research priorities

Potential Research Priorities

The following formula was developed to enable a common basis of illustrative comparison that incorporates the five elements above:

$$\text{Indicative Priority} = (DS + S + TC + SC) - (CMI^2)$$

The following charts provide a high-level comparison of the following to identify potential research priorities.

- Six Themes (T) by Indicative Research Priority (Section 6.4.2);
- Top 10 Domains (D) by Indicative Research Priority (Section 6.4.3);
- Top 20 Research Topics (RT) by Indicative Research Priority (Section 6.4.4); and,
- Research Topics (RT) by Theme (T) - Indicative Research Priorities (Section 6.4.5).

This content should be considered indicative and capable of providing general guidance only.

6.4.2 Six Themes (T) by Indicative Research Priority

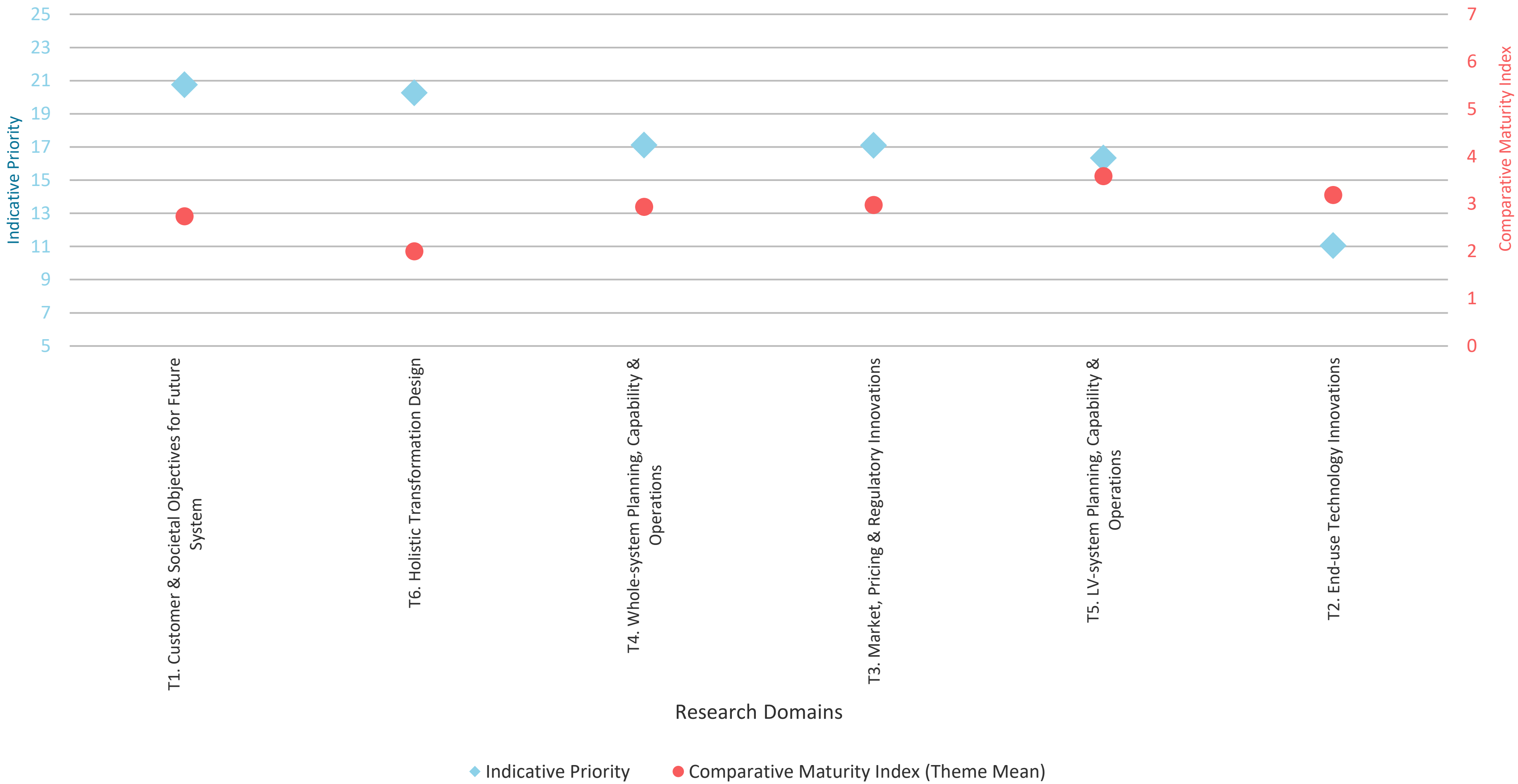


Figure 51 – High-level Comparison of 6 x Themes

6.4.3 Top 10 Domains (D) by Indicative Research Priority

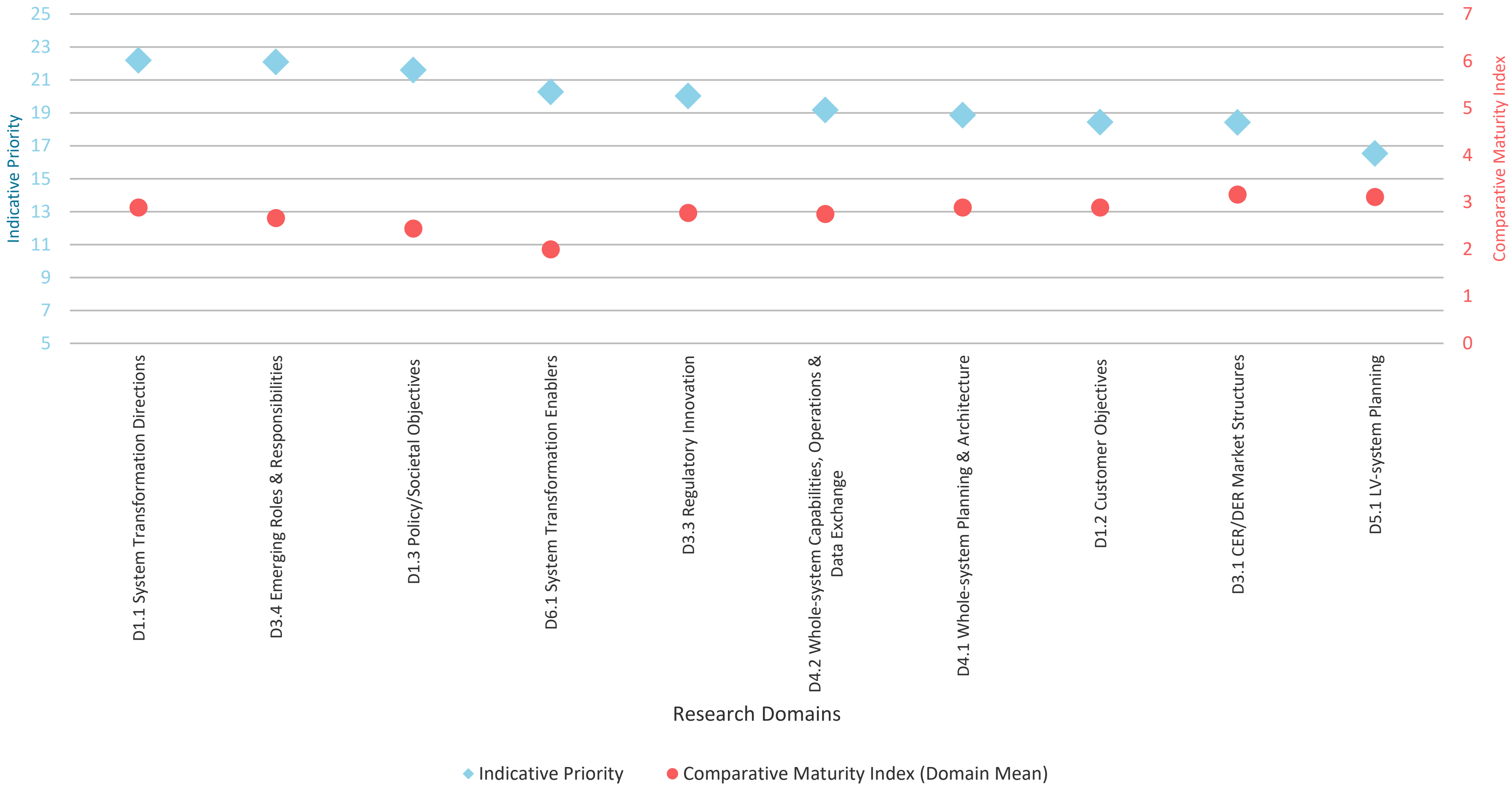


Figure 52 - Top 10 Domains (D) by Indicative Research Priority

6.4.4 Top 20 Research Topics (RT) by Indicative Research Priority

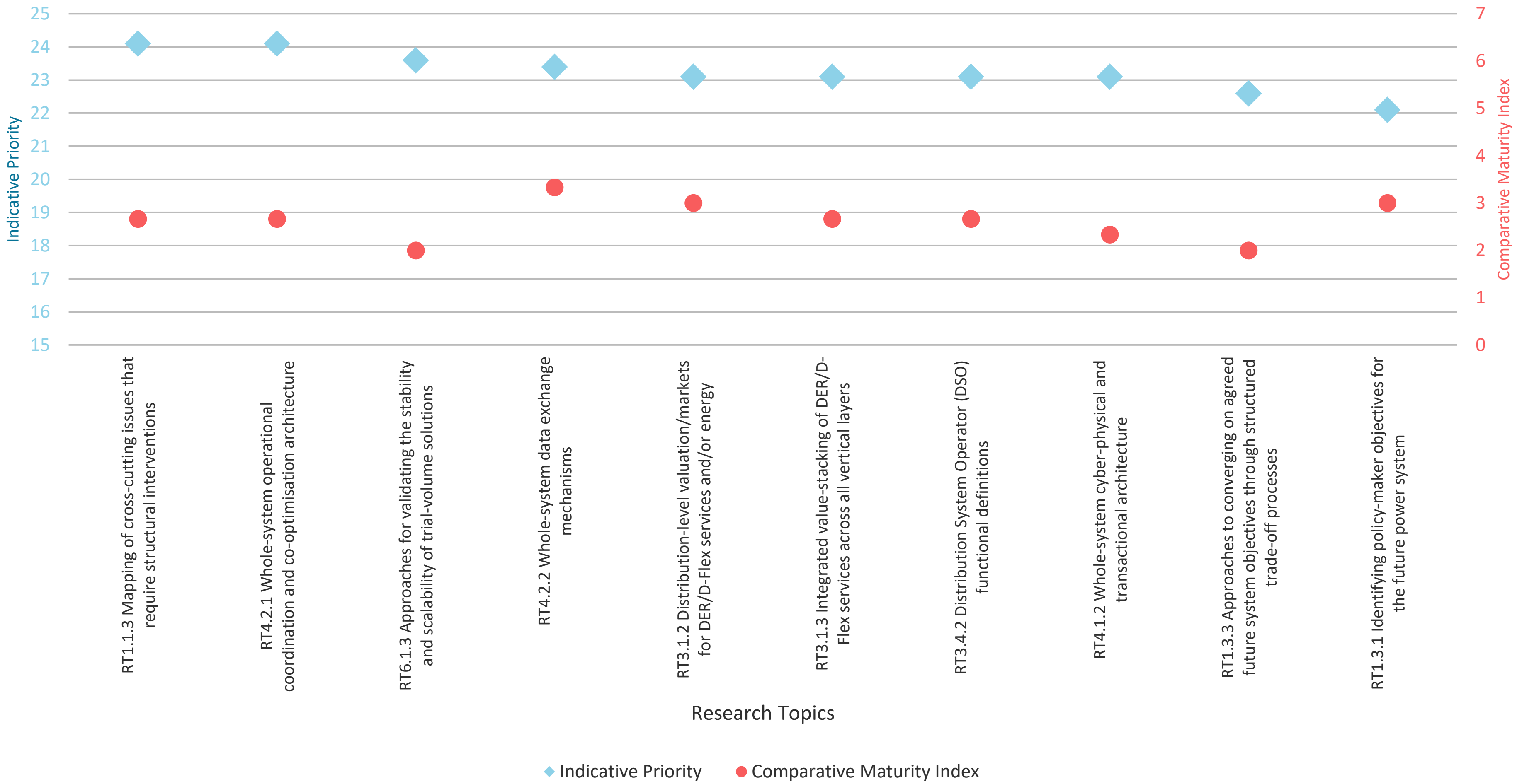


Figure 53 – Top 20 Research Topics by Indicative Research Priority (First 10)

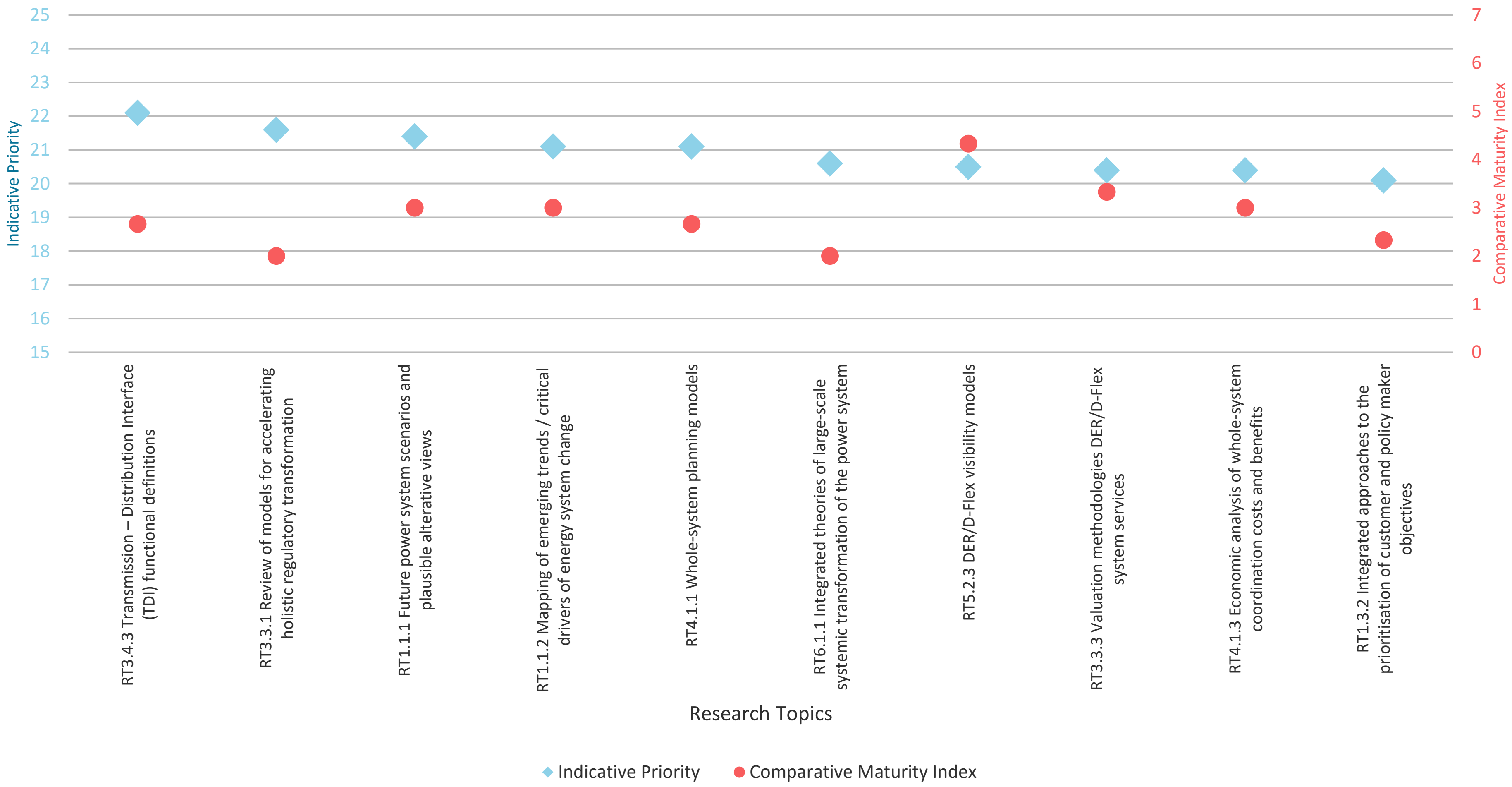


Figure 54 - Top 20 Research Topics by Indicative Research Priority (Next 10)

6.4.5 Research Topics (RT) by Theme (T) - Indicative Research Priorities

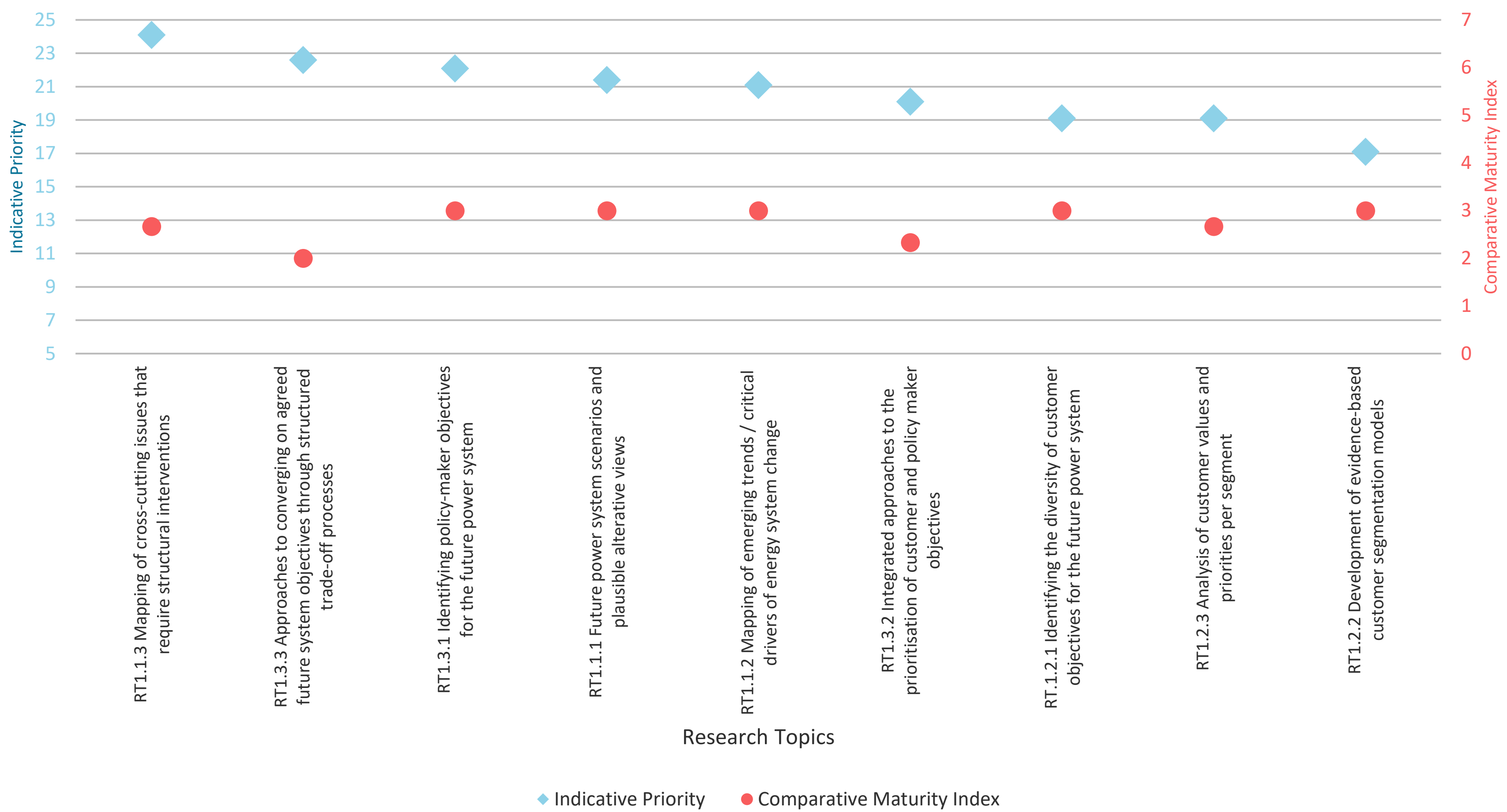


Figure 55 - Theme T1: Customer & Societal Objectives for Future System (Research Topics by Indicative Priority)

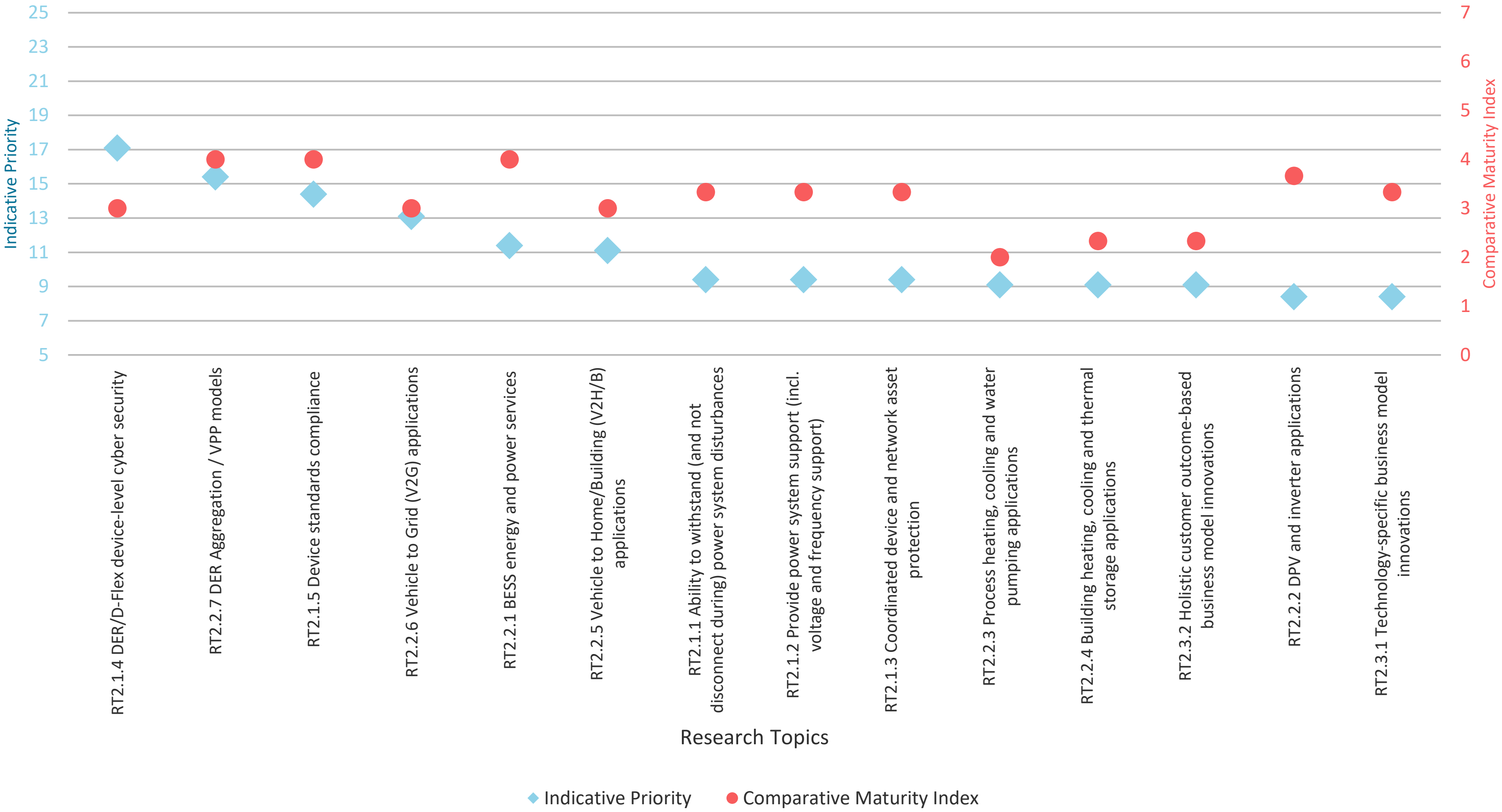


Figure 56 - Theme T2: End-use Solution Innovations (Research Topics by Indicative Priority)

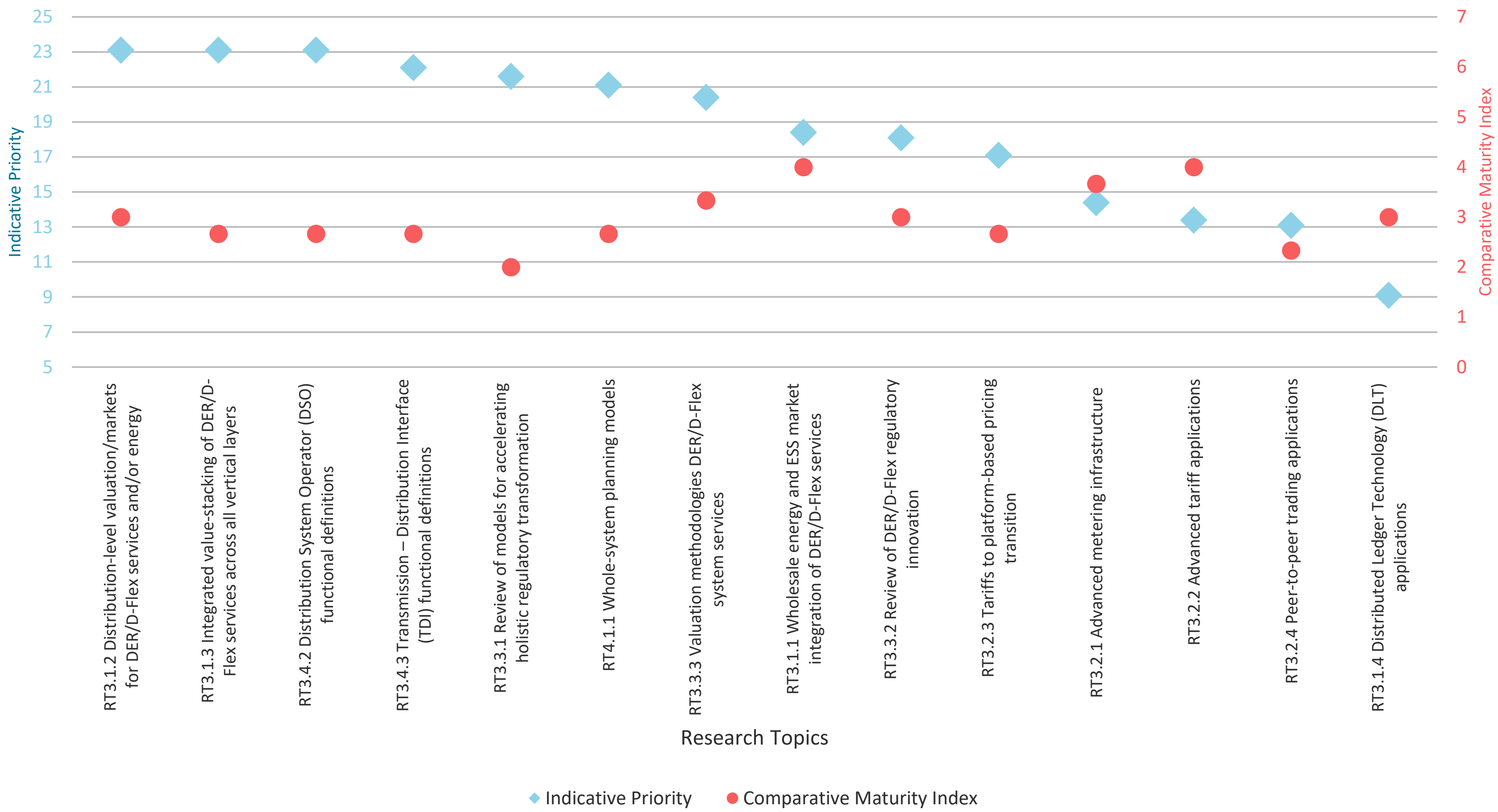


Figure 57 - Theme T3: Market, Pricing & Regulatory Innovations (Research Topics by Indicative Priority)

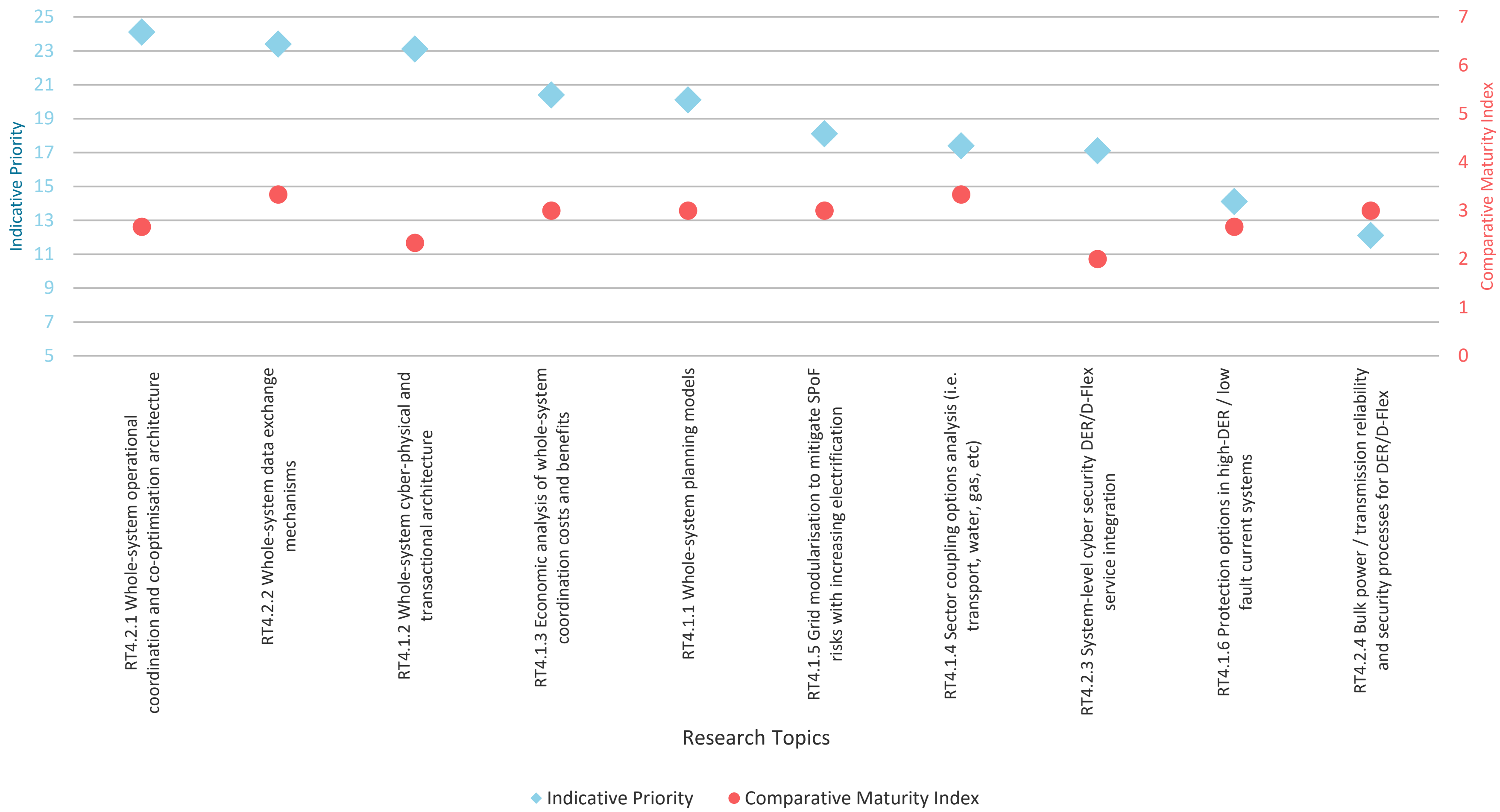


Figure 58 - Theme T4: Whole-system Planning, Capability & Operations (Research Topics by Indicative Priority)

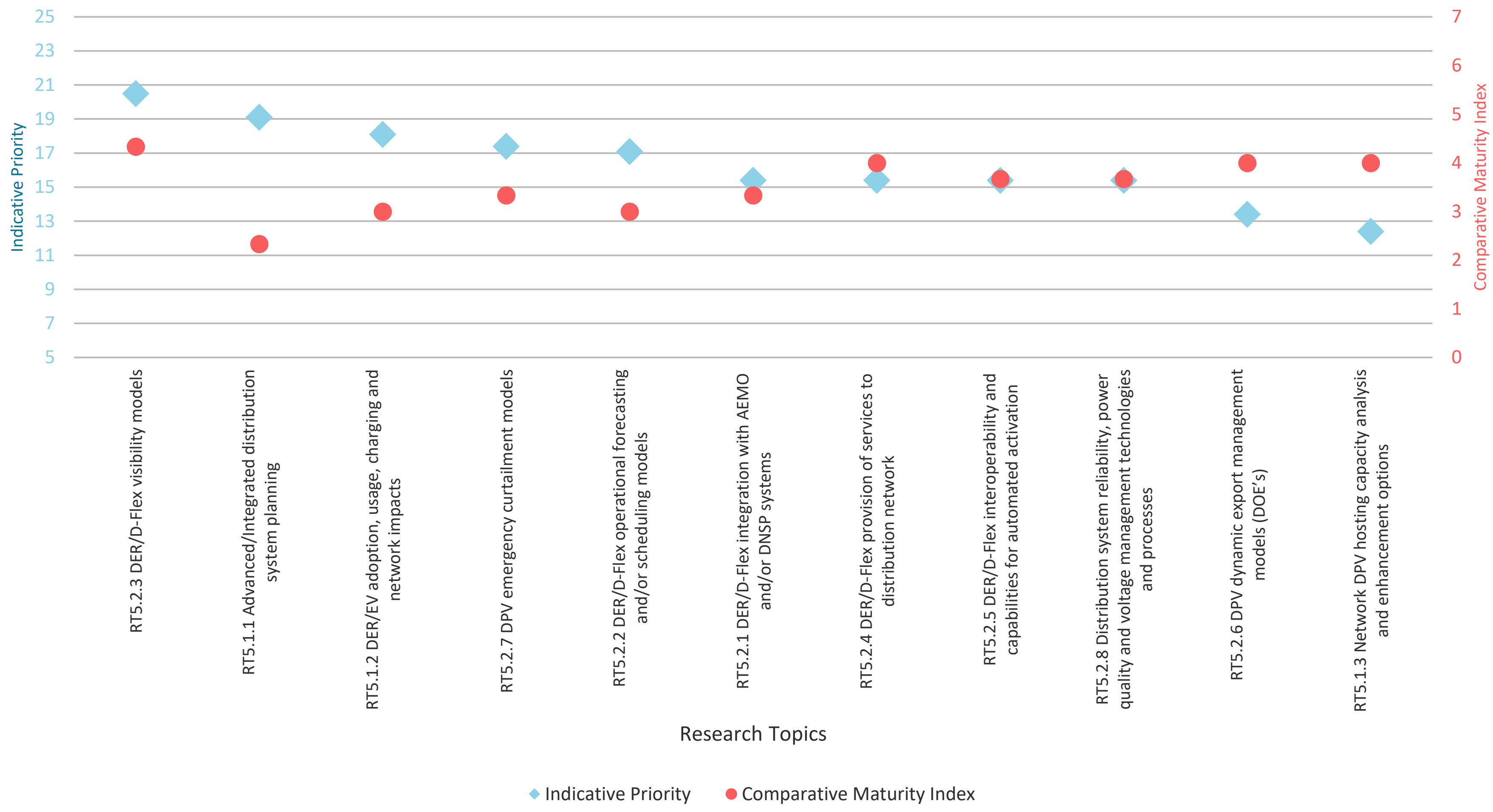


Figure 59 - Theme T5: LV-system Planning, Capability & Operations (Research Topics by Indicative Priority)

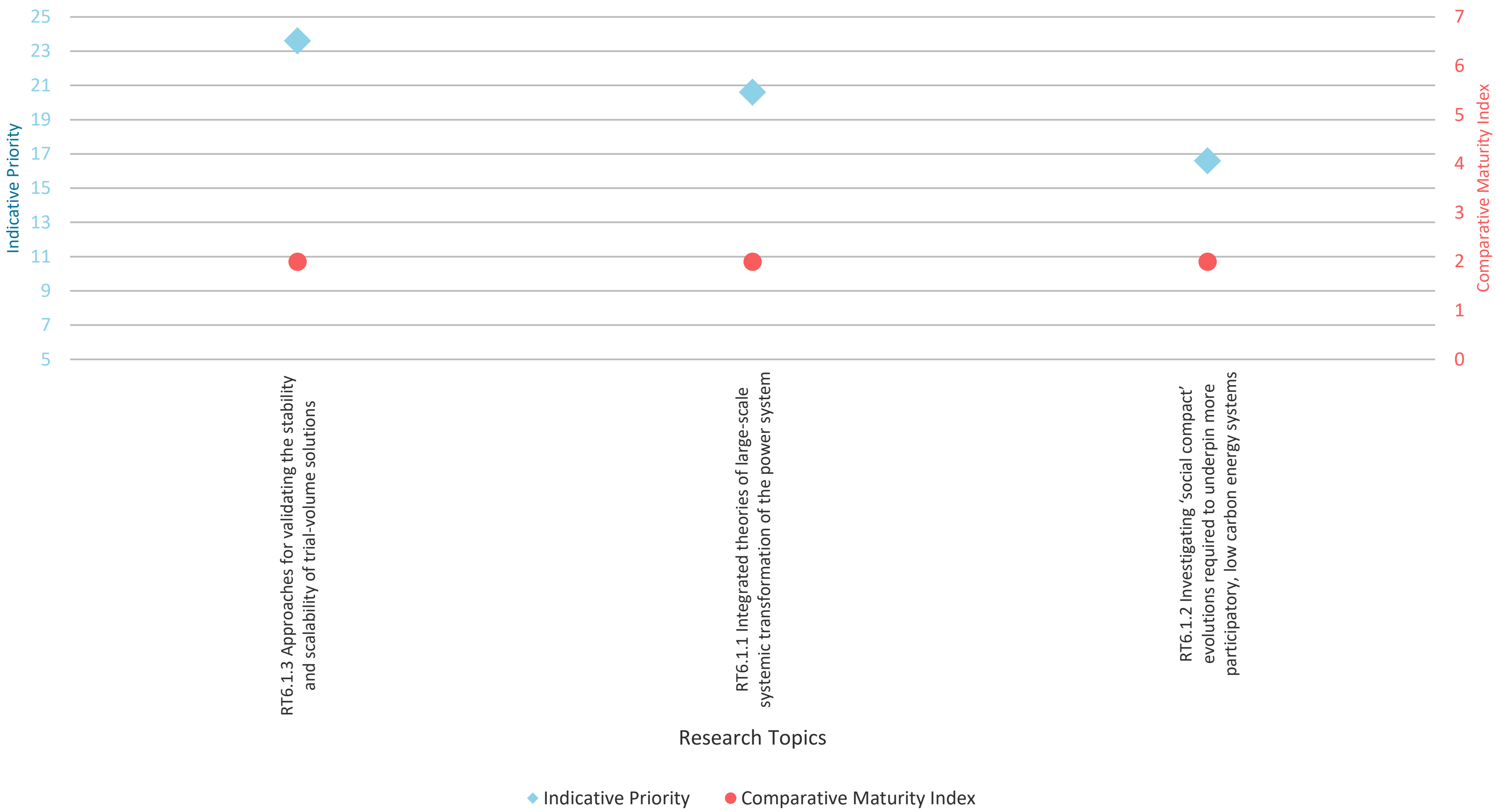


Figure 60 - Theme T6: Holistic Transformation Design (Research Topics by Indicative Priority)

7 Conclusion & Recommendations

7.1 Conclusion

Australian consumers are leading the world in their adoption of Distributed PV and other CER technologies, with the result that Australia's GW-scale power systems are becoming some of the world's most decentralised. Effectively unleashing the full potential of Australia's distributed energy revolution is estimated to be worth at least $20 – 30bn over the coming decades, and potentially up to $100bn.[37]

In this transformational context, Australia has undertaken an enormous volume of CER/DER-related research over recent years. Well over 200 research initiatives have been advanced, 182 of which have been examined in this study where sufficient information was available in the public domain.

Australia's CER/DER research initiatives have been undertaken either as individual projects that stand alone, or as programs of projects as with the relevant AEMO/ENA Open Energy Networks (OpEN) and the Energy Security Board initiatives.

Informed by the strategic objective of this report[38], and recognising the inherent limitations of such a wide-ranging review[39], the study found that Australia's first major phase of CER/DER research has:

1. Provided an ***extensive body of knowledge*** on foundational CER/DER technologies and enablers, with over 60% of all research focus being on distribution network capabilities, operations and end-use devices;

2. Been conducted largely ***within the historical segments*** of the legacy supply-chain and placed primary emphasis on the ***mitigation of negative operational impacts*** that may arise with the integration of CER/DER technologies;

3. Had limited focus on examining ***where*** Australia's power systems are heading in the medium to long term, ***what*** comprehensive range of functions CER/DER may serve to enable our future grids, and ***how*** these ultra-complex grids may be holistically transitioned to fully unleash this value with consumer benefits as a core objective;

4. Beyond the mitigation of potential negative impacts, not had the advantage of an ***authoritative, positive vision for CER/DER*** as a beneficial part of Australia's

[37] Refer Footnote 5

[38] Examine Australia's portfolio of CER/DER studies, trials and demonstration projects to map strategic and topical gaps that must be addressed to unleash the full potential of millions of distributed resources as an integral part of dynamic, efficient and self-balancing power systems.

[39] Refer Section 2.6 for more information

future power systems, nor a mandate for ***unlocking its full customer, societal and system value*** through a whole-system approach to integration;

5. Generally assumed and/or had no mandate to examine whether Australia's ***legacy structural and market arrangements*** are capable of scaling to Operationally Coordinate the extremely high levels of CER/DER envisaged by plausible future scenarios such as AEMO's Step Change scenario; and,

6. Been impeded by the *lack of a systems-based approach to CER/DER integration* and the ***deferral of several foundational matters*** key to the holistic integration of CER/DER, including Distribution System Operator (DSO) and Transmission-Distribution Interface (TDI) models, underpinning cyber-physical architectures, evolving functional roles, etc.

In summary, Australia's next phase of research would greatly benefit by moving from a historically quite atomised collection of different topics to a more systems-based program with a particular focus on unlocking the whole-system value of CER/DER for customers and society.

While recognising the above findings, it is also noted that initiatives such as Project EDGE, Project Symphony and Project Edith have made significant efforts to advance CER/DER research from a more whole-system perspective. These projects provide a legacy that should continue to be expanded upon.

7.2 Recommendations

Informed by this analysis, following are three proposed objectives for supporting Australia's transition to a holistic, systems-based program of CER/DER research. The proposed objectives are:

1. Aligned Vision and Enablement: CER/DER research efforts are closely aligned with, and seen as an integral and beneficial part of, transitioning Australia's GW-scale power systems to achieve emission reduction goals in a manner that is secure, cost-efficient and focused on the long-term interests of all consumers.

2. Maximum Societal Benefits Targeted: Research is undertaken as a balanced and holistic portfolio designed to unlock the full system value of CER/DER and informed by in-depth social and consumer research to ensure benefits for individual consumers and enhanced outcomes for society that align with consumer expectations.

3. Efficient and Accelerated Progress: CER/DER research projects, and related funding mechanisms, are configured to support efficient and accelerated progress by addressing critical gaps, reducing the potential for unintended duplication and leveraging collaborative, scale economies.

These three objectives provide a framework for twelve recommended actions which are set out in Table 7 below.

Proposed Objectives & Recommended Actions

Target Objective	Recommended Actions
1. **Aligned Vision and Enablement:** CER/DER research efforts are closely aligned with, and seen as an integral and beneficial part of, transitioning Australia's GW-scale power systems to achieve emission reduction goals in a manner that is secure, cost-efficient and focused on the long-term interests of all consumers.	1.1. **Representative working group.** Establish a representative working group to review and expand the national CER/DER research database, analytical framework/taxonomy and gap analyses through recurring annual cycles, giving priority to holistic consumer outcomes and directly informing policy and regulatory evolution.
	1.2. **Strategic vision and target outcomes.** Collaboratively develop a set of *Guiding Principles* and a positive *Whole-system Vision for CER/DER* to inform a more integrated next phase of research and transformative action, together with a *Balanced Scorecard of Outcomes* to be achieved.
	1.3. **Enabling system characteristics.** Collaboratively examine and document the future power system characteristics and capabilities needed to enable the *Whole-system Vision for CER/DER*, presented in a form that supports collaboration across the end-to-end power system and involves a diversity of existing and emerging stakeholder representatives.
2. **Target Maximum Societal Benefits:** Research is undertaken as a balanced and holistic portfolio designed to unlock the full system value of CER/DER and informed by in-depth social and consumer research to ensure benefits for individual consumers and enhanced outcomes for society that align with consumer expectations.	2.1. **Open research database.** Develop and maintain an open, searchable public database of all CER/DER studies, trials and demonstrations that may be reviewed by research proponents to ensure priority gaps are targeted and duplication of effort avoided.
	2.2. **Mapping of beneficial services.** Collaboratively examine and document the full set of beneficial physics-based services that CER/DER can provide across the vertical tiers/layers of our future power systems as the basis for monetising and incentivising mass consumer participation.
	2.3. **Enhanced research design.** Expand power sector capability for designing research informed by a coherent theory of change, multi-time horizon analyses and formal systems-based tools that ensure solutions are considered in their whole-system environment as it transforms over time.
	2.4. **Research priorities and collaboration.** Strengthen early-stage project conception and design processes that ensure priority gaps are targeted and collaboration with upstream and downstream actors occurs from research concept to completion.
	2.5. **Enhanced future resilience.** Enhance Australia's focus on the 'future-proofing' of CER/DER systems-integration by developing formal mechanisms to validate the mass-scalability of solutions, from trial volumes in the hundreds/thousands to mass-deployment in the millions/tens of millions.

Target Objective	Recommended Actions
3. Efficient and Accelerated Progress: CER/DER research projects, and related funding mechanisms, are configured to support efficient and accelerated progress by addressing critical gaps, reducing the potential for unintended duplication and leveraging collaborative, scale economies.	3.1. Leverage global research. Increase international CER/DER scanning and collaboration to identify where research in other countries addresses specific gaps in Australia's research portfolio.
	3.2. Utilise research infrastructures. Strengthen the overall pace and effectiveness of Australia's CER/DER research by leveraging standing research infrastructures (e.g. Cooperative Research Centres, CSIRO, National Collaborative Research Infrastructure Strategy investments, etc).
	3.3. Strategically coherent research. Enhance CER/DER research project detailed design by ensuring that formal planning, approval and funding mechanisms that explicitly address: • How the proposed research targets identified gaps and will enable whole-system outcomes; • How current and future consumer needs and priorities are a substantive focus, including in-depth social and consumer research; • The current status of relevant Australian and international research and the potential for leveraging existing research infrastructures; • How the solution(s) researched will interface/interoperate with both upstream and downstream actors now and in the future; • How solution(s) are designed for scalability and extensibility across current, medium and long-term time horizons; and, • How the mass-scalability of solution(s), beyond trial and demonstration volumes, will be validated to ensure maximum customer and whole-system benefits when deployed at scale.
	3.4. Strategically coherent research funding. CER/DER research grant and funding mechanisms are aligned with and reinforce the above processes to accelerate Australia's achievement of maximum customer and whole-system benefits.

Table 7 – Key objectives and recommended actions for enhancing Australia's next generational phase of CER/DER research.

APPENDIX A – Expanded Definitions & Key Concepts

The following expanded set of definitions and key concepts are derived from the Future Grid Accelerator resource.

Term	Definition
Active CER/DER	Consumer Energy Resources (CER/DER) capable of automatically altering their operating behaviour in response the needs of the wider power system. This may be in response to changes in the price of energy, the operating conditions of the local distribution network and/or upon receipt of instructions, control inputs or data feeds from authorised external entities. Active CER/DER are significantly more valuable to the power system than Passive CER/DER as they can provide specific Electric Products in a manner that is highly correlated with the time, location and physics-based needs of the power system.
Architecture	A holistic conceptual model that details how the many components of a system are linked together by its underpinning structures, enabling the whole system to function in a manner that achieves specific objectives. At its highest level, a Systems Architecture conveys the essence of the structural relationships, linkages and interdependencies between the components that enable them to function together. Simplistically, the boxes in a block diagram represent the many components and the architecture is represented by the lines that connect the boxes. A key purpose of a Systems Architecture is to make explicit, and enable collective reasoning about, how all the physical, informational, operational, and transactional components function together, and to reveal non-scalable legacy constraints. Although the system components are typically more visible, the underpinning structural relationships always have a disproportionate influence on the systems operational capabilities and constraints. Ensuring legacy structural relationships are capable of scaling to support very different future requirements is key to ensuring secure, reliable and cost-efficient operation at times of substantial transformation.

Architectural Issues	The application of Systems Architecture disciplines to inform the decarbonisation of electric power systems is important to avoid the propagation of the following structural issues that would otherwise negatively impact system security, reliability and economic efficiency: a) **Tier/Layer Bypassing:** The creation of information flows or coordination signals that 'leapfrog' a vertical Tier/Layer of the Power System's operational hierarchy. b) **Coordination Gapping:** An element of the Power System does not receive an explicit flow of coordination signals from any higher Tier/Layer of the system and therefore operates in isolation. c) **Hidden Coupling:** Two or more Entities with partial views of the system state issue simultaneous but conflicting coordination signals to CER/DER and/or other components of the Power System. d) **Latency Cascading:** Creation of compounding latencies in information flows due to the serial routing of data through various computational systems, processes and organisations. e) **Computational Time Walls:** Where excessive data volumes, latencies and processing 'bottlenecks' occur, optimisation engines will hit a computational 'time wall' at some point where no amount of computing resource will be adequate to solve the optimisation problems in a reasonable time. f) **Cybersecurity Structural Vulnerabilities:** Structural choices result in communication and routings that create non-cyber vulnerabilities to system penetration. g) **Back-end Integration Constraints:** Multiple vertical silo structures found in many supply-chain organisations drive significant back-end integration costs, anti-resilience and are anti-extensible due to the coupling of applications in which where failure in one can ripple through to degrade others.
Consumer Energy Resources (CER/DER)	A diverse range of small to medium scale energy resources that are located behind-the-meter at residential, commercial and industrial premises and are owned and operated by the customer. CER/DER are a multi-application resource that include the following types of technologies: a) **Distributed Generation (DG)**: including Distributed Photovoltaics (DPV) and embedded generators; b) **Battery Energy Storage Systems (BESS)**: including small and medium-scale batteries; c) **Electric Vehicles (EV)**; d) **Smart Inverters**; and, e) **Flexible Resources (Distributed)**.

	Active CER/DER can provide valuable Electric Products to the shared system, in exchange for some form of value or additional benefit, where they are highly correlated with the specific needs of the power system through Orchestration. The term Distributed Energy Resources (DER) is commonly used of these technologies where they connected directly to the distribution system (i.e. front-of-meter).
Consumption	The total electricity used over a duration of time, expressed as kilowatt hours (kWh), megawatt hours (MWh), gigawatt hours (GWh) and terawatt hours (TWh).
Co-optimisation	A structured approach to ensuring that Energy Resource services dispatched and/or financially incentivised in one vertical Tier/Layer of the Power System (e.g. Bulk Power, Transmission or Distribution) are not driving unintended negative consequences in other Tiers/Layers of the Power System.
Customers	The human individuals, families, organisations, institutions and whole societies served by the power system and that are the fundamental reason it exists. Customers may choose only to receive, consume and pay for services from the power system. They may also elect to provide services to the power system, in the form of valuable Electric Products consistent with technical requirements, in exchange for some form of value or additional benefit.
Cyber-physical	Tightly integrated computational and physical elements that create a close coupling between the virtual and physical. In cyber-physical systems, computer-based algorithms and capabilities are embedded in, and interact with physical processes, often in real or near real-time.
Decentralisation Ratio	The ratio of CER/DER capacity to total installed capacity.
Demand	The electricity needed at a point in time, expressed as kilowatts (kW), megawatts (MW), gigawatts (GW) and terawatts (TW).
Distributed Energy Resources (DER)	A diverse range of small to medium scale energy resources that are connected directly to the distribution system (i.e. front-of-meter). Refer to Consumer Energy Resources (CER/DER).
Distributed Data Sharing Infrastructure(s)	An arrangement for sharing data among multiple entities wherein each entity owns and controls its data and provides access on an authorised basis to others via a platform that federates or otherwise consolidates data in a logical fashion but not necessarily in a physically centralised data store.
Distributed Photovoltaics (DPV)	Solar photovoltaic panel installations connected to the distribution network. In many cases, these resources are located behind-the-meter at residential and commercial customer properties.

Distribution Market Mechanisms	A general term reflecting a spectrum of approaches and mechanisms to value, incentivise, procure and coordinate energy, flexibility and/or essential system services from distribution-connected CER/DER. In basic form, this may include tariff-based incentives and/or bilateral contracts. In more advanced forms, it may include Network Services Markets and/or Flexibility Markets that are co-optimised with conventional wholesale market mechanisms.
Distribution System Operator (DSO)	A future-oriented set of capabilities required in a high-CER/DER power system where distribution-connected resources provide a growing proportion of energy, power and related grid services. While there are a range of different visions of DSO evolution, somewhat analogous to the activities of a conventional Market/System Operator (MSO), key functions may include: a) **Real-time distribution system operations:** to support local supply and demand balancing, manage network constraints and provide enhanced visibility to the MSO at the relevant Transmission-Distribution Interfaces (TDI); b) **Distribution Market Mechanisms:** to value, incentivise, procure and coordinate the local provision of energy, capacity, flexibility and/or ancillary services from diverse DER when and where required by the system; and, c) **Integrated distribution system planning:** including scenario analyses of CER/DER and EV adoption rates, to ensure efficient network investments over various time horizons.
Electric Products	The valuable physics-based services that may be provided to the power system by CER/DER in exchange for some form of value or additional benefit. All beneficial grid services are derivatives of the following '3Rs': a) **Real Power:** measured in MW, is the instantaneous rate at which electrical energy is generated, transmitted or consumed; b) **Reactive Power:** measured in MVAR, sustains the electrical field in AC systems while maintain voltage within the limits specified for safe operation (source or sink); and, c) **Reserves:** measured in MW, represent contracted commitments to deliver or reduce real power (MW) or energy (MWh) at a point of time in the future.
Energy Resources	A universal term for all technologies that provide one or several of the Electric Products required by the Power System, and includes: a) Conventional Synchronous Generation; b) Utility-scale Variable Renewable Energy (VRE); c) Distributed Energy Resources (DER/CER); and, d) Various forms of Energy Storage and Firming Resources.
Flexible Resources – Distributed	Certain categories of CER/DER that can, in a reliable and firm manner, modify their operational behaviour in response to bulk power system, transmission

	network and/or local distribution network needs in a manner acceptable to the customer or owner/investor. Enabled by advanced approaches to Operational Coordination, large fleets of these resources can beneficially alter the demand profile of a feeder, substation, distribution network, transmission network and/or the bulk power system. Examples include various types of responsive loads such as water pumping, industrial process loads, battery charging, EV charging, heating loads, cooling loads, etc. (Note: The terms demand management, demand response, load shifting, controllable load and interruptible load are generally synonymous with this concept).
Interfaces	A point of interaction or boundary where different subsystems, components, or modules communicate and exchange information or energy. It defines the protocols, standards, and methods through which these interactions occur, ensuring compatibility and coordination among the interconnected parts of the system. Interfaces are crucial for the integration and functionality of complex systems, allowing diverse elements to work together effectively.
Interoperability	The capability of two or more systems, components or applications to share, transfer, and readily use energy, power, information and services securely and effectively with little or no inconvenience to the user. Future-ready approaches to Interoperability recognise that is has an intrinsic relationship to the underpinning Structure and Roles & Responsibilities of the wider system, both in their current state form and as they will plausibly need to evolve to enable an increasingly decarbonised future system.
Inverter	An electrical device which uses semiconductors to transfer power between a Direct Current (DC) source and an Alternating Current (AC) system.
Inverter-Based Resource	A diverse range of energy resources that, unlike many conventional resources, do not have moving components that rotate synchronised with the frequency of the power system. In contrast, resources such as wind turbines, solar photovoltaics (solar PV) and battery energy storage systems (BESS) are interfaced with the power system via power electronic converters known as inverters, which electronically replicate the standard operating frequency of the grid.
Market/System Operator (MSO)	An entity that combines the functions of the Market Operator and System Operator to ensure secure, reliable and efficient provision of electricity services with a primary focus on the bulk power system. At the highest level, this will include responsibility for: a) **System forecasting and planning:** to ensure resource adequacy over various time horizons; b) **Real-time system operation:** maintaining the instantaneous balancing of supply and demand; and,

	c) **Market operations**: to value, incentivise, procure and coordinate the provision of energy, capacity, flexibility and/or ancillary services.
Operability	The ability to operate the end-to-end power system in a manner that ensures system security and reliability. As power systems transition from a few hundred transmission-connected resources to many millions of VRE and CER/DER resources connected across the transmission and distribution systems, significantly more advanced and scalable forms of Operational Coordination become essential to Operability.
Operational Coordination	The systematic operational alignment of utility and non-utility assets, via technical control and/or financial incentives, to ensure system security, resource adequacy and economic efficiency over time windows from days to milliseconds. As the proportion of conventional synchronous generation declines, and growing levels of operational volatility are experienced due to variable renewable generation, scalable new models of coordination become essential. In the Australian context, this presents significant challenges as GW-scale power systems such as the NEM transition from hundreds to tens of millions of participating energy resources. Importantly, while legacy power systems often have entrenched structural demarcations, the Laws of Physics interact with them as singular, integrated systems. In a high-VRE / high-CER context, advanced Operational Coordination mechanisms will be required to enable bulk power, transmission and distribution systems – and the rapidly expanding fleet of distributed resources – to function together more dynamically and holistically as a self-balancing system. *The concept of Operational Coordination is integral to the topic of CER Orchestration.*
Orchestration	The coordination of dispatchable Energy Resources, including but not limited to CER/DER, in a manner that moderates negative system impacts and may include facilitating the provision of Electric Products to various Tiers/Layers of the Power System under a commercial arrangement. *Refer also to Operational Coordination.*
Passive CER/DER	Consumer Energy Resources (CER/DER) that operate only under the direction of their own internal control algorithms and cannot be remotely orchestrated by a third party such as an Aggregator or Distribution System Operator (DSO). Passive CER/DER are significantly less valuable to the power system than Active CER/DER due to their inability to alter their behaviour in response to significant operational conditions experienced by the wider system. As a result, where deployed at scale they will both impose operational inefficiencies and escalate Minimum Operational Demand risks to the reliability of the power system as a whole.

Power System	An essential system that, in the case of GW-scale grids, exists to provide safe, reliable, and efficient electricity services to millions of Customers. The supply chain of a conventional power system incorporates the Bulk Power System, Transmission Networks and Distribution Networks supported by the related Energy Retail functions. A GW-scale power system is best understood as a 'Super-system of Systems'.[40] This is because a modern grid consists of a complex web of seven distinct, inter-dependent structures as follows: a) **Electricity Infrastructure** (Power Flows); b) **Digital Infrastructure** (Information/Data Exchange, Storage and Processing); c) **Operational Coordination Structure**; d) **Transactional Structure**; e) **Industry / Market Structure**; f) **Governance / Regulatory Structure**; and, g) **Sector Coupling Structures** (Gas, Water, Transport, etc). Many of these cyber-physical-transactional structures are functionally interdependent, which means that changes to one structure will have both intended and unintended impacts on the function of other structures.
Reference Architecture	An integrated set of documents and diagrams that capture the essence of the structural relationships, linkages and interdependencies that enable the functioning of a complex system. The purpose of a Reference Architecture is to provide shared clarity on how the underpinning structures and relationships of a system are currently configured, including how they may need to change to enable future needs and stakeholder requirements. The development of a Reference Architecture functions as the first major phase of the Systems Architecture process. The process facilitates a shared understanding across multiple organisations and disciplines of the current and plausible alternative structural arrangements. Necessitating a level of abstraction, it reflects the qualities and intrinsic nature of the system rather than its full detail and provides a foundational step toward the subsequent Detailed Architecture and Detailed Engineering Design phases.
Scalability	A measure of the degree to which the underpinning Structure of a system is capable of accommodating significant increases in the number of components and endpoints without degrading system functions and/or requiring major modifications. In the context of a transforming power system, scalability represents a critical dimension of future-readiness.

[40] Refer to Appendix D – Power Systems as a 'Super-system of Systems'.

Smart Inverter	An advanced type of power inverter that converts direct current (DC) into alternating current (AC) while incorporating smart technology features. These features often include grid support functions, remote monitoring, real-time data communication, and the ability to adjust power output to optimize energy usage and efficiency. Smart inverters are commonly used in renewable energy systems, such as solar and wind power installations, to enhance grid stability and integrate seamlessly with smart grids and other modern energy management systems.
Strategic Foresight	A planning-oriented discipline related to futures studies and focused on informing and shaping strategic decision-making, guiding policy, or exploring new markets, products, and services. Strategic foresight combines methods from futures studies with those used in strategic management.
Structure	The stable relationships, linkages and interdependencies that are established between the components of a system to enable the reliable achievement of its purposes. Although the components of a system are easier to see, studying the underpinning structure of a complex system is vital as it always has a disproportionate impact on what the system can reliably do.
Supply-side	The upstream end of a conventional power system where almost all generation plant was traditionally located. More broadly, the term includes all parts of the power system upstream of the customer connection point, including the bulk power system, transmission networks and distribution networks.
Synchronous Generation	Generation plant which is directly connected to the power system and rotates in synchronism with the frequency of the grid.
System	A set of components that are formally related together by a shared Structure to achieve outcomes that exceed the sum of the individual components. As such, a System is not the sum of its parts, but the product of the interactions of those parts – a concept referred to as Emergence. Simplistically, if the boxes in a Block Diagram are the Components, then the Structure is represented by the lines that connect the boxes. Importantly, the underpinning Structure always has a disproportionate and irreducible influence on the essential limits of what a System can reliably and efficiently perform. Given this decisive impact on System performance, changing or enhancing any number of Components cannot ultimately compensate for a failure to address an underpinning Architecture that is no longer fit-for-purpose.

System Flexibility	The ability of the power system to respond to expected and unexpected changes in the supply-demand position, including generation plant failures, fluctuations in renewable generation output and variations in demand over all necessary timeframes. Historically, dispatchable conventional generation has provided system flexibility services. As the proportion of dispatchable synchronous generation declines, and growing levels of operational Volatility are experienced with the scale deployment of VRE and CER/DER, large volumes of flexibility services will need to be sourced from Flexible Resources (Distributed).
Systemic Issues	Cross-cutting conditions and/or structural settings that: a) Are currently embedded in a GW-scale Power System and/or will arise from the convergence of various emerging trends; and, b) Will require architectural interventions if the emerging Customer and Societal Objectives for the future Power System are to be enabled in a secure, cost-efficient, timely and scalable manner.
Systems Architecture	A formal element of Systems Engineering, which enables objective, collective reasoning about the underpinning Structure of a complex System, together with its components, interfaces, feedback loops and other behaviours.
Systems Engineering	An established engineering discipline applied in numerous sectors focused on the development and operation of ultra-complex systems including aerospace, military, manufacturing, energy and electronics sectors. While many engineering disciplines are oriented toward individual component technologies or sub-systems, Systems Engineering is a transdisciplinary approach that brings a holistic or 'whole-system' approach to the realisation of successful Systems which consistently satisfy the needs of their Customers, users and other stakeholders.
Systems Science	A multi-domain, integrative discipline that brings together research into all aspects of complex systems with a focus on identifying, exploring and understanding the universal patterns and behaviours of complexity and emergence.
Theory of Change	A structured framework that outlines the causal pathways through which interventions are expected to lead to desired outcomes. Collaboratively developing a theory of change helps key stakeholders interrogate how and why an approach to transformation is expected to work, and surface and constructively debate differences early. In a complex, multi-stakeholder context, this enables more efficient and effective interventions by making the assumptions underlying interventions explicit, identifying the necessary conditions for success, and describing the logical sequence of events that are expected to result in the intended changes.

Transmission-Distribution Interface (TDI)	The physical point(s) at which the upstream Bulk Power / Transmission System and a downstream Distribution System interconnect, typically at one or several major substations. In a conventional, highly bifurcated Power System, these were traditionally known as the Supply-side and Demand-side respectively. Power Systems that host growing volumes of VRE and CER/DER will experience significantly greater levels of Volatility which can propagate upstream and downstream in a somewhat 'tidal' manner. In this context, simultaneously ensuring system Adequacy, Security, Reliability and Cost-efficiency will require a much greater level of dynamic interdependence across the Transmission-Distribution Interface (TDI) than in the past.
Ultra-large Scale (ULS)	Extremely large, inordinately complex Systems that consist of an unparalleled volume and diversity of hardware and software, data storage and exchange, computational elements and lines of code, participants and stakeholders, together with multiple complicated Structures that are interconnected in complicated ways. A ULS System also typically exhibits the following characteristics: a) Wide geographic scales (continental to precinct); b) Wide-time scales (years to microseconds); c) Long-term evolution and near continual deployments; d) Centralised and decentralised data, control, and development; e) Wide diversity of perspectives on the purpose(s) and priorities of the System; f) Inherently conflicting diverse requirements and trade-offs; g) Heterogeneous, inconsistent, and changing elements; and, h) Locational failures and response occur as a matter of normal operations. GW-scale Power Systems are prime examples of ULS systems, and arguably some of the world's largest and most complex.
Value Stacking	The process of providing Electric Products to several vertical tiers/layers of the Power System (e.g. Bulk Power System, Transmission Network, Distribution Network, etc) for the purpose of maximising the simultaneous value of providing these services in manner that does not create unintended negative impacts. Value Stacking is closely related to the topic of Co-optimisation.
Variable Renewable Energy (VRE)	A generic term for intermittent forms of generation that are powered by renewable resources that are variable such as wind and solar energy. While it is technically correct to also refer to Distributed Photovoltaics (DPV) as VRE, the term is mostly used to describe large, utility-scale applications of solar and wind generation.

Visibility	The degree to which information on Energy Resource characteristics and operational information is available to the Market/System Operator (MSO), Distribution System Operator (DSO), and other authorised third parties. Examples include real-time or near real-time information on: a) the demand and supply of each Energy Resource; b) the state of charge for Energy Storage; and, c) the availability of flexibility of response from each Energy Resource; and, d) The voltage, frequency and power flows experienced on major network elements.
Volatility	The propensity of rapid and/or unpredictable change, especially in a manner that is unfavourable and difficult to manage. Power systems served by growing levels of VRE and CER/DER experience significant growth in operational Volatility. This must be actively managed to ensure system security.
Whole-system	A systems-based approach to power system transformation that recognises the Laws of Physics interact with end-to-end system as one integrated whole, blind to historical structural separations.

Table 8 – Expanded set of key concepts and definitions

APPENDIX B – Customer & Societal Expectations of Future Power Systems

Power Systems are complex techno-economic systems that have a critical societal role. Given the many essential functions they perform in a modern economy – and the growing potential for customer participation – any consideration of future options must be informed by what customers and policy makers are expecting of their future Power Systems.

Research conducted for Australia's contribution to the Global Power System Transformation (GPST) initiative[41], funded by CSIRO, has examined the diversity of customer and societal expectations of future Power Systems as expressed in the Australian and global literature.

Figure 61 - Eight customer and societal expectations for future Power Systems

The eight key objectives above emerged from the literature. Like society itself, a complex set of relationships exists between the various expectations, several of which will impact other objectives. As such, the practical application of the various objectives would require a process of societal prioritisation and trade-offs.

[41] For more information refer to: G-PST Stage 2 – Topic 7: Power Systems Architecture, CSIRO, 2023

In summary, customers and policy makers variously state that they expect future power systems to be:

1. DEPENDABLE: Safe, secure, adequate, reliable and resilient;
2. AFFORDABLE: Efficient and cost-effective;
3. SUSTAINABLE: Enables 2030 and 2050 decarbonisation goals;
4. EQUITABLE: Broad accessibility of benefits and the fair sharing of costs;
5. EMPOWERING: Advances customer and community agency, optionality, and customisation;
6. EXPANDABLE: Enables electrification of transport, building services and industrial processes;
7. ADAPTABLE: Flexible and adaptive to change, including technological, regulatory and business model innovation; and,
8. BENEFICIAL: Socially trusted, public good/benefits, commercially investable and financeable.

The above expectations provide an overview of the key traits that future power systems would, to varying degrees, need to exhibit to satisfy customers and policy makers, and which therefore should inform and guide CER/DER planning and design decisions.

APPENDIX C – Structural Shifts Relevant to Whole-system CER/DER Integration

Erosion of a Defining Paradigm

Australia's GW-scale Power Systems developed over the last century around a 'Supply-side / Demand-side' bifurcation which has been one of the most dominant operational paradigms of the electric sector. In its historical context, this paradigm served Australia well based on the following assumptions:

- A 'Supply-side' of the system which consisted of a fleet of centralised MW-scale generators connected to the HV transmission system;
- A 'Demand-side' of the system where the vast majority of customers were connected to the LV distribution systems and consumers of energy (i.e., not producers);
- Unidirectional bulk power flow from the 'Supply-side' to the 'Demand-side';
- Almost all Essential System Services were provided by the fleet of dispatchable, synchronous, supply-side generators; and,
- Dispatch of centralised generation was based on a 'Load-following' model where customer demand was considered the primary independent variable and generation ramped up or down in line with it.

The transformational forces discussed earlier, however, are reshaping global electric systems. The significance of the erosion of this paradigm, which played a pivotal role in shaping the legacy Power Systems' underpinning Architecture cannot be overstated. As AEMO has noted:

> *"As penetrations of passive DPV continue to increase and become significant at the regional level, the aggregated impact affects almost all core duties of the bulk system operator in some way..."*[42]

This is especially the case in Australia due to our world-leading scale and pace of Distributed PV (DPV) adoption by customers. While our distribution systems remain the location of major load centres, they are transforming to host an ever-expanding fleet of CER/DER, including Electric Vehicles (EV). Although its visible effects are emerging gradually, the overall trajectory involves one of the most profound changes in a century of grid operations.

Two Emerging Bifurcations

It is noteworthy that mass adoption of CER/DER and EVs in Australia is largely customer-driven and agnostic to traditional bulk power, transmission, and distribution system boundaries and planning conventions. In addition, the erosion of this structurally influential paradigm is occurring

[42] Renewable Integration Study Stage 1 Appendix A: High Penetrations of Distributed Solar PV, AEMO, 2020

in parallel with the emergence of two new bifurcations of Energy Resources into new locational and functional categories as follows:

1. Energy Resources are bifurcating into two locational classes.

Firstly, Australia's fleet of Energy Resources is bifurcating into two major locational classes: Centralised and Decentralised. This involves an historically unprecedented shift:

- From a past where over 95% of Australia's generation fleet was concentrated at one extremity of the Power System (HV-connected);
- To a fast-emerging future where the generation fleet is bifurcated across two opposite extremities of the Power System. Under AEMO's widely accepted 2050 Step Change scenario, this will involve:
    - A progressive narrowing of the differential between HV-connected generation capacity in comparison to the volume that is LV-connected;
    - Significant regions of NEM increasingly needing to be capable of operating reliably during periods where 100% of instantaneous demand is met by Variable Renewable Energy (VRE) sources, both HV-connected and LV-connected;
    - Several regions experiencing periods where 100% of instantaneous demand is met by LV-connected DPV, especially at solar zenith on days experiencing low levels of demand;
    - At other times, such as during the night, due to the somewhat 'tidal' characteristics of high-VRE / high-CER/DER systems, these same regions must be capable of largely depending on utility-scale wind generation and other centralised Energy Resources; and,
    - Over time, power systems must be provisioned to operate reliably for increasing durations of time where 100% of instantaneous demand is met by VRE, whether centralised, decentralised or a combination of both.

Such changes are not peripheral. They are structural in character and drastically impact the physics-based Operability of any GW-scale Power System. Therefore, it simply may not be safely assumed that the underpinning System Architecture developed around a fixed 'Supply-side / Demand-side' paradigm, will be sufficiently Scalable or Extensible to accommodate such a level of transformative change.

2. Energy Resources are bifurcating into two primary functional/investment classes.

Secondly, Australia's fleet of Energy Resources is bifurcating into two primary functional/investment classes: Merchant and Private. This involves another historically unprecedented shift:

- From a past where the generation fleet was largely merchant resources installed for the primary or singular purpose of providing energy and services to the relevant markets; and,

- To a future where the proportion of private, customer-owned generation, storage and flexible capacity – as compared with traditional merchant resources – is trending upward.

Many of these customer-owned CER and EVs have under-utilised capacity and capabilities that would be of value for providing Electric Products to the wider Power System. However, as they were not primarily deployed as merchant resources, Australia risks a massive duplication of capital investment where this underutilised capacity is not efficiently and equitably unlocked.

Being installed primarily for customer purposes, however, the large-scale sourcing of this underutilised capacity will involve:

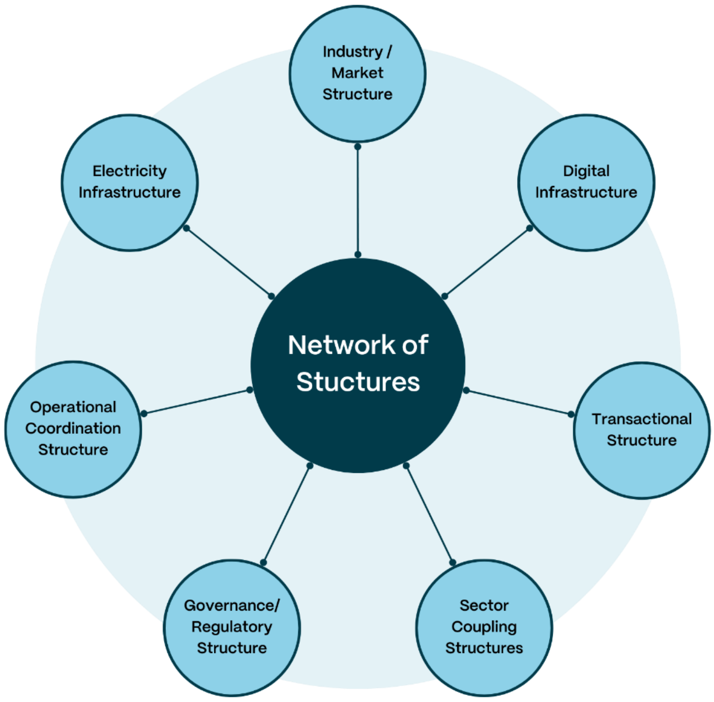
- Significantly different motivational dynamics and engagement approaches.
- New incentive, procurement and remuneration models that are:
  - Capable of reflecting the dynamically changing temporal and spatial value of different Electric Products at much higher resolution than traditional tariff models; and,
  - Supported by advanced automation to ensure the customer experience is seamless, effortless, and consistent with contract conditions approved by the customer.
- Advanced forms of Visibility and Operational Coordination to ensure the right physics-based services are dynamically procured when and where they are required by the wider power system.

APPENDIX D – Power Systems as a 'Super-system' of Structures[43]

GW-scale Power Systems consist of a complex web of the following seven inter-dependent structures:

1. Electricity Infrastructure (Power Flows);
2. Digital Infrastructure (Information/Data Exchange, Storage and Processing);
3. Operational Coordination Structure;
4. Transactional Structure;
5. Industry / Market Structure;
6. Regulatory Structure; and,
7. Sector Coupling Structures (Gas, Water, Transport, etc).

This 'Network of Structures' spans the vertical tiers/layers of the power system, impact multiple system actors (e.g., bulk power, transmission and distribution systems, energy retailers, aggregators, customers, etc.) and must be transitioned holistically. Importantly, they provide the underlying 'DNA' of each power system and are directly involved in the systemic integration of CER/DER.



[43] For more information refer to: G-PST Stage 2 – Topic 7: Power Systems Architecture, CSIRO, 2023

Figure 62 - Modern power systems are a 'Super-system' of interdependent structures[44]

The seven inter-dependent structures that make up the Network of Structures are now described in more detail below.

1. Electricity Infrastructure (Power Flows)

Infrastructures and subsystems that provide for the generation and physical movement of Electricity across the end-to-end Power System, including Generation Plant, Transmission Networks, Distribution Networks, Substations, Embedded Networks, Microgrids and diverse Energy Resources.

While historically designed for unidirectional operational, today Electricity Infrastructure increasingly experiences bi-directional Power Flows, especially in the Distribution Networks. A sample of conventional and emerging examples include:

a) Power Flows from the Bulk Power System through the Transmission Networks to Bulk Supply Points (BSP).

b) Power flows from BSP through Distribution Networks to Connection Points for each Customer.

c) Storage of excess Renewable Energy output for subsequent injection to the Power System at periods of Peak Demand.

d) Customer-owned Distributed Photovoltaics (DPV) and Battery Energy Storage Systems (BESS) that provide Power to their own Loads and/or exports to the local Distribution Network.

2. Digital Infrastructure (Information/Data Exchange, Storage, and Processing)

Infrastructures and subsystems that provide for all information and data exchange required to maintain the safe and reliable operation of the Power System and underpin its coordinated operation. A sample of conventional and emerging examples include:

a) Signals and data used for real-time control of the Power System such as State Estimation, Frequency monitoring, Topology configuration monitoring, etc.

b) Energy Resources participating in the Wholesale Market submit real-time asset performance reports to the Market/System Operator (MSO).

c) MSO and Distribution System Operators (DSO) exchange system condition information across the relevant Transmission-Distribution Interface (TDI) to support the conjoint Power System management.

[44] Image: Adapted from Pacific Northwest National Laboratory, United States

d) Energy Retailers and Aggregators participating in the Wholesale Market and Distribution-level Markets submit telemetry to the relevant entities to indicate asset performance in real-time.

3. Transactional Structure

Infrastructures and Subsystems that provide for the valuation, procurement, sale and measurement of Energy, Capacity and Essential System Services (ESS) at any Tier/Layer of the Power System through market or other financial arrangements. This may include participation in Wholesale Market, Distribution-level Markets, advanced Tariffs/Rates. This also includes market schedules and Dispatch instructions.

A sample of conventional and emerging examples include:

a) Energy Resources participating in the Wholesale Market provide bids/offers to the Market/System Operator (MSO) who subsequently schedules the Dispatch of participating resources.

b) Relevant to the Operational Coordination of the Power System, both the legacy and emerging market structures are calibrated to ensure Co-optimisation of Energy Resource behaviours across the different Tiers/Layers of the system.

c) Energy Retailers and Aggregators procure and contract services from Distributed Energy Resources (DER/CER) and other Flexible Resources (Demand-side) and sell them in various Wholesale Markets and/or Distribution-level Markets.

d) Support more granular 'market-control' alignment to incentivise and activate targeted provision of valuable services in the form of Electric Products when and where most needed.

4. Operational Coordination Structure

Infrastructures and Subsystems that support the systematic operational alignment of both Utility and non-Utility assets as Power Systems move from hundreds to tens of millions of participating Energy Resources. In an operational context characterised by greater Volatility, advanced Operational Coordination is essential for safe, secure and efficient Power System operation in a manner that has a high level of Resilience, Scalability and Extensibility.

A sample of conventional and emerging examples include:

a) Market/System Operator (MSO) exerts control over Energy Resources participating in the Wholesale Market by sending Dispatch instructions and basepoints to secure necessary services.

b) MSO exerts control over the Transmission Network in response to a constraint or contingency to preserve System Security and Reliability.

c) Aggregators provide the MSO and Distribution System Operator (DSO) resource availability forecasts for Energy Resources.

d) The MSO and DSO conjointly manage their respective sides of the Transmission-Distribution Interfaces (TDI) due to the growing dependence on Energy Resources located on both sides of the TDI.

e) Aggregators orchestrate contracted CER/DER in response to the various market structures for procuring the Electric Products required by different Tiers/Layers of the system.

Advanced Operational Coordination models are ultimately required to enable the transition to a more holistic Transmission-Distribution-Customer (TDC) model of system coordination.

5. Industry / Market Structure

The range of Entities involved in operating an end-to-end Power System, across its vertical Tiers/Layers and various markets, and within the boundaries of their formal Roles and Responsibilities, as set out in the legal and regulatory arrangements of a specific jurisdiction. Some examples of these Entities include:

a) Market/System Operator (MSO);

b) Generators;

c) Transmission Network providers;

d) Distribution Network providers;

e) Distribution System Operators (DSO);

f) Energy Retailers; and,

g) Aggregators.

6. Governance / Regulatory Structure

The range of Entities involved in the governance and regulation of an end-to-end Power System and its related markets, as set out in the legal arrangements of a specific jurisdiction. In Power Systems Architecture, this structure focuses on the mapping of various governance and regulatory relationships, with an emphasis on which Entity regulates which types of organisations as represented in the Industry / Market Structure. These may include:

a) Federal governments and agencies;

b) Federal regulatory bodies;

c) State governments and agencies;

d) State regulatory bodies; and,

e) Trans-national bodies.

7. Sector Coupling Structures

As decarbonisation advances, the proactive management of Interfaces between the Power System and other sectors becomes an increasingly critical part of enabling a more flexible and adaptive Grid. Examples of various sector couplings include:

a) Electricity and gas sectors;

b) Electricity and industrial processes;

c) Electricity and transport;

d) Electricity and building services;

e) Electricity and water systems;

f) Power system and ICT technologies; and,

g) Electricity and the emerging Green Hydrogen sector.

APPENDIX E – The Digital Architecture & Power Systems Architecture Relationship

When considering technological systems, the term 'architecture' can be used in several different ways. This can reduce the accuracy of communication between stakeholders, particularly in sectors that less mature in the adoption of Systems Engineering practices. In the global power sector, this has sometimes resulted in an unhelpful confusion of terms, lower quality decisions and unnecessary impediments to timely decision making.

A common mistake is that a focus on 'digital architecture' is the primary or singular focus of architectural disciplines when applied to Power System transformation. While digital architecture is indeed vital, it is one of seven overlaid structures that constitute the Architecture of a modern Power System, as illustrated in Figure 62 above. This is critical to the holistic consideration of transformation options as all seven structures have a significant influence on each other, four of which are dynamically inter-dependent on a hours-to-milliseconds basis (i.e. electricity infrastructure, operational coordination structure and transactional structure).

A closely related error is an assumption that the more generally known concept of Enterprise IT Architecture is broadly the same as Power System Architecture. As such, the following table provides a practical illustration of both the similarities and key differences that must be appreciated to enhance clarity of communication and quality of decision making in an inherently complex area.

Area of Comparison	Power Systems Architecture	Enterprise IT Architecture
Target System	GW-scale Power Systems	Enterprise IT systems
Focus/Scope	Employs the Network of Structures model to interrogate the seven structures spanning an end-to-end Power System and across its vertical Tiers/Layers. This enables holistic, structured consideration of current, transitionary and future states and the targeted structural interventions required to move from one to the other.	Focuses on Digital Infrastructure at enterprise level. For enterprises operating within the power sector, this will likely include consideration of interfaces between the Enterprise IT Architecture and the wider Power Systems Architecture.
Complexity & Risk	Industry Level: Ultra-Large-Scale (ULS) Complexity. Helps manage risk within and across the end-to-end Power System.	Enterprise Level: Large Scale Complexity. Helps manage risk within the enterprise.

Stakeholders	Diverse stakeholders including policy makers, regulators, industry, customer groups, environmental groups, etc.	Internal enterprise stakeholders, and generally reporting to CIO. Primarily reflects focus on corporate IT systems.
Motivation	Power Systems Architecture is focused on clearly identifying specific Power System challenges and opportunities that require structural interventions to resolve. Defines essential industry limits/constraints.	Focused on the various challenges and opportunities that an enterprise must address internally.
Requirements	Defines qualities and properties of the future end-to-end Power System based on a broad range of societal and stakeholder perspectives.	Defines business requirements primarily from the perspective of enterprise stakeholders only.
Current State	Employs the Network of Structures model to interrogate and map the 'as built' Power System structures and the relationships across: • Electricity Infrastructure (Power Flows); • Digital Infrastructure (Information/Data Exchange, Storage & Processing); • Operational Coordination Structure; • Transactional Structure; • Industry / Market Structure; • Governance / Regulatory Structure; and, • Sector Coupling Structures (Gas, Water, Transport, etc).	Defines the current state of the enterprise: • Strategic enterprise objectives mapped to capabilities; • Enterprise principles; • Business Architecture; • Information System Architecture; and, • Technology Architecture.
Target Future State	Supports the collaborative development of a future vision for the Power System and employs the Network of Structures model to interrogate and map the most credible enabling structural interventions to achieve the vision across: • Electricity Infrastructure (Power Flows);	Defines target state of the enterprise: • Strategic enterprise objectives mapped to capabilities; • Enterprise principles; • Business Architecture; • Information System Architecture; and, • Technology Architecture.

	• Digital Infrastructure (Information/Data Exchange, Storage & Processing); • Operational Coordination Structure; • Transactional Structure; • Industry / Market Structure; • Governance / Regulatory Structure; and, • Sector Coupling Structures (Gas, Water, Transport, etc).	
Transition Planning	Provides a framework underpinning the progressive transition of a GW-scale Power System from its historical current state to the desired future state.	Develop enterprise roadmap to move from current state to target future state.

Table 9 – Comparison of Power Systems Architecture and Enterprise IT Architecture[45]

[45] Content adapted from work undertaken by Eamonn McCormick and Stuart McCafferty