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Systems Engineering of the Energy System

PMC SEES Vision and Research Outlook

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1 Management Summary

The Dutch energy transition is entering an important next phase. Achieving a climate-neutral, resilient, and future-proof energy system by 2050 will require a significant acceleration in the development, integration, and operation of energy infrastructure. The sector is confronted with major challenges: rapidly increasing electricity demand, the electrification of industry and homes, the integration of renewable energy sources, limited public space, complex permitting processes, and a persistent shortage of skilled personnel. These issues are further intensified by the growing complexity and interdependencies of energy systems, the need for cross-sectoral integration, and the ongoing societal and political expectations for reliability, affordability, and sustainability: expectations that must still be met in an increasingly complex environment.

Systems Engineering (SE) is essential to mastering this complexity and accelerating the energy transition [1] [2]. The SEES (Systems Engineering of the Energy System) program, as outlined in this vision document, provides a coordinated, systems engineering-driven approach to address the sector's most pressing engineering needs. The program's mission is to foster excellence in systems engineering across the energy sector, enabling organizations to design, integrate, and deploy complex systems with confidence and agility.

The key needs and challenges addressed in this vision are the following:

1. **Accelerate energy infrastructure delivery** through modularization, standardization, and digitalization for faster, smarter, and more reliable project execution.
2. **Enhancing energy systems flexibility and increasing utilization** by providing advanced systems engineering practises for embedding digital and modular architectures and systems that support realization of dynamic and energy solutions.
3. **Foster cross-sector collaboration** to manage complexity and align technical, business, and societal objectives.
4. **Embed security and resilience** throughout the energy system lifecycle, ensuring robust and adaptive energy systems in a dynamic environment.
5. **Advance digital systems engineering** by adopting model-based, data-driven methods and interoperable digital tools, enabling efficient design, integration, and lifecycle management across the sector.
6. **Develop future competencies** by investing in systems engineering skills, digital fluency, and continuous learning.

Strengthening systems engineering, including digital systems engineering, is critical for the Dutch energy sector to deliver on the ambitions of the energy transition. By adopting advanced SE practices, stakeholders can accelerate innovation, manage complexity, and ensure that future energy systems are reliable, affordable, and sustainable.

Contents

2 Introduction

2.1 Purpose of this document

The purpose of this document is to define a vision plan for i) alignment on future Systems Engineering methodology improvement activities for the energy sector, and ii) for managing the Digital Transition Energy Systems (DTES) program.

The Digital Transition Energy Systems (DTES) program operates at the intersection of two major societal transitions: the energy transition and the digital transition of energy systems. The Dutch energy sector faces urgent challenges, such as grid congestion, energy transport capacity shortages, and the need for rapid decarbonization with renewable energy sources. Digitalization is recognized as a key enabler for transforming energy system operation, planning, and integration. DTES addresses these challenges by fostering systems engineering and systems-thinking methodologies, which are essential for managing the complexity of modern, cyber-physical energy systems. The program aligns closely with national strategies and agendas, including the National Energy System Plan [3] and the Action Agenda Digitalization of the Energy System [4], and collaborates with stakeholders across industry, government, and academia to drive innovation and accelerate the energy transition.

2.2 Overview of PMCs in the DTES program

DTES has established PMC (Product-Market Combination) teams to maximize the impact of embedding world-leading methodologies in the energy sector. Starting from the needs of the sector, PMC teams will i) develop a vision on trends and developments in systems engineering for the energy sector ecosystem, ii) identify and execute opportunities and formats for collaboration with the sector, and iii) manage the program – from ideation to embedding to scale-up.

The DTES program has defined two PMC teams as follows:

- **PMC team Digital Energy System Operations (DESO).** This PMC focusses on embedding leading-edge methodologies for smart and efficient development, operations, and life-cycle management realizing energy systems future-proof, interoperable, and functional in a standardized way with emphasis on obtaining grid and flexibility insights on an operational level, engineering digitalization for the flexibility chain, and ensuring energy system resilience.
- **PMC team Systems Engineering of the Energy System (SEES).** This PMC focusses on developing and providing the necessary methodologies and skills to master the complexity of, and successfully engineer and realize, digitalization in the energy domain at sub-system and system level. It, among others, explores how, and to what extent, methodologies developed for the high-tech systems domain can be applied to the complexity challenges in the energy domain and how they must be altered and adapted to be useful and effective.

The DTES program expects these PMCs to be mostly complementary. The SEES PMC team will predominantly focus on systems engineering methods and topics for transdisciplinary engineering challenges at higher abstraction level. In case any overlap between these PMC teams would occur, this will be aligned within the DTES program management.

2.3 PMC SEES scope

The scope of the PMC SEES team is Systems Engineering (SE) and managing systems complexity to ensure a future-proof energy system. Key areas of interest are the following:

1. Systems Thinking / Systems Engineering:
   - **SE multidisciplinary approach** for the effective design, realisation and lifecycle management for energy systems.
   - **SE thinking/leadership** to support orchestration of the energy transition and collective ownership.

2. Managing (eco-) systems complexity:
   - Designing-in **robustness and resilience** for coping with / adapting to emergent behaviour and change.
   - Anticipating/adjusting for **evolution** of the ecosystems' solutions and stakeholders.

The focus of SEES PMC activities is on the conception, design and realization of the future energy system and its full lifecycle management. For this the SEES team brings in knowledge & expertise on SE, MBSE / digital assistance, system- / reference- / value-based architecting, multi-perspective system design (cross-cutting 'ilities), and multidisciplinary system design. These methodologies connect technical innovations with business and organisational aspects in ways that are not done by other PMCs, and as such has the potential to complement the methods of other PMCs when embedding in practice.

2.4 PMC SEES vision and mission

The vision of the PMC SEES is that by 2050, the Netherlands will have a stable, resilient, sovereign, future-proof, and climate-neutral energy system. This system will be a multi-commodity, multi-scale system-of-systems, seamlessly integrating diverse energy carriers and operating across multiple scales to form a dynamic, adaptive, and intelligently coordinated energy ecosystem.

To realize this ambition, the PMC SEES program envisions a future in which such highly complex energy systems are engineered and deployed rapidly, reliably, and affordably. This will be achieved through the smart application of digital systems approaches, supported by robust systems engineering and systems architecting capabilities that enable scalable, interoperable, and cost-effective solutions across the energy ecosystem.

The PMC SEES mission is to foster excellence in systems engineering for the energy transition. It aims to achieve this by advancing the following key ambition areas contributing to the DTES program:

- Advancing Systems Engineering capabilities for the energy transition.
- Digitalization of SE: MBSE and Digital Engineering.

- Improving collaborative SE practises for energy system-of-systems and ecosystems.
- Connecting SE and SE outcomes to the broader business and societal objectives and energy system(s) lifecycle concerns, including affordability, sustainability, and resilience.

Together, these PMC SEES ambition areas provide a clear framework for strengthening systems engineering practices across the energy sector. By focusing on systems engineering, digital engineering, and effective engineering management of ecosystem complexity, PMC SEES aims to support stakeholders in designing, integrating and realizing solutions that are scalable, interoperable, and aligned with business and societal objectives. This approach will help the sector address increasing technical and organizational challenges, improve collaboration, and enable a more efficient and flexible energy system that meets future demands.

2.5 PMC SEES value proposition

PMC SEES is dedicated to strengthening systems engineering capabilities across the energy sector and its interconnected ecosystems. Here, S**ystems Engineering capability** refers to the demonstrated ability of an individual or organization to apply the knowledge, skills, behaviours, and processes needed to perform Systems Engineering effectively across the system lifecycle [5] [1].

By embedding advanced Systems Engineering (SE) capabilities, PMC SEES enables organizations to manage complexity, accelerate innovation, and deliver future-proof energy solutions that meet both societal and business objectives.

To achieve this, PMC SEES offers a portfolio of deliverables designed to embed Systems Engineering excellence across the energy sector, including:

- **Structured workflows and methodologies**: Validated approaches for high-quality engineering outcomes.
- **Competence development**: Training programs and role models to build skills and organizational maturity.
- **Systems Engineering guidance and expert support**, including:
  - Overview of relevant reference architectures and system-of-systems blueprints.
  - Consolidated insights and best practices for consistent application of SE principles.
  - Consultancy and continuous improvement services to kickstart and sustain capability growth.

A key tenet of PMC SEES is its the **‘industry-as-a-lab’** approach, which fosters co-creation and validation of high-impact systems engineering capabilities in close collaboration with energy transition partners. This collaborative model ensures that solutions are not only theoretically sound but also practically applicable, tested in real-world environments, and aligned with sector-wide needs.

The outcomes of DTES and PMC SEES efforts will enable the energy sector to accelerate the energy transition by more than doubling engineering productivity and effectiveness, while preparing future energy systems for dynamic usage, integrating intermittent renewable sources, and driving flexible energy usage, conversion and storage as they become available.

2.6 Structure of this report

This document provides an overview of the vision and research outlook of the PMC SEES The current revision of the paper presents a first vision on the future of Systems Engineering of the energy systems (SEES) for the energy sector. It focuses on the sector's needs and general research outlook, not yet distinguishing Technology Readiness Levels (TRL).

The document is organized as follows:

Section 3: The Energy System in Transition

- Introduces the context of the Dutch energy transition, highlighting the shift towards sustainability, decentralization, and digitalization. It outlines the major trends, challenges, and the diverse stakeholder landscape shaping the energy transition.

Section 4: Systems Engineering of the Energy System

- Explores the trends and challenges that drive the need for advanced systems engineering in the energy sector. This chapter identifies sector-specific needs and reviews relevant national and international visions and roadmaps, providing a foundation for the SEES vision.

Sections 5–10: Key Ambition Areas and Research Outlooks
Each of these chapters addresses a central ambition area for SEES, structured as follows:

- Building faster and smarter (Section 5):
  Examines the need for accelerated infrastructure development and smarter asset management, presenting research directions for standardization and digitalization.
- Increasing utilization and enhancing flexibility (Section 6):
  Focuses on maximizing grid utilization and system flexibility, with research outlooks on software-intensive energy systems and collaborative energy systems.
- Collaborative engineering for an evolving ecosystem (Section 7):
  Discusses the importance of systems-of-systems engineering and innovation within complex, multi-stakeholder ecosystems.
- SoS security and resilience (Section 8):
  Addresses the growing need for security and resilience in increasingly digital and interconnected energy systems.
- Digital Systems Engineering (Section 9):
  Details the transition to digital and model-based systems engineering, highlighting methodological and organizational challenges.
- SE competences for the future (Section 10):
  Explores the evolving competence profiles and lifelong learning needs for systems engineers in the energy sector.

Section 11: Conclusions

- Synthesizes the main findings and provides recommendations for strengthening systems engineering practices across the energy sector.

Section 12: References

- Lists the sources and literature underpinning the report's analyses and recommendations.

This structure intends to guide the reader from the broader context of the energy transition, through the identification of sector needs and ambition areas, to actionable research outlooks and recommendations.

3 The energy system in transition

3.1 The energy system in transition

The Dutch energy system is undergoing a fundamental transformation, characterized by the transition from a fossil-based, centrally managed infrastructure to a sustainable, integrated, and increasingly decentralized and digitalized system. This transition encompasses the full scope of the energy domain: electricity grid networks, gas infrastructure, and the broader energy industry, including major oil and gas companies, energy suppliers, and emerging actors in flexibility and digital services (both in a national and international, i.e., European context).

The future energy system will be defined by a significant increase in electrification across all sectors, with electricity demand projected to rise sharply due to the adoption of electric vehicles, heat pumps, and the electrification of industrial processes. In parallel, the role of gases is evolving, with a shift from natural gas to green gases and hydrogen as essential energy carriers for industry, heavy transport, and seasonal storage. Sector coupling. i.e. integrating electricity, heat, gas, and hydrogen networks, will be necessary to provide the flexibility and resilience required for a reliable energy supply.

Digitalization is a key enabler of this transition. As energy systems evolve into multi-commodity, multi-scale, and SW-intensive systems-of-systems (SoS), integrating electricity, heat, hydrogen, green gases, and emerging carriers, their complexity and interdependencies increase dramatically. The deployment of advanced digital technologies supports real-time system monitoring, optimization, and the integration of distributed energy resources, ranging from large-scale offshore wind farms to decentralized assets such as household batteries and electric vehicles. The system is evolving towards a dynamic, decentralized ecosystem, in which citizens, businesses, and local communities play an increasingly active role. This transformation is not only technical but also organizational and societal, requiring new forms of governance, market design, and stakeholder participation. Engineering methods and approaches for the sector must incorporate all these perspectives.

3.2 The impact on the energy sector

The energy transition exerts significant and multifaceted impacts on all stakeholders in the sector. Achieving national and European climate objectives within the required timeframe necessitates rapid deployment of new energy infrastructure, technologies, and business models in several sectors and domains. This is accompanied by a persistent shortage of skilled personnel, with the workforce becoming younger and less experienced, thereby increasing the need for training and knowledge transfer, both towards new personnel as across knowledge domains.

Affordability and profitability of solutions are under pressure as costs rise due to the increasing complexity and scale of projects, supply chain constraints, and the demand for high-quality manufacturing and fabrication. Project schedules are becoming more ambitious, but also more susceptible to delays and overruns. Contractors are exposed to substantial technical and financial risks, as they are required to deliver innovative solutions under evolving specifications and tight timelines.

Traditional project management and procurement processes are often inadequate for the dynamic and integrated nature of the new energy system. Inefficiencies in procurement, fragmented responsibilities, and a lack of standardization can result in delays, increased costs, and suboptimal outcomes. The sector must also meet continuously evolving auditability expectations, with growing requirements for transparency, traceability, and compliance. Specifications are expanding and being passed down the value chain, increasing the workload for each party involved and raising the administrative burden.

In summary, the energy transition is not only a technical and economic challenge but also an organizational and societal one. It requires new approaches to collaboration, innovation, and risk management, as well as a commitment to continuous learning and adaptation across the entire sector.

3.3 Stakeholders in the Energy System

The transition to a future-proof, resilient, and sustainable energy system involves a wide and diverse array of stakeholders, each with distinct roles, interests, and priorities. The energy system is shaped not only by technical and economic drivers, but also by the interplay of public authorities, market actors, knowledge institutions, and end-users. These stakeholders operate at different scales—national, regional, and local—and their objectives may at times align, overlap, or even conflict.

National government, provinces, and municipalities are responsible for spatial planning, permitting, and the orchestration of infrastructure expansion, while energy system operators ensure the safe and reliable operation of utility networks. Energy suppliers, contractors, consultants, OEMs, and component suppliers each contribute specific expertise and resources to the realization and operation of the energy system. Industrial clusters, business parks, and residential users represent the demand side, with evolving needs for reliability, affordability, and sustainability. In addition, private system operators, EMS providers, installers, and knowledge institutions play essential roles in system integration, innovation, and capacity building. Sectoral representative bodies act as conveners and enablers, facilitating alignment, standardization, and knowledge exchange across the ecosystem.

Given this diversity, effective collaboration and systems thinking are essential. The complexity of the energy transition requires that stakeholders work together across organizational and disciplinary boundaries, balancing sometimes competing interests to achieve shared goals. The following table (Table 1) provides an overview of the main stakeholder groups in the energy system and their contextualized needs and priorities within the scope of Systems Engineering for Energy Systems (SEES).

Table 1 - overview of energy system stakeholders

Stakeholder	Needs and Priorities (Contextualized to SEES Scope)
National government, provinces, and municipalities	Facilitate spatial planning, permitting, and alignment with regional energy strategies. Require scalable, future-proof solutions that align with climate goals and regional economic development, and safeguard energy sovereignty. Their role is pivotal in orchestrating infrastructure expansion, enabling system-level coordination, while also safeguarding the interests of their constituents, both businesses and residents.
Energy network Operators	Responsible for the safe and reliable operation of energy networks transporting electricity, gas, and other energy carriers, including active grid congestion management. Grid operators, and gas and further energy network operators require visibility into local energy systems and access to flexibility services. They must collaborate with ecosystem actors to construct and expand resilient energy systems based on interoperable solutions, while ensuring effective asset lifecycle management across planning, operation, and renewal phases.
Energy suppliers	Supply energy to transport networks, industrial clusters and business parks. Seek flexible contract models and integration of renewables to support new business models. Their involvement is key in shaping system-level energy flows and financial structures within the Energy System lifecycle.
Energy system contractors	Responsible for the physical realization of energy infrastructure installations commissioned by energy network operators and energy suppliers. Their role spans the construction, integration, and commissioning of system components—ranging from substations and cabling to metering between grid operators to (renewable) energy installations and control systems.
Energy consultants	Support industries, industrial clusters, and energy hubs in translating strategic energy ambitions into practical system designs and investment pathways, often through multi-stakeholder collaboration. They guide the selection and deployment of scalable, interoperable, and resilient energy systems that are technically robust, economically viable, and socially aligned with climate objectives and regional priorities.
OEM and component Suppliers	Design and deliver energy subsystems and components for integrated systems, e.g., High Voltage (HV) power transformers, HV switch gears, HV cables, HV power protection & control subsystems, batteries, electrolysers, converters, sensors, etc. Require clear technical specifications and interoperability standards. Their innovations must be embedded into SE frameworks to ensure system coherence and lifecycle performance.
Industrial clusters / business parks	Act as core users and co-investors in future collective energy systems. Require reliable, affordable, and sustainable energy for operations and growth. Their requirements drive the need for robust SE methodologies to manage complexity and ensure resilience.

Stakeholder	Needs and Priorities (Contextualized to SEES Scope)
Residential users	Indirect but essential stakeholders in the energy transition. As end-users of electricity, heating, and emerging energy services, their consumption patterns, and adoption of new technologies will significantly influence energy system design and integration requirements. Their collective behaviour shapes demand profiles, grid stress, and the need for resilience and adaptability in energy infrastructure.
Private and energy hub system operators	Manage, monitor, and optimize energy systems within industrial sites, clusters, and energy hubs. Responsible for controlling energy flows, ensuring SLA compliance, and overseeing asset performance and maintenance. They have system integration concerns, as they rely on interoperable solutions that support system visibility, flexibility integration, and lifecycle asset management, enabling decentralized energy resilience and alignment with broader climate and coordination goals.
EMS Providers	Develop and deliver energy management systems that coordinate the operations of individual components, enabling them to function together as an integrated and efficient whole. EMS providers face significant system integration challenges, as their solutions must seamlessly combine diverse system capabilities to achieve cohesive and reliable performance..
Installers	Assemble and integrate energy components on-site into functioning systems. They have system integration concerns, as they need scalable, interoperable energy system modules with clear specifications.
Knowledge Institutions	Conduct research, validate innovations, and support implementation. Require access to pilot sites and industry collaboration. They are key partners to PMC SEES in developing and adapting SE methodologies for the energy domain.
Sectoral Representative Bodies	These bodies (e.g., Netbeheer Nederland, TopSector Energy) act as strategic enablers and conveners within the Dutch energy ecosystem. As stakeholders in the PMC SEES program, they play a vital role in articulating sector-wide needs and priorities, facilitating alignment and collaboration, supporting standardization and interoperability, and help drive innovation and knowledge exchange. In the context of PMC SEES, these bodies are essential for embedding Systems Engineering into the broader energy transition, ensuring that engineering approaches are not only technically sound but also socially and politically viable.

3.4 Primary stakeholders for PMC SEES outputs

The successful realization of a future-proof, resilient, and sustainable energy system depends on the effective engagement and collaboration of a wide variety of stakeholders, each with their own roles, interests, and priorities. Within a broad landscape of energy stakeholders (see Table 1), the PMC SEES (Systems Engineering for Energy Systems) program specifically targets those stakeholders who are central to the engineering, realization, and system operation of energy infrastructure and systems.

The primary stakeholders for PMC SEES include the following:

- energy network operators (grid and gas network operators) and energy suppliers.
- Energy system contractors for operators and suppliers.
- Energy (OEM and component supplier) ecosystems.

These stakeholder groups are directly involved in the design, integration, and deployment of complex energy systems, and are therefore primary beneficiaries of digital system approaches and advanced systems engineering methodologies, developed within PMC SEES.

At the same time, PMC SEES recognizes the importance of engaging with the broader energy stakeholder ecosystem (including e.g. consultants, knowledge institutions, and sectoral representative bodies) to ensure that digital systems approached and advanced systems engineering methodologies are not only technically robust but also aligned with societal needs, regulatory frameworks, and evolving market structures.

4 Systems Engineering of the Energy System

4.1 Trends and challenges for the energy system

The energy transition in the Netherlands represents a dynamic and complex change process to a sustainable and climate neutral energy system by 2050 [6] [3]. It requires coordinated efforts from all stakeholders to achieve such a sustainable and resilient energy future.

Highlighted trends and challenges in this energy transition are the following:

1. Electricity demand increases manyfold: The demand for electricity is expected to rise significantly in the coming years due to the electrification of various sectors, including transportation, heating, and industrial processes. This increase is driven by the transition to electric vehicles, heat pumps, electrification of industry, and the growth of data centres.

2. Rise of sustainable, yet intermittent energy sources: The integration of renewable energy sources, such as wind and solar power is crucial for achieving climate goals. However, these sources are intermittent and require flexibility in the energy system and advanced grid management and storage solutions to ensure a stable supply of energy.

3. Scarcity of public space: With the increasing need for renewable energy installations, and expanded grid infrastructure, this represents a struggle with the already scarce public space. Efficient use of available space and coordinated planning of grid expansion activities is needed.

4. Increasing political and legislative pressure: The energy transition in the Netherlands faces significant political and legislative pressures, particularly regarding grid infrastructure. Ambitious climate goals and EU support are driving legislative actions to modernize the grid; new laws facilitate collective negotiations and energy hubs. These initiatives have large impact on the modernization and expansion of the grid infrastructure.

5. Digitalisation and AI: Digitalisation and AI can transform energy systems by enhancing their capabilities especially for more flexible generation and use. These technologies enable better grid management, predictive maintenance, and optimization of energy usage. AI can also help in forecasting energy demand and supply, improving the overall efficiency of the energy system.

6. Further integration of energy system(s): There is a need for a more integrated multi-commodity energy system that combines electricity, gas, hydrogen, and

heat networks. This integration allows for greater flexibility and resilience, ensuring a reliable energy supply even with fluctuating renewable sources.

7. **Globalization of supply chains:** The rapid scale-up of the energy system places significant strains on its supply chain. Energy network operators must now extend their reach beyond national borders and coordinate with international suppliers and partners, complicating logistics and communication. As relatively small players in the global market, the Dutch energy sector and energy system operators face challenges in securing critical components from key suppliers, amid increasing international demand.

8. **Scarcity of engineering experts**: There is a notable shortage of engineering experts in the energy sector. This scarcity necessitates efforts to reduce the learning curve for new team members and to decrease dependency on experts. There is a need to maximize productivity and quality of those scarce experts.

9. **Vulnerability of energy infrastructure**: The energy infrastructure is vulnerable to various threats, including cyberattacks, extreme weather events, and physical damage. This highlights the need for robust infrastructure and advanced security measures to ensuring the resilience and security of the energy system.

These trends and challenges place increasing demands on the sector's existing engineering practices and ways of working. The complexity, pace of change, and heightened expectations for reliability, flexibility, and integration expose the limitations of traditional approaches. To effectively respond, the energy sector must develop and adopt new systems engineering (SE) capabilities, encompassing organizational structures, competencies, processes, methodologies, and foundational principles. Strengthening these SE capabilities is essential to enable the sector to navigate ongoing transformation, manage complexity, and deliver future-proof solutions.

Against this backdrop, the following section introduces systems engineering as a discipline, outlining its relevance and necessity for addressing the evolving needs of the energy sector.

4.2 Systems Engineering as an Engineering Discipline

Systems Engineering is an engineering discipline that has emerged from the space and defence industry yet also is widely practised in infrastructure development. It focusses on the transdisciplinary, system-level approach to successfully realize, use, and retire systems. The International Council for Systems Engineering (INCOSE) defines it as follows [7]:

> *Systems Engineering is a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods.*

This INCOSE definition addresses the specific aspects of systems engineering in detail. Another, less detailed, description found in the SEBoK [8] of systems engineering emphasizes what it is all about:

> *A systems engineer helps ensure the elements of the system fit together to accomplish the objectives of the whole, and ultimately satisfy the needs of the customers and other stakeholders who will acquire and use the system.*

The Systems Engineering Handbook of NASA [9] explains this in more detail:

> *Systems engineering is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system. A "system" is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce system-level results. The results include system-level qualities, properties, characteristics, functions, behaviour, and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected. It is a way of looking at the "big picture" when making technical decisions. It is a way of achieving stakeholder functional, physical, and operational performance requirements in the intended use environment over the planned life of the systems. In other words, systems engineering is a logical way of thinking.*

The key difference between systems engineering and disciplines such as electrical or software engineering is its focus on integrating diverse domains into a unified whole. In the energy sector, systems engineering practises ensure that e.g. when building electrical substations, primary installations (such as transformers and switchgear) and secondary installations (such as station control and protection systems) are designed and constructed as one coherent system. Starting from stakeholder concerns and needs, and a clear problem statement, systems engineering defines system structures that cross the boundaries of engineering domains, including people, facilities, and documentation, as highlighted in the NASA definition [9]. Systems engineering concentrates on the design, realization, and lifecycle management of "the whole" rather than just the individual parts.

The energy transition, as detailed in section 4.1, brings forth a range of new challenges, including rising complexity, deeper interdependencies, and accelerating rates of change across technical, organizational, and societal dimensions. These trends intensify the need for advanced systems engineering practices, which are essential not only for managing complexity and expediting the engineering, integration, and deployment of solutions, but also for ensuring coherence, resilience, and adaptability of engineered system within the sector.

4.3 SE needs for the Energy Sector

The increasing complexity, scale of energy infrastructure expansion, and increasing interconnectedness of engineered energy systems demand a more comprehensive and integrative approach, requiring advancement of systems engineering capabilities.

Building on the analysis of energy sector trends and challenges in section 4.1, and the evolving role of systems engineering discussed in section 4.2, Figure 1.presents a structured overview of the key SE needs that form the foundation for the Systems Engineering (SE) vision within the energy transition.

The first row in this figure below provides an overview of external trends and drivers for energy system operators, contractors, and suppliers. The second row presents the needs of energy system operators, potentially in relation to systems engineering.

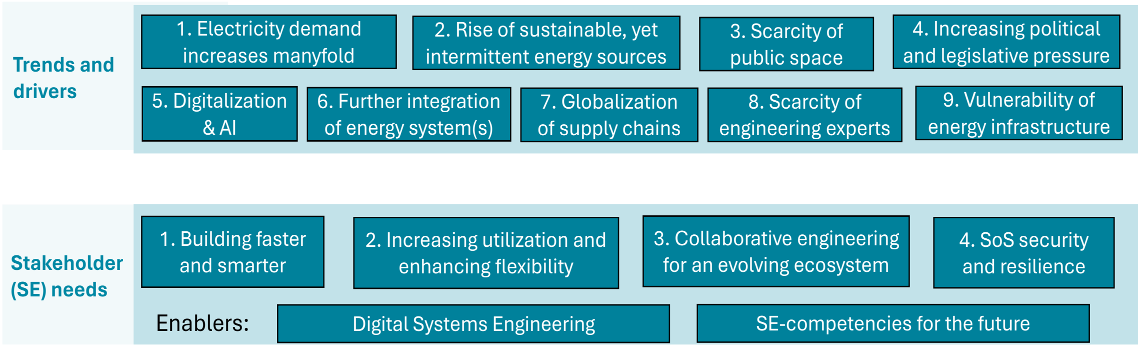

Figure 1- Trends and drivers for the energy transition, with the associated (SE) needs of stakeholders.

Detailed further, these needs entail the following:

- Building faster and smarter: To meet the rapidly growing electricity demand and enable the integration of renewable energy sources, the energy sector must both accelerate the expansion of grid infrastructure and scale up asset management practices. This requires smarter, more standardized solutions that facilitate coordinated project delivery and efficient resource use, while also adopting advanced asset management strategies to ensure reliability and longevity. By fostering closer collaboration among suppliers, energy system operators, contractors, and technology providers, the sector can reduce construction efforts, build faster, and optimize the performance of critical assets, supporting a sustainable and future-proof infrastructure.

- Increasing utilisation and enhancing flexibility: To achieve an affordable and future-ready energy system powered by intermittent sources, it is essential to enhance grid utilization and increase system flexibility. This requires the design and integration of flexible, smart, and modular energy systems with intelligent control capabilities, all embedded within interoperable system architectures. As the sector moves toward more integrated and software-intensive solutions, the complexity of engineering and the interdependence between subsystems will rise significantly. A key SE need for the sector is to ensure that the design, integration, and realization of these adaptive energy systems remain manageable and cost-effective throughout their lifecycle, enabling robust performance, scalability, and long-term value.

- Collaborative engineering for an evolving ecosystem: To address the challenges of a rapidly transforming and increasingly interconnected energy system, energy network operators, energy suppliers, OEMs, and component suppliers must collaborate across organizational boundaries, despite differing objectives and operational constraints. The sector requires advanced Systems-of-Systems (SoS) Engineering capabilities to enable the integrated design and continuous evolution of engineering frameworks, architectures, and processes that support voluntary cooperation, shared value creation, and dynamic coordination. These capabilities must safeguard the operational independence of each participant, while ensuring the coherence, adaptability, and resilience of the overall energy ecosystem and its constituent systems.

- SoS security and resilience: The increasing digitalization and integration of cyber-physical components expose the energy system to a broader spectrum of risks, including cyberattacks, cascading failures, and operational disruptions. Unpredictable changes in system context (such as shifting stakeholder roles or evolving supply chains) introduce additional uncertainties that existing standards alone cannot fully address. SE must integrate security and resilience as central concerns throughout the entire system-of-systems lifecycle, alongside traditional RAMS considerations (Reliability, Availability, Maintainability, Safety). A holistic “loss-driven” systems engineering approach ensures the continuity, safety, and trustworthiness of the energy system by enabling it to anticipate, withstand, recover from, and adapt to adverse events, whether cyber, physical, or organizational in nature

Finally, two enablers to support these needs are the following:

- Digital Systems Engineering: Digitalization and standardization of energy (cyber-physical) system design, information exchange, and asset lifecycle management are essential to improving engineering productivity, accelerating infrastructure deployment, and ensuring energy system resilience. By adopting model-based and data-driven engineering practices, energy network operators, contractors, OEMs and technology providers, can reduce integration errors, improve traceability, and support faster, more informed decision-making. Overall, digitalization can help accelerate and enhance the engineering and expansion of energy infrastructure.
- SE Competencies for the Future: Identifying and developing the necessary competencies for lead engineers and other personnel is crucial for effective collaboration within the organization and with external partners. This includes fostering skills in systems engineering (SE) and project management (PM) methodologies to support complex energy projects. By enhancing SE competencies, energy system operators can improve coordination, reduce project risks and failures, and achieve better outcomes in terms of delivery time, quality and costs of projects. Continuous professional development is needed to ensure the energy sector is equipped to handle future challenges.

These needs and corresponding research themes are further detailed in sections 5 - 10, detailing these SE needs for the energy sector.

4.4 Relevant energy and SE visions & roadmaps

4.4.1 National Action Programme for Grid Congestion

The Dutch “Landelijk Actieprogramma Netcongestie” [10] (LAN - National Action Programme for Grid Congestion) provides a national framework to address the urgent challenge of electricity grid congestion in the Netherlands, ensuring that the energy transition can proceed without unnecessary delays. Developed collaboratively by the Ministry of Economic Affairs and Climate, grid operators, regulators, provinces, municipalities, and industry stakeholders, the program sets out concrete measures to accelerate grid expansion and optimize the use of available grid capacity for both electricity production and consumption. The LAN is structured around three main objectives:

1. **Faster Construction**: accelerating the realization of grid expansions through integrated regional project management and streamlined collaboration between authorities and grid operators. Objective is to reduce transport capacity scarcity.

2. **Stronger Steering**: improving the utilization of existing grid capacity by updating regulations, introducing flexible and time-bound contracts, and incentivizing users to adapt their consumption and production patterns. Objective is to prevent and resolve grid congestion.

3. **Increasing Flexible Capacity:** promoting public-private actions for smart solutions, such as demand-supply coordination, local energy hubs, and large-scale storage, to make flexibility a standard part of business operations.

Implementation of the LAN [10] is organized through dedicated working groups for each objective, with regular monitoring and evaluation to ensure progress and adapt to new developments. By providing a practical roadmap for both immediate and long-term action, the LAN aims to relieve grid congestion, support the integration of renewable energy, and maintain the reliability and affordability of the Dutch electricity system during the energy transition.

4.4.2 Integral Infrastructure Outlook 2030-2050 (II3050)

The Integral Infrastructure Outlook 2030-2050 (II3050) [6], led by Gasunie in collaboration with Netbeheer Nederland and TenneT, provides a comprehensive scenario-based exploration of the future Dutch energy system. The study presents four ambitious pathways to a climate-neutral energy system by 2050, each reflecting different choices regarding government intervention, market forces, and the balance between national, regional, and international organization. All scenarios require a rapid phase-out of fossil fuels, a major scale-up of renewable energy, and deep transformation across industry, mobility, the built environment, and agriculture.

The II3050 scenarios reveal that a massive expansion and smarter use of energy infrastructure are essential. To meet future demand, the Netherlands will need to increase capacity by 100-200% for interconnection stations, 36-45% for medium-voltage cables, and 20-30% for low-voltage cables, with additional flexibility solutions requiring 40-70% more capacity. Electrification and hydrogen play central roles, with electricity demand rising by up to 250% and hydrogen becoming a key energy carrier for industry, transport, and flexibility. The scenarios also highlight the need for large-scale flexibility (such as storage, demand response, and sector integration) to balance variable renewable supply and ensure security of supply.

II3050 provides actionable recommendations for policymakers, including making timely choices on energy carriers and industrial policy, developing robust flexibility and storage solutions, and aligning infrastructure planning with spatial and societal needs. The study emphasizes that the transition will require unprecedented investments, innovation, and coordination across all sectors, and that continuous monitoring and adaptive policy are crucial to stay on track for a climate-neutral, reliable, and affordable energy system by 2050.

4.4.3 Action Agenda for the Digitalisation of the Energy System (ADE)

The Action Agenda for Digitalisation of the Energy System (ADE) [4] provides a national framework to accelerate and coordinate the digital transformation of the Dutch electricity system, supporting the transition to a sustainable, reliable, and affordable energy future. Developed collaboratively by the Ministry of Climate and Green Growth, TNO, and a broad coalition of stakeholders, the ADE translates the ambitions of the National Energy System Plan (NPE) [3] into concrete actions for the coming years. The agenda is designed as a living document, evolving alongside technological and societal developments, and places a strong emphasis on socially responsible digitalisation—ensuring that digital solutions serve public interests, such as security, affordability, sustainability, and inclusivity.

The ADE is structured around five interrelated themes: (1) data-driven insight into the electricity system, (2) optimal use of network capacity, (3) empowering participants, (4) system integration and resilience, and (5) digital support for planning and construction. For each theme, the agenda identifies key digitalisation solutions and clusters actions into clear lines of action, such as improving metering and data access, developing digital twins, supporting interoperability and flexibility, strengthening cyber resilience, and fostering digital skills across the sector. The action plan addresses urgent challenges like grid congestion, high infrastructure costs, and the growing complexity of a decentralized energy system, while also anticipating disruptive trends, such as artificial intelligence and new market models.

Implementation of the ADE is coordinated through a multi-year program involving government, network operators, knowledge institutions, and industry partners. The agenda outlines mechanisms for ongoing coordination, stakeholder involvement, and adaptation to new developments. By providing a practical roadmap for digitalisation, the ADE aims to stimulate innovation, remove bottlenecks, and ensure that the digital foundation of the Dutch energy system is robust, future-proof, and aligned with broader European policy frameworks.

4.4.4 Topsector Energie MMIP 13 Systeem Integratie

The Topsector Energie MMIP 13 Systeemintegratie [11] presents a national innovation agenda focused on developing a robust and socially supported energy system for the Netherlands. This Multi-Year Mission-Driven Innovation Program (MMIP: “Meerjarig Missiegedreven Innovatie Programma" in Dutch) recognizes that the energy transition requires more than technological advances alone; it calls for integrated solutions that connect various energy carriers and sectors, while also embedding societal values and regional needs.

Alongside MMIP 13, the Topsector Energie coordinates several other MMIPs, each addressing specific aspects of the energy transition, such as renewable energy production, energy efficiency, and sustainable mobility. Together, these MMIPs form a comprehensive innovation framework that supports the realization of a climate-neutral, resilient, and future-proof energy system for the Netherlands. By emphasizing system integration within this innovation framework, MMIP 13 aims to foster flexibility, reliability, and efficiency across electricity, heat, gas, and hydrogen networks, as well as in industry, the built environment, and mobility. Central to MMIP 13 is the ambition to ensure that innovations are not only technically sound but also widely accepted and supported by society.

MMIP 13 is structured around several key innovation lines. These include the development of system flexibility through solutions for balancing supply and demand, such as storage, demand response, and sector coupling. The program also prioritizes digitalization and the use of data-driven approaches to enhance system monitoring, control, and optimization. Another important theme is the support for regional energy systems, which involves designing and implementing integrated solutions that are tailored to local opportunities and constraints. Societal engagement is woven throughout the program, with a strong emphasis on co-creation and collaboration to ensure that system innovations are not only technically sound but also socially embedded and widely supported.

Implementation is coordinated by the Topsector Energie in partnership with public and private stakeholders, knowledge institutions, and regional authorities, and is closely aligned with national policy frameworks, such as the National Energy System Plan [3] and the Action Agenda for Digitalisation of the Energy System (see section 4.4.3). Through multi-year innovation projects, living labs, and demonstration pilots, MMIP 13 provides a practical roadmap for accelerating the energy transition, addressing challenges like grid congestion and renewable integration, and working towards a resilient, future-proof, and inclusive Dutch energy system.

4.4.5 HTSM Systems Engineering roadmap

Since 2024, the DTES program has been closely connected to the strategic Systems Engineering program [12] of the Topsector High Tech Systems and Materials (HTSM), coordinated by TNO-ESI. The HTSM Systems Engineering Roadmap [13] serves as a guiding framework for investments and collaborative research across industry, academia, and research organizations, with a focus on advancing systems engineering methodologies for complex, multidisciplinary domains, including semiconductors, precision equipment, and increasingly, energy transition technologies. The objectives of this HTSM strategic program are fully aligned with the vision and ambitions of PMC SEES, particularly in driving innovation and capability development for the energy sector.

As of late 2025, the HTSM Systems Engineering Roadmap [13] is undergoing a substantial revision in partnership with a broad set of stakeholders. This update is explicitly shaped by the priorities of the National Technology Strategy [14] (NTS), which identifies ten key technology domains for the Netherlands. The roadmap aims to deliver tailored systems engineering methods and strategies for broader adoption, directly addressing the complex needs of energy systems and infrastructure as prioritized in the NTS. The collaborative approach not only strengthens the alignment between national technology priorities and sectoral innovation needs but also accelerates the adoption of advanced systems engineering practices within the energy ecosystem. The updated HTSM Systems Engineering Roadmap is scheduled for final delivery in April 2027.

4.4.6 INCOSE Vision 2035

The International Council On Systems Engineering (INCOSE) created a vision on the future, i.e., 2035, state of Systems Engineering [2]. According to the INCOSE vision 2035 “SE will leverage digital transformation in its tools and methods, and will be largely model based using integrated descriptive and analytical digital representations of the systems.” [2]. This vision intends to guide and inspire the diverse stakeholder and engineering communities into their strategic direction of systems engineering [2].

The SE Vision 2035 is driven by the following six global mega trends:

1. Environmental sustainability becomes a high priority,
2. The interconnected world increases interdependence,
3. The digital transformation changes products and the way we work,
4. Industry 4.0 [15] and society 5.0 [16] underpin change strategies,
5. System complexity explodes,
6. Smart systems proliferate.

The INCOSE vision provides insights on these trends and their impact on enterprise competitiveness. The vision articulates how systems engineering as a discipline will respond to these trends. It describes the needed future state of systems engineering, and what is required to realize the vision.

4.4.7 NXTGEN Hightech Systems Engineering vision

NXTGEN Hightech aims to position the Netherlands at the forefront of high-tech innovation by (amongst others) advancing Systems Engineering (SE) as a foundational discipline [17]. The program recognizes that the increasing complexity and interdisciplinarity of high-tech systems require a new generation of systems engineers and a distinctly Dutch approach to SE.

At the heart of this vision is the Dutch Approach to Systems Engineering (DASE). DASE is characterized by its pragmatic, context-driven, and collaborative methodology. Rather than relying solely on international standards, DASE emphasizes practical solutions, rapid iteration, and strong stakeholder engagement. Dutch companies often develop company-specific SE practices that prioritize adaptability, teamwork, and integration across disciplines: qualities essential for managing the complexity of both high-tech and energy systems.

NXTGEN Hightech’s SE efforts focus on:

- Developing a continuous learning line for SE, connecting education and industry to foster lifelong competence development.
- Accelerating the adoption of digital and model-based systems engineering (MBSE) to improve engineering productivity and innovation.
- Strengthening collaboration across industry, academia, and research organizations to address multidisciplinary challenges.
- Promoting SE methods that are flexible, scalable, and tailored to the needs of complex, evolving systems.

In addition, NXTGEN Hightech contributes to the energy transition by developing advanced technologies, such as next-generation electrolysers and sustainable energy systems, aiming to accelerate the shift to clean energy in the Netherlands. Through these efforts, NXTGEN Hightech seeks to double engineering productivity and effectiveness, support the acceleration of the energy transition, and establish the Netherlands as a leader in adaptive, effective systems engineering for future-proof, high-tech systems.

5 Building faster and smarter

5.1 Energy sector needs for building faster and smarter

To meet the rapidly growing electricity demand and enable the integration of renewable energy sources, the energy sector must both accelerate the expansion of grid infrastructure and scale up asset management practices. This requires smarter, more standardized solutions that facilitate coordinated project delivery and efficient resource use on regional and national level, while also adopting advanced asset management strategies to ensure reliability and longevity. By fostering closer collaboration among suppliers, energy system operators, contractors, and technology providers, the sector can reduce construction efforts, build faster, and optimize the performance of critical assets, supporting a sustainable and future-proof infrastructure.

From a systems engineering perspective, the key need is to improve the building productivity under the constraints of personnel shortage ("do more with less" [18]). Systems engineering capabilities and methods are needed to address two priorities as follows: (1) enabling modular and scalable grid development across all lifecycle phases (from requirements definition, before and during design phase, to integration in the realization phase and maintenance and asset management) and (2) optimizing project delivery processes for efficiency and coordination [19]. Importantly, included in both are asset management considerations. These priorities are driven by observed trends (see section 4.1), particularly:

- *Electricity demand increases manyfold (trend i),*
- *Further integration of energy system(s) (trend vi)*
- *Scarcity of engineering experts (trend viii)*

The first trend requires architectures and processes that accelerate grid expansion without compromising its reliability and resilience. The second trend requires modular designs with standardized functions and interfaces, also for integrating renewables and further systems enabling higher utilization and flexibility. The latter trend is driving the need for reuse through model-based approaches and standardization, as well as automation and digitalization to reduce effort and accelerate decision-making and speed-up delivery. If grid expansion is not accelerated, persistent transport capacity scarcity and net congestion could jeopardize sustainability objectives and constrain economic growth in both the green energy sector and society at large.

Outcome

Advanced systems engineering capabilities for the energy transition will enable faster, smarter, and more reliable delivery of electricity infrastructure in line with societal needs. Structured methods and integrated frameworks support modular grid architectures and coordinated project execution at program and portfolio level, embedding asset management across all lifecycle phases. Model-based approaches and digital tools streamline decision-making, automate processes, increase reuse, and enhance collaboration among multiple stakeholders, accelerating deployment while safeguarding resilience and sustainability.

Source: inspired by ADE [4], II3050 [6], LAN [10], and INCOSE vision 2035 [2].

5.2 Research Outlook for building faster and smarter

To accelerate the delivery of electricity infrastructure in support of the energy transition, our research focuses on advancing systems engineering and systems architecting methods that enable modular, scalable solutions and optimize project delivery processes. These methods aim to integrate lifecycle asset management and digitalization from the outset, ensuring reliability, maintainability and adaptability as the grid evolves. We concentrate on two key areas:

- SE standardisation and Product Line Engineering, and
- Digitalisation and lifecycle management.

A brief introduction is given per area, with a short overview of relevant research topics.

SE standardisation and Product Line Engineering

Standardization and Product Line Engineering (PLE) are essential for faster and smarter infrastructure development. Modular and standardized grid architectures support grid expansion by enabling a shift from an “engineer-to-order” philosophy to a “configure-to-order” way of working. The engineer-to-order approach focuses on optimizing each individual project, product, or system for a specific context. In contrast, a configure-to-order approach leverages commonalities across projects and introduces variability only where necessary, reducing complexity and improving scalability. This not only accelerates project delivery but also enhances predictability, quality, and cost efficiency. Implementing this strategy requires PLE methods tailored to the sector, and alignment with business strategy and organizational context to ensure successful adoption and long-term benefits.

Key research questions regarding SE standardisation and Product Line Engineering are the following:

- How can Product Line Engineering (PLE) methods and reference architectures be tailored and integrated with existing project management practices to accelerate the transition from “engineer-to-order” to “configure-to-order” approaches in grid infrastructure expansion?
- What best practices support the alignment of PLE and standardization efforts with diverse stakeholder and environmental requirements, and how can essential interfaces be standardized to ensure interoperability, adoption, and scalability in grid infrastructure projects?
- How can lifecycle asset management consideration be integrated into early design phases to embed maintainability, upgradeability, and resilience into grid infrastructure from the outset?

- How can Systems Engineering best support balancing standardisation and innovation in grid infrastructure projects, enabling new solutions to be integrated without compromising efficiency and scalability?
- What digital tools and workflows can automate design validation, configuration management, and simplify compliance and validation checks to reduce manual effort and mitigate the impact of engineering resource scarcity?

Digitalisation and lifecycle management

With the increasing pace of energy infrastructure projects, the efficiency and reliability of engineering information exchange between grid operators and contractors are becoming increasingly important. To meet construction targets, these exchanges need to be more streamlined, automated, and less prone to error than traditional approaches allow. The use of digital asset threads—linking relevant data, models, and requirements throughout the asset lifecycle—helps all parties work from a unified, current source of information. Technologies such as Building Information Models (BIM), Object Type Libraries (OTL), Activity Type Libraries (ATL), Specification Libraries (SPL), when integrated into digital Product Line Engineering, can support the further modularization, standardization, and automation of information flows. For contractors, receiving standardized information based on harmonized terminology greatly simplifies working with different energy system operators, reducing confusion and rework. To fully benefit from these advances, the sector will need to strengthen its Systems Engineering capabilities in harmonized and standardized data modeling, robust configuration and change management, and lifecycle-oriented digital collaboration.

Key research questions regarding digitalisation and lifecycle management are the following:

- What Systems Engineering, PLE capabilities and digital technologies (such as BIM, OTL, ATL, SPL) are needed to harmonize data modelling, configuration management, and lifecycle-oriented collaboration across diverse organizations and IT landscapes?
- What are the practical challenges and best practices for aligning workflows and information exchange protocols between grid operators and contractors, particularly in the context of differing IT systems, maturity levels, and regulatory requirements?
- How can harmonized terminology and standardized information structures be developed, maintained, and adopted to enable efficient data interpretation and use by contractors and operators, reducing confusion and rework?
- Which governance models and collaborative processes are most effective for achieving consensus on standards (such as OTL, CIM, and RDS) and ensuring their consistent application across the sector?
- What strategies are most effective for implementing digital asset threads that connect data, models, and requirements throughout the asset lifecycle, ensuring a unified and up-to-date source of truth for all stakeholders?

6 Increasing utilization and enhancing flexibility

6.1 Energy sector needs for increasing utilization and enhancing flexibility

To achieve an affordable and future-ready energy system powered by intermittent sources, it is essential to enhance grid utilization and increase system flexibility. This requires the design and integration of flexible, smart, and modular energy systems with intelligent control capabilities, all embedded within interoperable system architectures. As the sector moves toward more integrated and software-intensive solutions, the complexity of engineering and the interdependence between subsystems will rise significantly. A key SE need for the sector is to ensure that the design, integration, and realization of these adaptive energy systems remain manageable and cost-effective throughout their lifecycle, enabling robust performance, scalability, and long-term value.

The key SE needs of the energy sector for increasing utilization and enhancing flexibility focus on developing advancing capabilities to ensure that the engineering, realization, and integration of collaborative, software-driven energy systems remains manageable and cost-effective. The energy systems engineering capabilities are expected to address digitalization and AI for real-time monitoring, control, and optimization, while ensuring interoperability, resilience, and scalability across decentralized and centralized infrastructures. These capabilities are needed in response to the observed trends (see section 4.1), in particular the following:

- *Rise of sustainable, yet intermittent energy sources (trend ii)*
- *Digitalisation and AI (trend v)*
- *Further integration of energy system(s) (trend vi)*

The energy transition demands modular, intelligent systems and SoS that are engineered for flexibility, modularity, and interoperability. This requires a systems engineering and systems integration approach that leverages digital technologies, supports decentralized and centralized coordination, and aligns technical innovation with regulatory and societal needs.

Outcome
Systems Engineering for modular, collaborative, software-intensive energy systems enables the development, integration and delivery at scale of a fully federated and digitally orchestrated energy infrastructure that maximizes grid utilization and ensures dynamic flexibility. Systems engineering for such modular, interoperable SW-intensive systems ensure seamless yet robust coordination and control of distributed assets. Standardized and fully digitalized engineering processes reduce complexity and accelerate deployment, support lifecycle management, making flexibility and

adaptability a core capability of every energy system across centralized and decentralized networks.

Source: inspired by II3050 [6], National Plan Energy System [3].

6.2 Research Outlook for increasing utilization and enhancing flexibility

In the research outlook for increasing utilization and enhancing flexibility, we consider a few topic areas as following:

- SW-intensive energy systems,
- Collaborative energy systems.

A brief introduction is given per subject. Then, a short overview of relevant research topics is provided.

SW-intensive energy systems

Future energy systems will be increasingly software- and data-driven, with advanced orchestration of distributed assets, flexibility services, and real-time optimization within large systems-of-systems and collaborative solution ecosystems [4]. In this context, the role of SE must evolve to address the new challenges posed by software-intensive systems.

This research area focuses on strengthening SE and MBSE methodologies that enable the effective design, integration and V&V of SW-intensive, and data-driven energy systems. As these systems operate in dynamic and potentially evolving contexts, it is of the essence that Engineering ensures that such systems can operate robustly, reliably and cost-effectively while remaining adaptable and future-proof, with appropriate lifecycle management capabilities built-in (including secure updates and upgrades facilities). The objective is to improve the development and integration capability for intelligent, modular, and scalable energy systems, which can be seamlessly integrated into cohesive, resilient systems-of-systems.

Key research questions regarding future SW-intensive energy systems are the following:

- How should SE capabilities evolve to effectively manage the increasing integration of software, data, and AI in energy systems, ensuring reliability, adaptability, and interoperability (similar to the transformation observed in the automotive sector with Software Defined Vehicles)?
- How can MBSE approaches link operational scenarios to system concepts and engineering concerns including lifecycle consideration, i.e. balancing operational usage with lifecycle management, versus value and cost for modular energy systems?
- What reference architecting methodologies can provide insight into fostering incremental integration of new technologies and concepts into existing systems and system family concepts, avoiding costly redesign?

- How can SE workflows manage variability in vendor-specific modules and platforms while ensuring interoperability and resilience in large-scale, federated energy systems-of-systems?

Collaborative energy systems

Future energy ecosystems will depend on collaborative energy cyber-physical systems operating in multi-commodity, multi-energy carrier contexts. Effective engineering of constituent systems in such complex environments requires advancing systems engineering capabilities to safeguard their integrity throughout the lifecycle. The scope for systems engineering is to provide methodologies and frameworks to architect, realize, and manage robust integration by establishing integration principles and model-based workflows. These approaches support modularity and interoperability without compromising autonomy, safety, or robustness.

Key research questions regarding SE for collaborative energy systems are the following:

- How can SE support the development of system-of-systems blueprints that enable autonomous clusters to share or balance energy dynamically while respecting operational independence, robustness and lifecycle constraints?
- How to architect constituent energy systems to ensure reliability, robustness and safety as real-time, data-driven collaboration among multiple independent constituent systems becomes central to system operations and coordination.
- What SE workflows and methodologies can ensure that flexibility and upgradeability are designed into constituent systems from concept through operation, enabling modular expansion of an SoS with additional assets and systems without disrupting existing constituent systems and configurations?

Systems engineering must provide the capabilities to architect, engineer, and manage over the lifecycle the robust and reliable integration of constituent systems within collaborative energy system environments. This includes establishing robust architecting capabilities, lifecycle management strategies that ensure modular components and control mechanisms can be seamlessly integrated. These engineering capabilities are essential to embed robustness, reliability, interoperability, and scalability as intrinsic properties of the overall system, enabling flexibility and effective utilization while safeguarding long-term sustainability across all constituent systems.

7 Collaborative engineering for an evolving ecosystem

7.1 Energy sector needs for collaborative engineering for an evolving ecosystem

To address the challenges of a rapidly transforming and increasingly interconnected energy system, energy network operators, energy suppliers, OEMs, and component suppliers must collaborate across organizational boundaries, despite differing objectives and operational constraints. The sector requires advanced Systems-of-Systems (SoS) Engineering capabilities to enable the integrated design and continuous evolution of engineering frameworks, architectures, and processes that support voluntary cooperation, shared value creation, and dynamic coordination. These capabilities must safeguard the operational independence of each participant, while ensuring the coherence, adaptability, and resilience of the overall energy ecosystem and its constituent systems.

The key SE need for collaborative engineering in an evolving energy ecosystem is the capability to design, manage, and continuously evolve the system-of-systems (SoS) so that it remains coherent, adaptable, and aligned with shared objectives. Even in the absence of centralized governance and amid ongoing changes in technology and ecosystem composition, SoS engineering must ensure architectural coherence and resilience, enabling the ecosystem to adapt effectively to new conditions while maintaining overall system integrity. This capability is needed to respond to the observed trends (see section 4.1), in particular the following:

- *Rise of sustainable, yet intermittent energy sources (trend ii)*
- *Increasing political and legislative pressure (trend iv)*
- *Further integration of energy system(s) (trend vi)*

The energy transition demands an energy system that operates as a coherent, adaptable system-of-systems, even in the context of decentralized governance and continuous technological change. Future infrastructures will likely be highly decentralized, modular, dynamic, and deeply interconnected, functioning as complex systems-of-systems. In this context, Systems Engineering should focus on enabling the continuous evolution of these ecosystems and orchestrating interactions across stakeholders and technologies, helping to ensure that architectures and constituent energy systems remain robust and flexible as the ecosystem transforms.

Outcome

Systems Engineering for evolving energy systems-of-systems enables the creation and sustained lifecycle management of coherent, adaptable, and resilient energy ecosystems. By embedding architectural alignment, modularity, and engineering coordination from the outset, SE supports voluntary cooperation and shared value creation among diverse stakeholders. This collaborative engineering approach ensures that decentralized infrastructures and constituent systems can continuously innovate and transform, remaining aligned with shared objectives even as technologies, regulations, and market conditions change. Through integrated frameworks and processes, SE fosters flexibility, scalability, and effective adaptation while maintaining constituent system integrity.

Source: inspired by Systems Engineering applied to SOS [20], INCOSE position paper [21].

7.2 Research outlook for collaborative engineering for an evolving ecosystem

As the Dutch energy landscape shifts from a centrally managed, fossil-based infrastructure to a more decentralized, modular, and digitally integrated ecosystem, systems engineering faces new challenges. In this context, two main themes are central for engineers and architects:

- Systems-of-systems engineering for the energy transition and
- Innovation and evolution in SoS ecosystems

Advancing systems-of-systems engineering is a key research priority to enable the coordinated integration, validation, and management of diverse, autonomous subsystems throughout the energy transition. At the same time, designing for evolvability ensures the ecosystem remains flexible, future-ready, and able to incorporate new technologies, business models, and societal needs as they emerge.

A brief introduction is given per subject. Then, a short overview of relevant research topics is provided.

Systems-of-Systems Engineering for the energy transition

The energy transition creates a landscape where infrastructures, industrial clusters, and digital platforms form a system-of-systems (SoS), i.e. a network of autonomous yet interdependent systems. Each constituent system (e.g., the grid, heating networks , renewable source energy systems, power-to-X energy conversion systems, industrial plants) has its own governance, and operational constraints, but must collaborate to achieve shared sustainability and reliability goals. Engineering within such a SoS requires moving beyond traditional system design toward architecture-guided integration and lifecycle coordination.

Key research questions regarding Systems-of-Systems Engineering for energy transition are the following:

- How should SoS Engineering workflows & methodologies be setup for energy ecosystems to thrive, ensuring both technical alignment and effective stakeholder collaboration?

- How can validation and assurance approaches be designed to manage complexity and emergent behaviours in large-scale, interconnected energy ecosystems [22]?
- What integrated strategies for modelling, V&V, and monitoring can ensure reliability and compliance across diverse systems and stakeholders in a transitioning energy landscape, considering both technical and social dimensions?
- How can roles such as orchestrators and complementors be formalized within technical architectures to enable clear responsibilities and collaborative decision-making?
- How can Systems Engineering artifacts and models facilitate stakeholder alignment by linking technical analysis with societal needs in energy transitions?

Innovation and evolution in ecosystems

As energy systems become more interconnected and dynamic, there is a growing need for constituent systems and the system-of-systems to be designed for evolvability: supporting the integration of emerging technologies, new forms of economic value, and flexible ways of working together [23]. From a systems engineering perspective, this means moving past static system design to focus on how technical, organizational, and business elements can co-evolve, ensuring the ecosystem remains fit for the future [24].

Key research questions regarding innovation and evolution in ecosystems are the following:

- How can energy ecosystems be designed to be inherently evolvable (using architecting and modular design principles) to enable integration of emerging technologies, business models, and regulatory changes while maintaining stability and coherence?
- How can SE methodologies enable the continuous verification and validation of energy system performance, resilience, and interoperability as energy ecosystems evolve?
- What strategies can SE employ to balance the need for standardization with the flexibility required for innovation and adaptation in rapidly changing energy environments?
- How can systems engineering help anticipate and manage, or mitigate risks associated with innovation and change, such as potential lock-in, fragmentation, or unintended consequences in complex, multi-system, multi-stakeholder environments?

8 SoS security and resilience

8.1 Energy sector needs for SoS security and resilience

The increasing digitalization and integration of cyber-physical components expose the energy system to a broader spectrum of risks, including cyberattacks, cascading failures, and operational disruptions. Unpredictable changes in system context (such as shifting stakeholder roles or evolving supply chains) introduce additional uncertainties that existing standards alone cannot fully address. Systems engineering must integrate security and resilience as central concerns throughout the entire system-of-systems lifecycle, alongside traditional RAMS considerations (Reliability, Availability, Maintainability, Safety). A holistic "loss-driven" engineering approach ensures the continuity, safety, and trustworthiness of the energy system by enabling it to anticipate, withstand, recover from, and adapt to adverse events, whether cyber, physical, or organizational in nature

The key SE need for the energy sector in the area of security and resilience is to design and manage future energy systems-of-systems so they remain secure, resilient, yet adaptable. As infrastructures become more interconnected and geopolitical risks rise, systems must be prepared to anticipate and withstand disruptions and recover quickly. Resilience and security should be embedded from design through operation. These capabilities are needed in response to the observed trends (see section 4.1), in particular the following:

- *Digitalisation and AI (trend v)*
- *Further integration of energy system(s) (trend vi)*
- *Vulnerability of energy infrastructure (trend ix)*

The energy transition with its rapidly growing electricity demand must be supported by an adequate, secure, and resilient infrastructure: this is a clear societal expectation. Future energy systems will be highly decentralized, dynamic, software-intensive, and operating as complex systems-of-systems. Resilience and security must therefore be integrated from the outset as part of a holistic Loss-driven Systems Engineering approach [25], including lifecycle risk management ensuring adaptability under evolving threats and conditions.

Outcome

Systems Engineering for secure and resilient energy systems-of-systems delivers robust, adaptive energy systems and infrastructure that meets society's expectation for reliable service. Security and resilience are designed-in throughout, enabling coordinated protection, rapid recovery, and dependable operation across distributed assets. Adaptive design frameworks integrate risk management, diagnostics, and resilience from the outset, allowing energy systems to anticipate, withstand, and recover from disruptions. Standardized digital engineering workflows and advanced risk assessment frameworks make resilience intrinsic to every energy SoS.

Source: INCOSE position paper [21], TNO SoS position paper [26], Cyber-informed Engineering Implementation Guide [27].

8.2 Research Outlook for SoS security and resilience

As energy systems become more decentralized, software-intensive, and governed by diverse stakeholders, their complexity and interdependencies increase dramatically. These systems operate across local, regional, and national scales, combining physical infrastructure, digital platforms, and socio-technical governance. Ensuring resilience, security, and sovereignty in this context is not optional: it is foundational for a future-proof, sustainable energy ecosystem. There is a growing need for Systems Engineering to provide the methodological backbone to manage this complexity, embedding resilience and security as intrinsic properties throughout the lifecycle [21] [27].

In the research outlook for SoS security and resilience, we consider two research areas as following:

- Ensuring energy system resilience
- Energy system security and sovereignty

Here, resilience focuses on the ability of energy systems to anticipate, absorb, and recover from disruptions [28] [29], ensuring continuity of service under dynamic conditions. In contrast, security and sovereignty emphasize preventing unauthorized access, safeguarding critical assets, and maintaining trusted, autonomous control over infrastructure and data, protecting the system against external threats and undue dependencies [30].

A brief introduction is given per subject. Then, a short overview of relevant research topics is provided.

Ensuring energy system resilience

Energy system resilience in the future multi-commodity, multi-scale energy system-of-systems context means designing and managing interconnected systems and infrastructures (electricity, heat, hydrogen, green gases) so they can anticipate, withstand, and recover from disruptions. These systems are highly decentralized, digitally integrated, but also socio-technical in nature, lacking central ownership nor having central management [31], thus requiring coordination across diverse stakeholders and scales.

In these future multi-commodity, multi-scale energy system-of-systems, resilience must be embedded from the outset through adaptive architectures, modularity, and functional redundancy, supported by digital engineering workflows and digital twins. Systems engineering plays a critical role in managing complexity, ensuring interoperability, and balancing trade-offs between flexibility, security, resilience, and cost. The challenge lies in engineering resilience not only at the component level but across the entire SoS lifecycle, considering emergent behaviours, cascading failures, and dynamic interactions between physical and cyber layers.

Key research questions regarding ensuring energy system resilience are the following:

- How can systems engineering frameworks and design methodologies (e.g. [32]) integrate resilience as a design principle across heterogeneous energy carriers and scales?
- What reference architectures and SoS design patterns enable modularity and adaptability without compromising interoperability and resilience?
- How can MBSE be leveraged to predict, diagnose, and mitigate cascading of potential failures in multi-commodity energy systems (e.g. as in [33])?
- How can resilience strategies be optimized under uncertainty, balancing redundancy, flexibility, and cost across interconnected systems and infrastructures?

To enable the further integration of the energy system, the increase of digitalisation and use of AI, collaboration across organizations and ecosystems becomes increasingly relevant to ensure the resilience of the future energy system.

Energy system security & sovereignty

Security and sovereignty in future energy systems-of-systems extend beyond cybersecurity to include physical protection, operational independence, and governance integrity. As energy systems become software-intensive and globally interconnected, vulnerabilities increase due to an expanded attack surface, complex supply chain dependencies, and the concentration of digital control within large technology providers. From a systems engineering perspective, ensuring sovereignty in energy systems requires the adoption of open standards, transparent protocols, and robust governance frameworks. These elements reduce dependency on external parties and help maintain trusted control over critical energy functions.

Systems engineering must address these concerns by embedding security-by-design principles, integrating risk management across lifecycle stages, and ensuring interoperability without sacrificing autonomy. The challenge is how to engineer for secure, sovereign energy systems that maintain trustworthiness while enabling innovation and scalability in a complex, evolving ecosystem.

Key research questions regarding energy system security & sovereignty are the following:

- How can systems engineering methodologies incorporate security and sovereignty requirements into SoS architectures from the outset?
- What architecting frameworks and engineering methodologies help ensure security and trusted control over critical energy functions in collaborating energy systems?
- What risk modelling and assessment approaches at SE level can capture cyber-physical interdependencies and suggest proactive mitigation strategies balance with cost and risk appetite?
- How can lifecycle risk management be institutionalized across multi-stakeholder ecosystems to maintain safety, security and sovereignty under dynamic conditions?

9 Digital Systems Engineering

9.1 Energy sector needs for Digital Systems Engineering

Digitalization and standardization of energy (cyber-physical) system design, information exchange, and asset lifecycle management are essential to improving engineering productivity, accelerating infra-structure deployment, and ensuring energy system resilience. By adopting model-based and data-driven engineering practices, energy network operators, contractors, OEMs and technology providers, can reduce integration errors, improve traceability, and support faster, more informed decision-making. Overall, digitalization can help accelerate and enhance the engineering and expansion of energy infrastructure.

The transition to Digital Systems Engineering is a key enabler to improve Systems Engineering effectiveness and efficiency for the energy sector. Methodological and tool support can ease and automate many SE tasks and provide much greater consistency and overview. This digital transformation of SE supports the energy sector needs related to the observed trends (see section 4.1), notably the following:

- *Digitalisation and AI (trend v)*
- *Further integration of energy system(s) (trend vi)*
- *Scarcity of engineering experts (trend viii)*

Development and integration of engineering system models to support engineering, and to maintain overview of assets are central goals of the digital engineering strategy for the energy sector. By providing an authoritative source of truth, embedding technical innovation, and improving engineering quality, these models enable a consistent, data-driven engineering and lifecycle management collaboration across various stakeholders, such as grid and gas network operators, contractors, OEMs and technology providers. They also help establish a supportive environment for cross-organizational coordination and foster a cultural shift toward digital engineering practices throughout the energy system lifecycle and value chain.

Outcome
Digital Systems Engineering will be a core capability enabling the design, realization, and lifecycle oversight of both decentralized energy systems and grid infrastructure. Through explicit, standardized information flows and robust digital thread and asset management, engineering teams will seamlessly capture, structure, and share knowledge across organizational boundaries. This capability ensures that models,

data, and expertise are accessible and interoperable throughout the system lifecycle, supporting transparent, auditable processes and compliance. As a result, the sector will achieve resilient, adaptive, and knowledge-driven engineering, enabling all stakeholders to deliver and maintain a secure, efficient, and future-proof energy system.

Source: ADE [4] and INCOSE vision 2035 [2].

9.2 Research Outlook for Digital Systems Engineering

In the research outlook for Digital Systems Engineering, we consider a few topic areas as following:

- Digital Systems Engineering for the energy sector,
- Introduction and embedding of Digital Systems Engineering.

A brief introduction is given per subject. Then, a short overview of relevant research topics is provided.

Digital Systems Engineering for the energy sector

The digital transformation of the energy sector presents unique challenges for Digital Systems Engineering, requiring approaches distinct from those in high-tech equipment manufacturing [34] [35] [36], or defence [37] . Energy systems must integrate legacy infrastructure, support multiple energy carriers, and function within a distributed, multi-stakeholder ecosystem. To meet sector needs, i.e. explicit knowledge management, standardized information flows, digital lifecycle and asset oversight, and sector-wide transparency, the digitalisation of SE must deliver robust, interoperable, and knowledge-driven digital engineering environments to the energy sector.

Key research questions regarding digital Systems Engineering for the energy sector are the following:

- What digital SE methodologies can best support product line, platform-based development and reuse across energy infrastructure projects?
- How can engineering models and data be seamlessly integrated and leveraged to support comprehensive asset lifecycle management in the energy sector?
- What digital SE methods and standards are needed to support long-term, strategic supply chain and ecosystem collaboration, ensuring shared data among partners?
- How can such methods, energy systems models and digital assets data remain composable and interoperable across organizations, platforms and ecosystems?
- What model-based approaches can support multi-disciplinary analysis of energy system qualities (e.g., resilience, flexibility, cybersecurity) at the scale and complexity of national energy systems?

Introduction and embedding of Digital Systems Engineering

The transition to Digital Systems Engineering and MBSE in the energy sector is a long-term, multi-year process that requires not only technological adaptation but also significant organizational and cultural change. Successful embedding depends on developing both individual and organizational competencies, fostering a culture of continuous learning, and establishing governance structures that support digital workflows. This transition must be inclusive, address workforce development, and ensure that digital skills and knowledge management are embedded at every level [4]. Change management strategies must be tailored to the sector's complexity, legacy systems, and distributed stakeholder landscape.

Key research questions regarding the introduction and embedding of Digital Systems Engineering are the following:

- How must systems engineering processes and organizational structures evolve to effectively adopt Digital SE, considering sector-specific trends such as decentralization, interoperability, and regulatory requirements?
- How can organizations assess and build the necessary readiness and maturity in systems engineering capabilities to ensure a smooth transition to digital engineering practices?
- What change management strategies best support the introduction, scaling, and sustained embedding of Digital SE and MBSE in diverse energy sector organizations?
- How can knowledge sharing, digital skills development, and stakeholder engagement be coordinated sector-wide to accelerate adoption and maximize the benefits of digital systems engineering?

10 SE competences for the future

10.1 Energy sector needs for SE competences for the future

Identifying and developing the necessary competencies for lead engineers and other personnel is crucial for effective collaboration within the organization and with external partners. This includes fostering skills in systems engineering (SE) and project management (PM) methodologies to support complex energy projects. By enhancing SE competencies, energy system operators can improve coordination, reduce project risks and failures, and achieve better outcomes in terms of delivery time, quality and costs of projects. Continuous professional development is needed to ensure the energy sector is equipped to handle future challenges.

The research for future Systems Engineering competencies and associated competence development (in support of the energy sector needs) relates to all observed trends (see section 4.1). Notably the following trends drive the competence development of individuals and also development of organizational SE capabilities:

- *Digitalisation and AI (trend v)*
- *Further integration of energy system(s) (trend vi)*
- *Globalization of supply chains (trend vii)*
- *Scarcity of engineering experts (trend viii)*

Keeping the competencies of SE individuals and organizations up to date requires a life-long learning perspective.

> **Outcome**
>
> A life-long educational, training, mentoring, and learning journey is in place to empower energy systems engineers and systems engineering organizations in the energy sector with strong multi- and transdisciplinary integrative competencies.
> A wide range of education and training curricula provide systems engineers the requisite systems engineering fundamentals and help them and their organizations continue to stay abreast of advances in practices and technologies.
>
> Source: inspired by NXTGEN initiative [38] and INCOSE “Building the systems engineering workforce of the future” white paper [39]

10.2 Research Outlook for SE competences for the future

In the research outlook for Digital Systems Engineering, we consider a few topic areas as following:

- Competence profile of an energy systems engineer,
- Organizational SE capabilities and competencies
- Lifelong learning/continuous education and competence development.

A brief introduction is given per subject. Then, a short overview of relevant research topics is provided.

Competence profile of an energy systems engineer

Future energy systems engineers will operate in an increasingly digitalized environment, supported by advanced tools and data-driven workflows. This shift is changing the competencies required for systems engineers, with new emphasis on digital fluency, modular design, and the ability to manage complexity across various energy domains and systems [39]. As digitalization accelerates, engineers must also be adept at leveraging automation, and collaborative platforms to collaborate with external partners and contractors.

A competence profile captures essential skills, knowledge, and behaviours necessary for proficiently executing a specific job, role, or function. Such a profile should reflect not only technical expertise, but also strong systems thinking, integration across organizational boundaries, and effective communication and leadership. The ability to work effectively in multidisciplinary teams and to coordinate with external partners is increasingly vital as projects span organizational and national boundaries. Continuous professional development and a commitment to lifelong learning are essential to maintain relevance in this dynamic context. The INCOSE systems engineering competency framework [5] provides a solid foundation. It should be further tailored to address the specific needs of the energy sector.

Key research questions regarding the future competence profile of a systems engineer are the following:

- What are the key competencies and future roles required for energy systems engineers to thrive in an increasingly digitalized, software-intensive, and modular energy sector?
- How does digitalization influence the ability to maintain systems thinking, critical analysis, and adaptability in complex, rapidly evolving environments [40]?
- How can competence profiles and training programs be designed to accelerate the acquisition and continuous updating of system-level knowledge and skills, ensuring effective collaboration across diverse teams and stakeholders throughout the energy value chain?
- How can competence development support energy systems engineers in integrating specialized and generalist roles, enabling productive teamwork and innovation across organizational and sectoral boundaries?

In summary, as the energy sector continues to evolve, competence profiles for energy systems engineers will need to be regularly adapted. Ongoing attention to emerging technologies, new forms of collaboration, and sector-specific requirements will help ensure that energy systems engineers remain equipped to address the increasing complexity and interdisciplinary nature of future energy systems.

Organizational and ecosystem SE capabilities and competencies

A stronger emphasis on organizational and ecosystem SE capabilities is needed in the energy sector. Systems Engineers routinely work together in teams and increasingly collaborate with partners and supply chains in a co-creation development mode. By collaborating in ecosystems, the scope of their engineering expands quickly beyond their own systems. System Engineers need to understand further systems beyond their own systems and need broader domain knowledge.

Key research questions regarding organisational and ecosystem SE capabilities and competencies are the following:

- How can various SE roles be effectively combined and integrated in teams to enable productive collaboration with other system-level stakeholders across the lifecycle and value chain?
- How will SE processes and organizational structures need to evolve as the sector adopts Digital Systems Engineering and responds to broader trends such as modularization, data-driven decision-making, and increased stakeholder diversity?
- What approaches and role models, best practices from high-tech and other sectors, and learning communities can be adapted or developed to foster organizational maturity, continuous improvement, and knowledge exchange in collaborative, multi-stakeholder energy ecosystems?
- What collaborative SE capabilities and competencies are needed for effective cooperation across value and supply chains, and how can education and competence development programs best support these needs?

The need for collaborative SE competencies will continue to grow for all actors in the energy sector, including energy system operators and energy suppliers, energy system contractors and OEMs, and their partners and suppliers. Building these capabilities is critical for accelerating innovation, ensuring interoperability, and delivering resilient, future-proof energy systems.

Lifelong learning/continuous education and competence development

The way systems engineers learn evolves throughout their careers. Early on, formal learning formats, such as structured courses and training programs, are effective for building foundational competencies. As their careers progress, experiential learning becomes increasingly important: learning on the job, engaging in peer review, rotating through different roles, mentoring, and building professional networks all play a critical role in deepening expertise and adapting to new challenges.

In the energy sector, the technological change of the energy transition, the ongoing digitalization, and the need for cross-organizational collaboration further emphasize the importance of lifelong learning. Engineers must continuously update their skills to remain effective in multidisciplinary, software-intensive, and modular environments. Organizations are encouraged to foster a culture where knowledge sharing, mentoring, and collaborative learning are embedded in daily practice, supporting both individual growth and sector-wide, cross organisation, innovation.

Key research questions regarding lifelong learning for energy systems engineers include the following:

- How can energy sector organizations stimulate and support engineers to embrace lifelong learning as a core professional value, including on the level of senior (Lead) Engineers in the energy sector?
- What strategies are effective for developing independent critical thinking and hands-on problem-solving skills, especially as digital tools and assistants become more prevalent in engineering workflows?
- How can lifelong learning be organized and sustained at the individual, team, organizational, and ecosystem levels to ensure adaptability and resilience?
- In what ways can human factors, such as communication, leadership, and adaptability, be integrated into systems engineering education and ongoing professional development for the energy sector?
- What are the most effective approaches to supporting continuous learning and capability development for systems engineering organizations working collaboratively in digitalized, multi-stakeholder energy ecosystems and value chains?

The ongoing transformation of the energy sector requires systems engineers to continuously update their skills and adapt to new ways of working. Lifelong learning and competence development are therefore necessary to keep pace with technological, organizational, and sectoral changes, and to remain effective performance in an evolving energy systems landscape.

11 Conclusions

11.1 Summary of future Systems Engineering needs of the energy system

In this vision document, we have reviewed the trends and challenges across the energy transition and its stakeholders. These trends and enablers are in support of the ongoing digitalization of the business in the sector. They necessitate the energy sector to upgrade their Systems Engineering capabilities to stay relevant faced with the energy transition.

We have clustered the energy sector needs on future Systems Engineering capabilities in the following four categories:

1. Building faster and smarter
2. Increasing utilization and enhancing flexibility
3. Collaborative engineering for an evolving ecosystem
4. SoS security and resilience

Furthermore, the following two enablers for these needs were addressed as well:

5. Digital Systems Engineering
6. SE competences for the future

For these topics, we have elaborated the energy sector needs and provided an envisioned outcome for the Systems Engineering capabilities in 2035. This envisioned outcome then is the basis of the research outlook what new capabilities, competence development, of Systems Engineering guidance and support are needed to meet that outcome.

11.2 Summary of Research Outlook on SEES

The research outlooks presented in this vision document respond to the evolving needs of the energy sector, structured around six central themes that define the sector's Systems Engineering (SE) priorities. For each theme, targeted research topics and guiding questions have been formulated to steer the development of new methodologies, digital tools, and competence profiles.

Key research directions focus on accelerating infrastructure development through modularization, standardization, and digitalization, enabling more efficient project delivery and improved scalability across the energy system. The integration of advanced digital and model-based engineering practices is central to supporting data-driven decision-making, enhancing design quality, and streamlining lifecycle management. In parallel, research is directed toward strengthening the flexibility and resilience of energy systems, addressing the challenges posed by increasing complexity, decentralization, and the integration of diverse energy carriers and technologies.

The outlook further emphasizes the importance of collaborative approaches, both within organizations and across the broader energy ecosystem. This includes fostering effective partnerships among network operators, technology providers, contractors, and other stakeholders to address system-level challenges and drive innovation. Continuous competence development is also highlighted, ensuring that engineers and organizations can adapt to rapid technological and organizational changes, maintain high standards of performance, and support the ongoing energy transition.

Collectively, these research directions provide a robust foundation for advancing Systems Engineering in the energy sector. They enhance the sector's ability to address complexity, foster innovation, and contribute to the successful and expedient realization of the energy transition. By focusing on modularity, digitalization, collaboration, resilience, and lifelong learning, the SEES research agenda supports the development of future-proof energy systems that are reliable, sustainable, and adaptable to changing societal and technological demands.

11.3 PMC SEES outlook and invitation

This vision document has outlined the perspective of the Product Market Combination Systems Engineering of the Energy System (PMC SEES) on the evolving needs of the energy sector. It has presented an initial research outlook across six key themes, elaborating on the Systems Engineering requirements and providing directions for future research.

It is important to consider this document within the broader context of the full set of PMC visions. Some overlap and collaboration between PMCs will be necessary to comprehensively address the challenges and requirements of the energy sector.

The TNO-DTES Product Market Combination SEES intends to use this document as a foundation for ongoing dialogue with industry and academia, with the aim of advancing Systems Architecting and Systems Engineering in support of the energy transition. The insights and discussions generated from this document will help guide TNO-DTES research activities to ensure continued relevance and impact for the energy sector.

Readers are invited to view this document as a starting point for engagement. TNO-DTES Program Management and the TNO DTES PMC teams welcome discussions on your organization's needs, research questions, and ideas for enhancing Systems Engineering capabilities, productivity, and effectiveness in your organisation or ecosystems.

11.4 Revisions

This document is the first version of the "Systems Engineering of the Energy System - PMC SEES Vision and Research Outlook".

Future versions may expand and revise contents, or categorize the research outlook along TRL levels, addressing fundamental research with academic partners, TNO applied research, consultancy, training, and collaboration with Implementation Partners.

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