7. Analysing Energy Systems Integration: A Socio-Technical Approach and a System Architecture Methodology

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7.1. Introduction

One possible pathway to drive the energy transition flexibly and cost-effectively is energy systems integration (ESI), also known as sector coupling, of electricity, gas, and heat. ESI aims to capture and exploit interactions and diversity across multiple energy vectors by connecting energy systems physically and virtually across infrastructures and markets. ESI is perceived as a possible solution as it

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provides the required system flexibility by diversifying input and output energy streams. This solution also allows a peak in demand or production to be shifted from one system to another by conversion between vectors. This would create new interactions and interfaces between the different components of the energy system resulting in emergent properties such as flexibility. Moreover, ESI is expected to have an impact on the current energy system architecture with changes in the planning and operations paradigm, the market structure, and the regulatory framework.[5]

This chapter presents a methodological framework to identify and analyse those interactions across energy systems and understand the possible architecture of the future integrated energy system. The framework is based on a system-of-systems (SOS) modelling approach that represents the future integrated energy system architecture. It includes structural and functional interlinkages across systems and stakeholders while reducing complexity through abstraction. In this vein, focusing on ESI as a case study, this chapter aims to answer the following research questions:

- How to identify and analyse interactions across socio-technical systems?
- How to identify the structure of current and possible future socio-technical networks?

This chapter is structured as follows. First, section 2 discusses ESI from a socio-technical transitions perspective. Next, section 3 describes the methodology and the underpinning conceptual framework. Afterward, section 4 explains the framework application. Finally, section 5 summarises the contributions made here and discusses future work horizons.

5. Mark O'Malley, et al., *Energy Systems Integration: Defining and Describing the Value Proposition* (Golden: International Institute for Energy Systems Integration, 2016). http://dx.doi.org/10.2172/1257674; Richard Hanna, et al., *Unlocking the potential of Energy Systems Integration* (London: Energy Futures Lab, 2018). http://bitly.ws/qsBs; Tooraj Jamasb and Manuel Llorca, 'Energy Systems Integration: Economics of a New Paradigm.' Economics of Energy and Environmental Policy,' *The Energy Journal* 8, no. 2 (April 2019): 7–28. http://dx.doi.org/10.5547/2160-5890.8.2.tjam

7.2. A Multi-System Perspective for Energy Systems Integration

This section explores relevant concepts from the transitions literature and discusses ESI from a socio-technical transitions perspective. In the scope of the socio-technical transition literature, integration has been identified as one of the multi-regime interactions that could occur within or across socio-technical systems. The concept of multi-regime interactions extends from the multi-level perspective (MLP) theory, moving to a multi-system perspective (MSP) that highlights the fact that interactions between multi-regimes across systems, rather than within systems, are of main interest. This perspective is applied to ESI, where interactions occur between the multi-regimes (i.e., generation, networks, and consumption) of its different integrated systems (i.e., electricity, gas, and heat). In this train of thought, a SoS conceptualisation of ESI is suggested and a method to operationalise this understanding is later presented below.

The Multi-System Perspective

The energy system is considered socio-technical and is composed of actors and institutions in addition to technological artefacts and knowledge interacting to provide energy services for society.[6] This system is undergoing a transition to achieve the energy policy trilemma objectives of delivering decarbonisation, maintaining a secure and reliable energy supply, and providing acceptable and affordable energy.[7] A key theory presented in the literature to understand the dynamics of sustainability transitions is the MLP, which distinguishes between three levels. First, the niche-innovations level is where radical novelties emerge in protected spaces. The second level is the socio-technical regime and constitutes the institutional structuring of existing systems. The third level regards the socio-technical landscape where exogenous developments that affect niche and regime activity take place. According to the MLP, transitions happen upon

6. Jochen Markard, Rob Raven, and Bernhard Truffer, 'Sustainability transitions: An emerging field of research and its prospects,' *Research Policy* 41, no. 6 (July 2012): 955–67. https://doi.org/10.1016/j.respol.2012.02.013

7. Kathleen Araújo, 'The emerging field of energy transitions: progress, challenges, and opportunities,' *Energy Research & Social Science* 1 (March 2014): 112–21. https://doi.org/10.1016/j.erss.2014.03.002.

interactions between processes at the three levels. Typically, niche innovations pick up momentum internally through learning processes while changes at the landscape level create pressure on the regime. At some point, the regime gets destabilised creating an opportunity for niche innovations.[8]

Different types and timings of interactions between the multiple levels lead to diverse types of transition pathways, namely: transformation, technological substitution, de-alignment and re-alignment, and reconfiguration.[9] This latter happens when, for instance, innovation is initially adopted to solve local regime problems, but leads to an adjustment in the system architecture.[10] It stems from the concept of architectural innovations that alter the architecture of a system without changing its components by reconfiguring an established system to link existing components in a different way.[11] However, although reconfigurations and architectural changes are of interest in the scope of ESI, the MLP, as initially described, focuses on breakthroughs of singular innovations and the transition pathways only describe the interactions between the different levels of the MLP.

An extended version of the MLP accounts for interactions between multi-regimes and multi-niches. For example, multiple regimes exist and interact in the mobility system such as auto-mobility, bus, rail, and cycling.[12] Similarly, in the electricity sector, multiple regimes typically include generation, networks, and consumption.[13] In this case, the transition pathway becomes a whole system

8. Frank W. Geels, *Technological Transitions and System Innovations: A Co-Evolutionary and Socio-Technical Analysis* (Cheltenham: Edward Elgar Publishing Limited, 2005).

9. Frank W. Geels and Johan Schot, 'Typology of sociotechnical transition pathways,' *Research Policy* 36, no. 3 (April 2007): 399–417. https://doi.org/10.1016/j.respol.2007.01.003

10. George Papachristos, Aristotelis Sofianos, and Emmanuel Adamides, 'System interactions in socio-technical transitions: Extending the multi-level perspective,' *Environmental Innovation and Societal Transitions* 7 (June 2013): 53–69. https://doi.org/10.1016/j.eist.2013.03.002

11. Rebecca M. Henderson and Kim B. Clark, 'Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms,' *Administrative Science Quarterly* 35, no. 1 (March 1990): 9–30. https://doi.org/10.2307/2393549

12. Frank W. Geels, 'Low-carbon transition via system reconfiguration? A socio-technical whole system analysis of passenger mobility in Great Britain (1990–2016),' *Energy Research & Social Science* 46 (December 2018): 86–102. https://doi.org/10.1016/j.erss.2018.07.008

13. Andrew McMeekin, Frank W. Geels, and Mike Hodson, 'Mapping the winds of whole system reconfiguration: Analysing low-carbon transformations across production, distribution and consumption in the UK electricity system (1990–2016),' *Research Policy* 49, no. 5 (June 2019): 1216–31. https://doi.org/10.1016/j.respol.2018.12.007.

reconfiguration due to multiple change mechanisms.[14] Thereby, a new whole system architecture is expected as a result of reconfiguration since linkages between subsystems are changing.[15]

The MSP builds on the multi-regime interactions, but it is distinguished by focusing on interactions between multiple regimes across systems rather than multiple regimes within the same system.[16] For instance, in the context of ESI, beyond looking at the interactions within the multiple regimes of the electricity system (generation, networks, and consumption), emphasis should be placed on the interactions across the different energy systems (electricity, gas, and heat) each of which has their multiple regimes within. This can be expanded to other utility sectors such as water and telecom.[17] It is therefore essential to clearly define the boundaries of the systems under study to identify those internal and external ones.[18]

In a review of the MSP, Rosenbloom mentions that the focus of the MSP is on identifying three aspects.[19] First, the functional and structural interlinkages between the systems. Second, the system interaction patterns and their implications for sustainability transitions. Third, are the emerging interfaces where interactions take place. Identifying interfaces is particularly important as it helps understand how the system architecture could be shaped upon a transition and how system boundaries may be accordingly redefined.[20]

By the same token, the author points out four types of multi-regime interactions:

- Competition: It is where regimes compete in delivering similar functions.

14. Geels, 'Low-carbon transition.'

15. McMeekin, Geels, and Hodson, 'Mapping the winds.'

16. Daniel Rosenbloom, 'Engaging with multi-system interactions in sustainability transitions: A comment on the transitions research agenda,' *Environmental Innovation and Societal Transitions* 34 (March 2020): 336–40. https://doi.org/10.1016/j.eist.2019.10.003

17. Kornelia Konrad, Bernhard Truffer, and Jan-Peter Voß, 'Multi-regime dynamics in the analysis of sectoral transformation potentials: evidence from German utility sectors,' *Journal of Cleaner Production* 16, no. 11 (July 2008): 1190–1202. https://doi.org/10.1016/j.jclepro.2007.08.014

18. Papachristos, Sofianos, and Adamides, 'System interactions.'

19. Rosenbloom, 'Engaging with multi-system.'

20. Ibid.

- Symbiosis: It refers to where regimes cooperate in delivering a societal function
- Integration: It implies where regimes become integrated to form a new entity for delivering a societal function.
- Spill-over: It is where elements from one regime are taken up within another (i.e., transfer of rules).

In conclusion, system interactions are characterised by the MSP as diverse because systems tend to share a range of different connections, layered stretching across regime and niche levels at multiple geographic scales. These evolve with system boundaries and objectives changing over time.[21]

Conceptualising Energy Systems Integration

The MSP is applied to understand the dynamics between multiple regimes across socio-technical systems. ESI involves multiple energy systems, namely: electricity, gas, and heat. The systems are linked by coupling components such as combined heat and power (CHP), power-to-x (P2X), and heat pumps (HPs). These technologies enable energy vector conversion or electrification of end-use sectors. These are examples of niche innovations that create new linkages between regimes.[22] Each of the energy systems has multiple regimes responsible for generation, networks, and consumption. Interactions occur between multiple regimes across different systems. For instance, CHP couples the electricity and heat systems at the generation level, both being fed by the same energy source. On the other hand, P2X couples the different energy systems at the networks level. In turn, HPs can relate energy systems at both networks and consumption levels, depending on their scale.

ESI originates from a holistic approach that considers the whole energy system (WES) comprising multiple energy vectors, the energy supply chain span from generation to end-use, and the system environment embracing multiple perspectives and objectives of different energy actors. This is similar to the MSP

21. Ibid.

22. Geels, 'Low-carbon transition.'

characterisation of system interactions, which are diverse, layered, and evolving as described earlier and reflected in the methodological framework proposed below. System interactions involved in ESI clearly fall under the integration type defined earlier. Integration of socio-technical regimes involves coupling previously separated regimes to form a new entity, which does not necessarily mean that parent systems would disappear.[23] This chapter conceptualises this new entity for the case of ESI as a SOS. This latter is defined as an integration of independent systems that act jointly towards a common goal, through synergies, to collectively offer emergent functionality that cannot be provided by constituent systems (CSS) alone. A SOS is characterised by operational and managerial independence, geographical distribution, evolutionary development, and emergence.[24] The SOS features apply to ESI where different utility companies are independently responsible for operating, managing, and developing the CSS. These latter are naturally geographically dispersed and emergent behaviour that cannot be delivered by individual components separately as a result of interaction between the CSS.[25]

Integration can take place at the actors and institutional level or take a hard form with technological integration.[26] Both forms of integration are expected in ESI, which will involve a whole system reconfiguration bringing about different system architectures. At the technological level, ESI will create new interactions and interdependencies between the different energy systems beyond traditional boundaries, making it more complex to manage the WES. Moreover, interactions lead to emergent behaviour that would affect the system performance and it should be anticipated and captured. Thus, new planning

23. Ron Raven and Geert Verbong, 'Multi-Regime Interactions in The Dutch Energy Sector: The Case of Combined Heat and Power Technologies in the Netherlands 1970-2000,' *Technology Analysis & Strategic Management* 19, no. 4 (2007): 491–507. https://doi.org/10.1080/09537320701403441

24. Claus Nielsen Ballegaard, et al., 'Systems of Systems Engineering: Basic Concepts, Model-Based Techniques, and Research Directions,' *ACM Computing Survey* 48, no. 2 (November 2015): 1–41. https://doi.org/10.1145/2794381

25. Saurabh Mittal, et al., 'A system-of-systems approach for integrated energy systems modeling and simulation,' paper presented at *the Society for Modeling & Simulation International Summer Simulation Multi-Conference*, Chicago, USA, July 26–29, 2015. http://bitly.ws/qtqe

26. Raven and Verbong, 'Multi-Regime Interactions.'

and operational paradigms need to be designed to account for the complexity involved and the emerging behaviour. At the markets and institutional level, ESI will bring together multiple actors with different objectives and motivations. In this vein, new opportunities to develop ESI will foster partnerships between separate energy businesses, each of which has an independent market structure and regulatory framework. In addition, new actors could emerge with new business models posited to take advantage of ESI. This will lead to a change in the market structure and the governance framework, which again mean a new energy system architecture.

A number of other relevant studies can be found in the sustainability transitions literature. For example, CHP is deemed as a case study of a technology that would create multi-regime interactions between distinct systems (electricity and gas) to demonstrate that transitions would possibly cross traditional regime boundaries.[27] Another study delves into the interactions between the different energy systems (electricity, heat, transport) in the case of electrification, stressing the relationships between the actors implied.[28] Lastly, another research suggested exploring future system changes through different possible system architectures, focusing merely on the electricity system, though.[29]

7.3. A System-of-Systems Architecture Methodology

To operationalise the MSP in the context of ESI and understand the interactions across the integrated energy systems, a SOS architecture methodology is proposed here. The methodology was initially developed to facilitate the sustainability assessment of integrated energy systems by modelling the whole system as a SoS and analysing its system architecture. The methodology yields

27. Ibid.

28. Daniel Rosenbloom, 'A clash of socio-technical systems: Exploring actor interactions around electrification and electricity trade in unfolding low-carbon pathways for Ontario,' *Energy Research & Social Science* 49 (March 2019): 219–32. https://doi.org/10.1016/j.erss.2018.10.015

29. Kristina Hojčková, Björn Sandén, and Helena Ahlborg, 'Three electricity futures: Monitoring the emergence of alternative system architectures,' *Futures* 98 (April 2018): 72–89. https://doi.org/10.1016/j.futures.2017.12.004

appropriate criteria and indicators for evaluating the effectiveness of ESI as a pathway to achieving the energy transition objectives. This is done first by identifying the system requirements representing different stakeholders' needs and objectives and then mapping them with the relevant system functionalities or capabilities that fulfil those requirements.

Due to the integrated and complex nature of the system under study, the system needs to be broken down into its different components to study the interfaces and interdependencies between them. The modelling process highlights the interactions between the different energy systems at different levels and the system environment involving multiple stakeholders. In doing so, abstraction at different levels is employed to capture emergent behaviour and reduce complexity. Moreover, the possible structure and relations are manifested in a system architecture model. Thus, this methodology is proposed to understand the interactions across socio-technical systems and the possible future structure of socio-technical networks.

The first aim of the methodology is to develop a conceptual model of the WES with appropriate evaluation principles. This means that the model should be multi-dimensional (i.e., representing different perspectives of multiple stakeholders), multi-vectoral (i.e., covering multiple energy vectors), and systemic (i.e., spanning the energy supply chain from generation to end-use through networks). Likewise, the model should be future-oriented to adapt to possible structural changes in the energy system and systematically replicable for different situations. Finally, the model should lead to the evaluation of the system but the applicability of this depends mainly on data availability. This is supported by the conceptual framework shown in FIGURE 9.

As shown above, the modelling and analysis are carried out using systems engineering methods, namely model-based systems engineering (MBSE), architectural frameworks, and requirements analysis.[30] Similarly, the SOS architecture methodology is used as a structured approach to develop or represent the potential future conditions of a system. Furthermore, a system architecture

30. Nielsen Ballegaard, et al., 'Systems of Systems Engineering.'

includes principles and guidelines governing the structure, functions, and interactions between its components and with its environment, and how it will meet its requirements. Besides, 'system requirements' refer to the functions and capabilities that the system needs to fulfil or acquire and relate mainly to the needs of stakeholders. This approach enables the system to be broken into a number of interacting perspectives and helps translate system requirements into possible solutions and visualise the potential impact. This approach also highlights interfaces between sub-systems, components, and actors involved.[31] Using this approach allows for a socio-technical evaluation emphasising not only interactions between systems but also the relations between the whole system and its stakeholders. Thereby, this approach delivers on the requirement for the model to be multi-dimensional and futuristic.

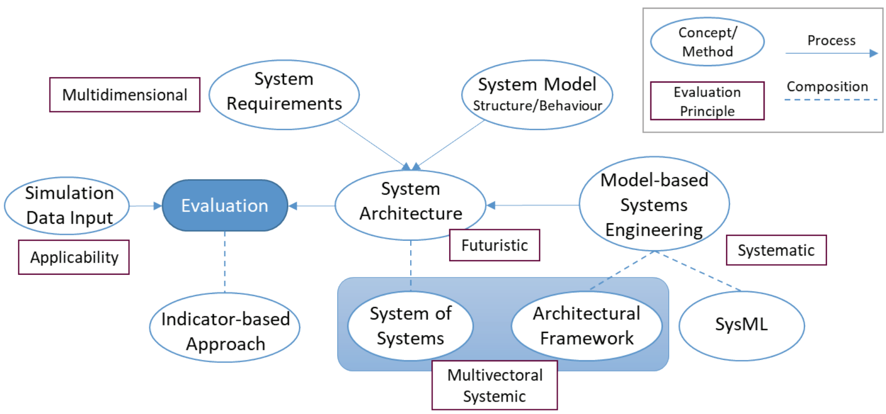

FIGURE 9. Conceptual Framework

Source: Prepared by authors.

By the same token, the system is modelled as a sos. Such an approach applies to large scale interdisciplinary problems that span multiple distributed systems.[32] It also allows the system to be decomposed into its different constituent systems

31. Energy Systems Catapult, *Systems thinking in the energy system: A primer to a complex world* (Birmingham: Energy Systems Catapult, 2018). http://bitly.ws/qvgP

32. Ibid.

(i.e., electricity, gas, and heat) and system elements (i.e., generation, networks, and consumption) stressing the interdependencies between them. A sos approach supports a diverse and holistic understanding of the evolving systems and a focus on the boundaries and interactions between the different systems.[33] This satisfies the requirement for the model to be multi-vectoral and systemic.

Additionally, MBSE techniques are used to develop the conceptual model and represent the system architecture. MBSE is the formalised application of modelling to support system design, architecture, analysis, and evaluation. MBSE is supported by the systems modelling language (SysML), which is a graphical modelling language for designing and analysing complex systems.[34] SysML diagrams include structural and behavioural diagrams, in addition to requirements and parametric diagrams. The modelling is guided by a framework that considers the system views required to describe a system architecture systematically.

7.4. Framework Application

The architectural framework employed for this analysis is an adapted version of the framework 'system-of-systems approach to context-based requirements engineering' (SoS-ACRE).[35] The main feature of this architectural framework is it decomposes the system under study into different levels as for the sos architecture. System views are divided into four system levels, namely: the Context, sos, CS, and whole system levels. At each level, several views are developed to show the system structure, composition, stakeholders, requirements, and measures of effectiveness, using SysML diagrams. Another significant characteristic of this framework is it shows the interactions between the different CSs contexts and the ones between CSs and the sos as a whole.

33. Erik Pruyt and Wil Thissen, 'Transition of the European Electricity System and System of Systems Concepts,' paper presented at *2007 IEEE International Conference on System of Systems Engineering*, San Antonio, USA, April 16–18, 2007. http://doi.org/10.1109/SYSOSE.2007.4304305

34. Ana Luisa Ramos, José Vasconcelos Ferreira, and Jaume Barceló, 'Model-based systems engineering: An emerging approach for modern systems,' *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)* 42, no. 1 (January 2012): 101–11. http://doi.org/10.1109/TSMCC.2011.2106495

35. COMPASS. "D21.1 – Report on Guidelines for SoS Requirements". COMPASS Project; 2012.

After modelling the system, appropriate evaluation criteria are derived from system requirements at different levels.. Indicators are finally assigned considering the indicative parameters to measure levels of fulfilment. This process also entails making choices on benchmarking and grouping indicators, and these depend on two main factors: evaluation and data availability. Finally, the conceptual system model is coupled with a simulation model representing the same system topology and conditions to quantify the performance and relationships, and consequently, the indicators for evaluation.

In this train of thought, scenario analysis is conducted to evaluate and compare the performance of the system with different configurations and under different conditions of energy supply and demand. This has been applied to case studies based in the Findhorn village and the North of Tyne region in the UK.[36] The case studies imply several scenarios to deliver heat with different network configurations (electricity, heat, and gas) and coupling technologies (CHP, P2X, and HPs). Each of these constitutes a CS. The conceptual system model is developed for all scenarios as described by the architectural framework. This enables the creation of diagrams that show:

- The SOS structure and composition in terms of CSS (i.e., electricity, gas, heat, and coupling technologies).
- The CSS composition regarding system elements (i.e., generation, networks, and individual technologies).
- The systems stakeholder groups involved (i.e., local government, local community, network operators, end-users, and prosumers).
- System requirements reflecting the non-functional relationships between stakeholders and the SOS (energy trilemma objectives).
- System requirements reflecting the functional relationships among the CSS and with the SOS (e.g., delivering energy, transforming energy, and providing grid services, etc.)

36. Ali El Hadi Berjawi, et al., 'Whole Energy Systems Evaluation: A Methodological Framework and Case Study,' in *Whole Energy Systems*, eds. Vahid Vahidinasab and Behnam Mohammadi-Ivatloo (Cham: Springer, 2022), 41–82.

- The mapping of the system's functions, components, requirements, and indicators.

As a result, the framework proposed here provides a method to encompass stakeholders' perspectives in evaluating the effectiveness of a socio-technical pathway that involves multi-systems interactions towards achieving the transition objectives. The evaluation is conducted using metrics that allow for a reduced representation of the complex system architecture, including structural, and functional interlinkages.

7.5. Conclusion and Future Work

In summary, this chapter makes several contributions. First, it discusses a socio-technical transitions analysis of energy systems integration (ESI) through the multi-system perspective (MSP). Second, it justifies a system-of-systems (SOS) conceptualisation of ESI in line with the MSP in order to understand multi-system interactions. Third, it presents a structured methodological framework to identify and analyse multi-system interactions implied in ESI and to evaluate the potential future system architecture. Reflecting on those contributions, multiple streams for future research work are discussed below. These streams include generalisability to other socio-technical systems, coupling with quantitative simulation modelling, and understanding the co-evolutionary dynamics between the physical reconfiguration and the market reconfiguration.

This chapter presents the case of integrated electricity, gas, and heat systems to illustrate the interactions across socio-technical systems. In terms of generalisability to other socio-technical systems beyond energy (e.g., food, water, mobility, and telecom), the proposed SOS conceptualisation is expected to still apply to a case of integration. Accordingly, since the proposed methodology is context-based, it can be used to identify possible structural and functional interlinkages across systems and to evaluate potential future system architectures. However, patterns of change could turn out to be different due to the different physical and institutional properties that different systems exhibit. Therefore, more empirical evidence is still needed to support the understanding of the patterns of change entailed in multi-systems transitions including integrated energy systems.

In this regard, some studies have called for coupling sustainability transition frameworks with quantitative simulation models to understand future transition pathways.[37] On the other hand, among the challenges identified for future systems engineering practise, there is a need for methods that can both incorporate assessments for higher-level goals such as sustainability for SOSs and involve stakeholders in the assessments.[38] In this context, the proposed methodological framework contributes to both areas of research. This is because, first, it acts as a bridge between the MSP framework and the simulation models for integrated energy systems. Likewise, it enables a whole system socio-technical evaluation that implies multiple stakeholders' perspectives and multiple technological levels. These contributions should be further enhanced by developing a functional specification guideline describing the formal coupling of the conceptual system model and the quantitative simulation models.

Finally, considering ESI as a pathway for the energy transition implies that both social and technological changes are expected to unfold to achieve the transition objectives, including those for physical infrastructures, market structures, and consumer behaviours.[39] While the focus of this chapter has been on the physical (technical) system architecture, this can be a basis to expand the analysis to the market system architecture using the same methodological approach. This raises a question for future work on the co-evolutionary dynamics of change between the physical system reconfiguration induced by ESI and the consequent, or prerequisite, market reconfiguration required to implement ESI.

37. George Papachristos, 'Towards multi-system sociotechnical transitions: why simulate,' *Technology Analysis and Strategic Management* 26, no. 9 (August 2014): 1037–55. https://doi.org/10.1080/09537325.2014.944148; Danie Rosenbloom, 'Pathways: An emerging concept for the theory and governance of low-carbon transitions,' *Global Environmental Change* 43 (March 2017): 37–50. https://doi.org/10.1016/j.gloenvcha.2016.12.011

38. Wim J. C. Verhagen, Josip Stjepandić, and Nel Wognum, 'Future perspectives in systems engineering,' In *Systems Engineering in Research and Industrial Practice: Foundations, Developments and Challenges*, eds. Josip Stjepandić, Nel Wognum, and Wim J. C. Verhagen (Cham: Springer, 2019), 403–20. https://doi.org/10.1007/978-3-030-33312-6

39. Bruno Turnheim, et al. 'Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges,' *Global Environmental Change* 35 (November 2015): 239–53. https://doi.org/10.1016/j.gloenvcha.2015.08.010

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