Renewable and Sustainable Energy Reviews 145 (2021) 111163

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

An evaluation framework for future integrated energy systems: A whole energy systems approach

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ARTICLE INFO

Keywords:
Energy systems integration
Energy transition
Energy trilemma
Sustainability assessment
System-of-systems
Multi-criteria analysis
Scenario analysis

ABSTRACT

The energy system is undergoing a transition driven by the need of achieving the energy trilemma objectives: decarbonisation, acceptability and security. Energy systems integration connecting the power, gas, heat and transport systems, is one possible pathway to drive the transition flexibly and cost-effectively. Nevertheless, more quantified evidence on the performance of future integrated energy systems towards achieving policy objectives is still needed for decision makers to support this route. This paper first identifies the expected changes to the energy system upon integration, including new interactions and interdependencies between its components and actors. The paper then argues the need for a whole energy systems approach for the evaluation of integrated energy systems, represented by six characteristics: multidimensional, multivectoral, systemic, futuristic, systematic, and applicability. Based on the identified characteristics, the paper reviews existing evaluation frameworks for energy systems sustainability, and qualitatively appraises their adequacy for evaluating future integrated energy systems. The review concludes that existing frameworks are not capable of assessing the performance of integrated energy systems, lacking one or more of the characteristics. The paper finally presents a novel holistic evaluation framework based on the System-of-Systems approach for systems analysis coupled with an indicator-based approach for evaluation. The proposed framework demonstrates the six characteristics as it enables evaluation with respect to multiple perspectives and objectives at different system levels. Moreover, this framework captures future changes to the whole energy system architecture and highlights the interdependencies between energy systems. This framework can also be systematically applied to various scenarios in different contexts.

1. Introduction

The energy system is expected to undergo a transition to achieve the energy policy objectives of delivering decarbonisation targets for 2050, while maintaining a secure and reliable energy supply, and providing acceptable and affordable energy for all, to address what is known as the energy trilemma. The energy transition is expected to have significant impact on the current energy system architecture with changes in the planning and operations paradigm, the market structure and the regulatory framework. The future energy system therefore needs new and extended functionalities, to flexibly and cost-effectively manage uncertainties and to address the need for coordination across the energy systems, namely power, gas, heat and transport [1].

One possible technical pathway for the energy transition is Energy Systems Integration (ESI), which aims to connect energy systems physical and virtually across infrastructure and markets and exploit synergies among them. ESI originates from a holistic theoretical approach that considers the Whole Energy System (WES), as being comprised of:

- multiple energy vectors: power, gas, heat, and transport
- the energy supply chain span from generation to end-use, through infrastructure and markets
- the system environment embracing different stakeholders with multiple perspectives and objectives, including the technical, environmental, economic, political and social aspects

This would change the energy system structure and function and consequently affect the way its performance is evaluated. In this regard, previous reviews on ESI have identified gaps around evaluation and suggested research recommendations. Specifically, while ESI provides an opportunity to improve the system performance in terms of the energy trilemma there is still a need for (i) more quantified evidence to validate this claim and support decision making in this direction; (ii)

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https://doi.org/10.1016/j.rser.2021.111163
Received 17 December 2019; Received in revised form 11 March 2021; Accepted 25 April 2021
Available online 28 April 2021
1364-0321/

List of abbreviations

ESI	Energy Systems Integration
WES	Whole Energy Systems
SoS	System-of-Systems
MCA	Multi-Criteria Analysis
RES	Renewable Energy Sources
EVs	Electric Vehicles
HPs	Heat Pumps
CHP	Combined Heat and Power
P2X	Power-to-X
ICT	Information and Communication Technologies
MBSE	Model-Based Systems Engineering
SoSE	System-of-Systems Engineering
CSs	Constituent Systems
SysML	Systems Modelling Language

new tools and metrics to identify the full range of benefits of ESI under different situations; (iii) and comprehensive assessment methodologies to capture the interdependencies across energy systems and the emergent complexity of the whole system [2–6]. However, the literature still lacks findings and methodologies that address the identified gaps.

This paper aims to fill the literature gap by presenting a novel holistic methodological framework for evaluating the performance of future integrated energy systems towards achieving the energy policy objectives. The paper starts by discussing the expected changes to the energy system and the impacts of ESI on the overall structure and dynamics, in section 2. Accordingly, the characteristics necessary for the evaluation of integrated energy systems that any framework should exhibit are identified. The characteristics relate to the scope and nature of the evaluation, and correspond to the different WES domains and changes. The characteristics are used to qualitatively appraise existing frameworks' ability to capture the changes expected upon ESI, and consequently their capability to evaluate integrated energy systems. Section 3 describes the identified characteristics and reviews existing evaluation framework for energy systems.

The proposed evaluation framework is presented in section 4. The underlying concepts and methods are first explained before describing the framework procedure. The framework aims to address the identified gaps in the evaluation of integrated energy systems by demonstrating the required characteristics. The framework combines a System-of-Systems (SoS) approach for systems analysis, with an indicator-based approach using Multi-Criteria Analysis (MCA), to model the system under study, identify interactions and emergent properties, and assign appropriate criteria and indicators for the holistic system evaluation. The framework could then be applied to case studies under various future scenarios to realise trade-offs. This serves as an evidence for informing decision making on the future energy system and the potential benefits of ESI. The proposed framework was validated using expert elicitation in a structured group interview. Section 5 summarizes the contributions and concludes with future work.

2. Changes to the energy system

The energy system is constrained by the requirement to achieve the energy trilemma targets in terms of environmental sustainability, social acceptability and energy security. In this sense, the energy trilemma itself is considered the main driver for the energy transition since the current energy system arrangements are considered not enough to achieve it [7]. A shift from conventional technological and market paradigms, regulatory frameworks, consumption patterns and social practices is therefore likely to fulfil the trilemma objectives [8].

The energy system transition would create uncertainties that require additional flexibility to manage. A possible solution is ESI through coupling multiple energy vectors. Changes to the energy system would therefore involve increasing complexity and interconnectedness between its components. Thus, a holistic view of the WES considering the interactions and interdependencies within is needed in planning, operation and evaluation of future integrated energy systems.

2.1. Drivers of change

This shift in the energy system is driven by technological and market changes attributed to three D's: Decarbonisation, decentralisation and digitalisation [9]. These changes can be across the energy system. On the supply side, change is driven by the increased use of Renewable Energy Sources (RES), both large and small scale, and decentralisation of energy generation and storage technologies. On the demand side, change is driven by electrification of transport and heat through greater deployment of Electric Vehicles (EVs) and Heat Pumps (HPs). Furthermore, digitalisation of the grid is governing the interaction of smart appliances, smart meters and demand-side response with varying tariffs. These drivers have an impact on the current energy system structure and dynamics [10]. Moreover, new market opportunities are emerging for established and new actors to provide a range of aggregated energy services [1].

Decarbonisation, using RES, creates a technical challenge related to their supply intermittency and the effect on the balance between supply and demand over time and space [2]. Decarbonisation would also have a significant impact beyond the power system, with the rise of new energy carrier systems such as district heating and hydrogen, and a greater interconnectedness between energy vectors due to the electrification of transport and heat [6,11]. Electrifying transport and heat is considered vital for their decarbonisation but presents new and unfamiliar challenges to the energy system. For instance, electrified transport would lead to an increase in electric demand and investment for charging infrastructure, while it could provide flexibility to better integration of RES if vehicle-to-grid technologies were adopted [12].

Decentralisation of energy generation is facilitated by RES since it can be implemented at smaller scales and at the point of consumption. This allows energy consumers to also be producers, i.e. prosumers, giving them more control over their energy use based on real-time grid conditions and dynamic energy prices [10]. Consequently, resource-side and customer-side decisions will be variably interdependent, creating additional uncertainty over the mismatch between supply and demand [11,13]. The heat system can encounter a similar shift from hierarchical large scale towards distributed infrastructures [14].

Digitalisation of the energy system supports the energy transition by enabling smart operation and control strategies of multiple energy systems, supported by advanced data collection and analysis capabilities [7,14]. This entails increased reliability on the supply side by better predicting, responding and adapting to the intermittency of RES. On the network level, digitalisation enables automated control and response with smart meters and flexibility options, while allowing more active participation of end-users on the demand side [2].

2.2. Energy systems integration

The uncertainties the energy transition is expected to bring, mainly over the balance between energy supply and demand, can be managed through additional flexibility [15]. Additionally, there is a need arising from the electrification of transport and heat to coordinate the increasingly interconnected energy vectors. This makes ESI a possible solution, beyond the traditional paradigms, to provide the required flexibility to drive the decarbonisation transition cost-effectively.

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 has developed as an overarching concept that may encompass other modern concepts such as smart grids and smart cities, but goes beyond the limited spatial scale provided by those concepts [3]. The concept of ESI originates from a WES approach that holistically considers integrating energy vectors to achieve horizontal synergies and efficiencies at all levels [16].

Integration of energy systems would provide flexibility to the whole system by diversifying both input and output energy streams and allowing peak in demand or production to be shifted from one system to another by conversion between vectors [2]. Moreover, ESI would enable the effective analysis, design and control of the system interactions and interdependencies along technical, economic, environmental, political, and social dimensions [17]. Other potential benefits of ESI include reducing costs by improving overall efficiency through increased resource utilisation and sharing of assets across energy systems. Additionally, ESI helps reduce carbon emissions by enabling integration of RES, and increases system security and resilience given the greater flexibility and diversity of energy resources provided [2].

ESI is enabled by technologies such as Combined Heat and Power (CHP), Power-to-X (P2X), HPs, and EVs. These technologies facilitate energy vector conversion or electrification of end-use sectors. Moreover, energy storage in different forms enables long-term storage, for instance by transforming electricity into thermal or chemical energy, with the latter allowing long-distance transportation [14]. CHP systems generate electricity and heat and can be connected to the electricity grid at different levels and to district heating networks at different scales. CHP systems can provide a number of flexibility services to the power system by increasing or decreasing power generation while maintaining the level of heat generation [18]. P2X systems involves converting power, ideally surplus from RES, into hydrogen as a first stage, and ultimately into different forms of energy (power, gas, heat) or to use for different purposes (mobility, industrial feedstock). This can support decarbonisation of transport and heat through the use of hydrogen produced from RES. On the other hand, HPs and EVs allow the direct electrification of heat and transport, respectively. These solutions are based on a holistic view that looks at different energy systems simultaneously to provide opportunities for flexibility and more RES integration [12].

2.3. Impacts of energy systems integration

Adopting ESI as a pathway for the energy transition will impact the structure and function of the energy system. First, ESI will create new interactions and interdependencies between the different energy systems, making it more complex to manage the WES. New interactions could be related to physical, commercial or informational flows between different components across energy systems. Second, integrating different energy systems will bring together multiple actors with different objectives and motivations. This will lead to a change in the market structure with the emergence of new actors and new business models, in addition to new policy and governance frameworks. These are discussed in further detail below.

Traditionally, energy systems and associated networks were designed and operated separately with limited interactions between them. However, ESI enables approaches that expand the system boundaries beyond one sector. This consequently brings new perspectives to energy systems analysis to find innovative solutions to the different constraints [4]. Thus, energy systems are expected to be more interconnected through ESI. This creates new interactions and further interdependencies between the different energy systems. Interactions include having a shortfall in energy available in one network being met by energy carried by another one, or one network providing its surplus energy to another to help with constraints across networks [19].

Due to the greater interconnection and new interactions between energy systems, ESI would make the management and operation of the whole system more complex. Greater interconnection means that solutions in one system can have implications on the others. For instance, electrification in the transport sector through deployment of EVs would lead to an increase in electricity demand, which may compete for supply under a constrained network [20]. Moreover, interactions lead to emergent behaviour that could be harmful or beneficial for the energy system, and can affect the reliability performance of integrated energy systems [21]. For instance, interdependencies between energy systems make the whole system vulnerable to disruptions occurring in one system. This can create new failure models such as cascading failure, where an infrastructure is impacted by the failure in an interdependent system [22]. On the other hand, the flexibility provided by energy vector conversion facilitated by ESI improves the resilience of the system. For example, at times of high wind energy output and constraints on the electricity system, wind energy can be converted to gas rather than be constrained off, and injected into a gas network. Thus, new planning and operational paradigms need to be designed to manage and control the energy system accounting for such emerging interactions.

On the market level, new opportunities would develop upon ESI for partnerships between separate energy businesses, each of whom has an independent market structure and regulatory framework [6]. This would bring together actors and stakeholders from different energy systems that did not necessarily need to communicate with each other previously. Actors in each energy system tend to act in ways that maximise value for their domain, but not necessarily for the WES. If this is to change, actors should coordinate and collaborate while having a common understanding of each other's objectives, incentives and information they have access to [3]. Looking at a future integrated energy system, actors need to acknowledge the relationships between their business models, processes and technologies in practice [11]. Fig. 1 shows a schematic of the whole energy system moving from (a) separate configuration with independent planning and operation; to (b) an integrated system with interactions and combined actors.

Actors in the energy system have divergent views of how the future energy system will look like and what impact this would have on how they manage or operate energy technologies and infrastructure [23]. Actors such as generators and storage operators, distribution and transmission network operators, suppliers, intermediaries and service providers, can see their roles and relationships to each other and to end-users changed in an integrated energy system [16]. New actors could also emerge upon integrating energy systems. These include aggregators, mobility-as-a-service companies, EV charging infrastructure companies, local energy companies making use of distributed energy resources, cities and municipalities, and new service providers for services such as flexibility and smart homes [24]. This emergence of new actors is reflected in Fig. 1(b).

Furthermore, ESI can create new markets for emerging services and products. Potentially, this would foster the market competition across various energy sectors, adding value to the end-user and allowing additional revenue stream for energy companies through diversification of their products or services [6]. For instance, ESI can provide business opportunities moving towards a model of providing energy as a service such as heat, light or mobility, rather than providing a commodity [16]. Similarly, new business models and innovative arrangements can be implemented to draw advantages from ESI. For instance, the integration of the electricity and hydrogen systems through P2X could facilitate collaboration between the electricity and transport sectors to boost the uptake of hydrogen vehicles [6].

Thus, market and regulatory structures have to be redesigned to capture the benefits emerging from ESI. Those structures should be adapted to new planning and operational paradigms, changing network features, incorporated Information and Communication Technologies (ICT) systems and flexible end-use technologies [3]. A change in market arrangements is also needed in a way to reward new and different types of flexibility services supporting ESI, such as energy vector conversion and storage technologies [2]. Moreover, market arrangements should create incentives for new opportunities that could facilitate the emergence of new types of firms [16].

In summary, to realise ESI and exploit its potential, new technologies and innovations should be adopted to enable the physical integration

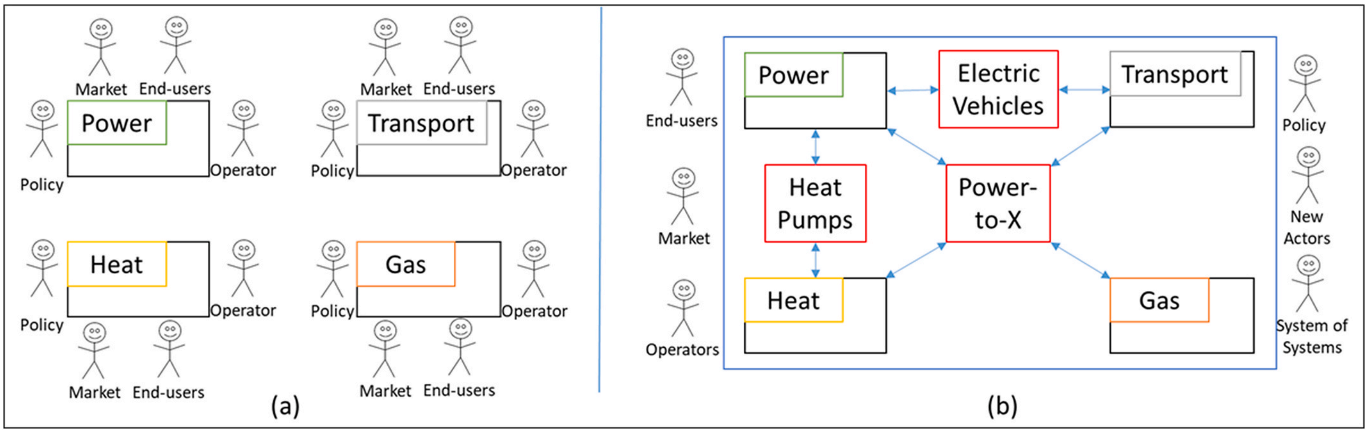

Fig. 1. Possible configurations for (a) Separate energy systems; (b) Future integrated energy system.

and interactions between energy systems. Moreover, ICT infrastructure and advanced collaborative control techniques are required to maintain interoperability between the different integrated components [10]. Additionally, appropriate markets structures and regulatory frameworks are needed to define actors' roles and relationships and reward and incentivise new forms of flexibility provided by ESI.

3. Characteristics for integrated energy systems evaluation

The evaluation of integrated energy systems will need to account for the increasing interactions, interdependencies and emergent properties in the WES. This is necessary to have an overall understanding of the mutual influences and the potential benefits and impacts of integration between the different energy systems at all levels [14]. ESI has a variety of potential benefits and impacts, including the technical, economic, environmental, regulatory and social aspects. In fact, different energy systems have established their own performance evaluation methods and criteria, and there is a gap in comprehensive assessment methods and indicators targeting the performance of integrated energy systems [4]. Accordingly, new metrics and methodologies are required to capture the whole system interactions, quantify interdependencies and identify the benefits particularly attributed to integration, while considering the trade-offs between the various aspects. A thorough evaluation of ESI would help policymakers make informed decisions to support this pathway.

In order to evaluate the performance of integrated energy systems towards achieving designated targets, evaluation frameworks should be able to capture the particularities of such systems and reflect the changes discussed in section 2. In particular, the framework should account for the WES approach to capture the interdependencies involved. In this context, the WES approach can be defined by three axes corresponding to the system components and the system environment. The first axis represents the multiple energy vectors of the system: power, gas, heat and transport. The second axis spans the system supply chain from generation to end-use, through infrastructure, markets and policies. The third axis relates to the multiple dimensions of the WES environment representing the technical, economic, environmental, regulatory, and social aspects. Accordingly, the three characteristics representing the WES approach that any evaluation for ESI should exhibit are multidimensional, multivectoral and systemic (Fig. 2). Three supplementary characteristics, related to the nature of the framework itself and based on the changes to the energy system discussed in section 2, are futuristic, systematic, and applicable.

The six characteristics are identified as insightful for a thorough

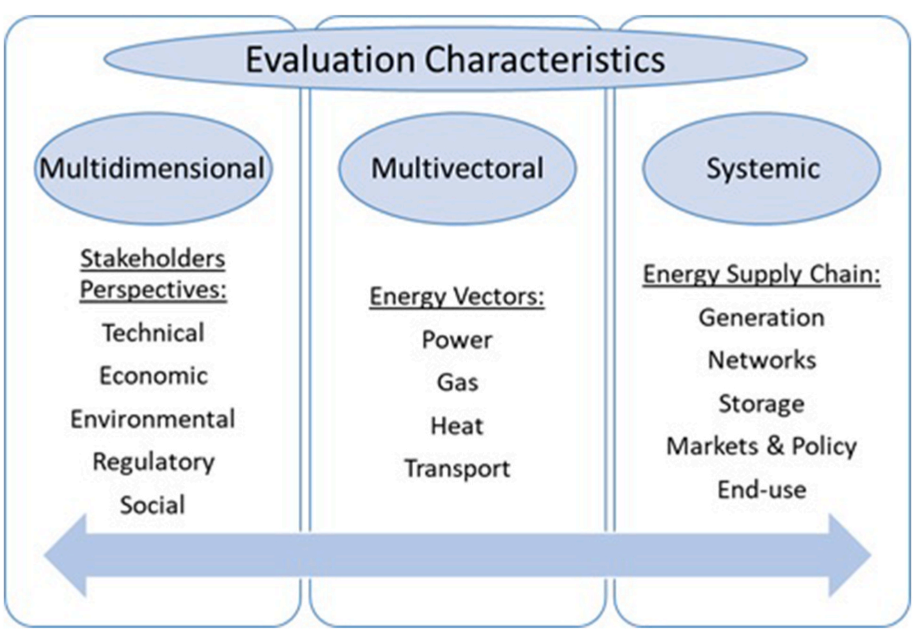

Fig. 2. Whole energy systems approach for evaluation of future integrated energy systems.

evaluation of future integrated energy systems, where:

- A *multidimensional* framework is necessary to consider the multiple perspectives and objectives of the different stakeholders involved in ESI. This permits one to ask if the energy system is heading towards achieving the various objectives and whether those objectives can be achieved synergistically or require trade-offs.
- The framework should be *multivectoral* to consider the interactions and influences between the coupled energy vectors and the interdependencies across different energy systems.
- A *systemic* framework is needed to span the energy system from generation to end-use, through networks and markets. This is important to capture properties emerging from interactions at the whole system level such as flexibility and resilience.
- The framework should also be *futuristic* in the sense of being able to evaluate major changes to the structure and function of the energy system expected in the future. Such changes would alter the way the system is planned and operated, and consequently the way the system performance is evaluated.
- The framework should be *systematic* in terms of procedures for the derivation and interpretation of evaluation criteria and indicators. This is important for transparency, validity and replicability in different contexts.
- It is important for the framework to be *applicable* to prove its usefulness in supporting decision-making in practice

Section 3.1 summarizes the literature of existing evaluation frameworks based on the identified characteristics. Sections 3.2-3.7 explain in more detail each of the characteristics with relevant examples from the literature.

3.1. Adequacy of existing evaluation frameworks

The identified characteristics are used to qualitatively appraise the ability of existing evaluation frameworks to capture the changes and complexity involved in future integrated energy systems, and consequently their adequacy for evaluating the performance of such systems.

Table 1 reviews a number of existing evaluation frameworks for energy systems against the set of characteristics required for ESI evaluation. Evaluation frameworks that satisfy at least one of the WES approach characteristics were included in the analysis. A large number of multidimensional evaluation frameworks can be found targeting different energy systems or different parts of the energy system [25]. Most of them aim to compare energy generation technologies including RES using different methods [26,27]. Multidimensional frameworks that present unique methods and relevant insights to the WES approach are included in this review and are discussed in the subsequent sections.

Table 1 shows the review of existing evaluation frameworks, and it is clear that no framework from those reviewed addressed all the required characteristics for effective ESI evaluation. Notably, only a few frameworks consider major changes to the energy system in the future, such as electrification, decentralisation and digitalisation of the system, but not particularly ESI. Most frameworks tend to focus solely on the electricity system, without linking it with other energy systems such as gas, heat or transport. Also, within the electricity system the focus is typically on primary energy resources and electricity generation technologies, rather than the whole system span from supply to demand. While most frameworks reviewed were applied, only three were not. Accordingly, existing frameworks seem to have common gaps and are rendered not fit for evaluating future integrated energy systems, lacking one or more of the described characteristics.

3.2. Multidimensional

Evaluation should be multidimensional, in terms of the dimensions with which energy systems are evaluated. Dimensions represent the objectives and perspectives of different stakeholders involved. Table 2 presents the dimensions used in the literature under various multidimensional conceptual frameworks to evaluate energy systems [28,51,53]. A multidimensional evaluation permits one to ask if the energy system is heading towards achieving the various objectives and whether those objectives can be achieved synergistically or require trade-offs.

The variety of conceptual frameworks and dimensions used for energy systems evaluation reflects two aspects. First, the variety means

Table 1
Comparative assessment of existing energy systems evaluation frameworks.

Framework	Multidimensional	Multivectoral	Systemic	Futuristic	Systematic	Applied
Energy Matrix [28]	✓	✓	✓	×	×	×
Sustainable Energy Security [29]	✓	✓	✓	×	✓	×
Renewable power & heat [30]	✓	✓	×	×	✓	✓
Hybrid Energy Systems [31]	✓	✓	×	×	✓	✓
MFMP [32]	✓	✓	×	×	✓	✓
Energy transition index [8]	✓	×	✓	✓	✓	✓
Security Interdependencies [33]	✓	×	✓	×	✓	✓
Decentralised energy [34]	✓	×	✓	✓	✓	✓
Biofuels systems [35]	✓	×	✓	×	✓	×
MCA of energy scenarios [36]	✓	×	✓	✓	✓	✓
Energy Security [37]	×	✓	✓	✓	✓	✓
UK Energy Security Future [38]	×	✓	✓	×	×	✓
Irish Energy System [39]	×	✓	✓	×	✓	✓
Integrated energy security assessment [40]	×	✓	✓	×	✓	✓
Energy Security under decarbonisation [41]	×	✓	✓	✓	✓	✓
Environmental Sustainability [42]	×	×	✓	×	✓	✓
WEC ETI [43]	✓	×	×	×	✓	✓
WEF EAPI [44]	✓	×	×	×	✓	✓
EJM [45]	✓	×	×	×	×	✓
RTP [46]	✓	×	×	×	✓	✓
Energy Security [47]	✓	×	×	×	✓	✓
UK Energy Security [48]	✓	×	×	×	✓	✓
AESPI [49]	✓	×	×	×	✓	✓
SEDI [50]	✓	×	×	×	✓	✓
Sustainability Assessment [51]	✓	×	×	×	✓	✓
Swiss Energy Pathways [52]	✓	×	×	×	✓	✓
The Framework presented in this paper	✓	✓	✓	✓	✓	✓

Table 2
Multidimensional conceptual frameworks for energy system evaluation.

Energy Trilemma	Energy Security	Energy Sustainability
Affordability	Availability	Environmental
Environmental Sustainability	Accessibility	Social
Security of Supply	Affordability	Economic
	Acceptability	Institutional
	Reliability	Technological
	Environmental Sustainability	Educational
	Efficiency	Security
	Governance	
	Generation and Grid Adequacy	
	Supply and Demand Flexibility	
	Geopolitics and Terrorism	

that evaluation or good performance could mean different things in different contexts. Previous research has shown that there exists diverse perspectives forwarded by various experts and stakeholders from different domains in the energy sector, and accordingly different criteria are prioritised for evaluation [47,48]. Secondly, it means that a multidimensional evaluation is necessary in order to include the different criteria considered important for evaluation regardless of what is prioritised [54,55]. In comparison, evaluation by single metrics in isolation would provide an incomplete and often misleading assessment [8,37,47].

Energy systems evaluations presented in the literature range from being one-dimensional to multidimensional. Examples of one-dimensional studies include for instance those focusing on security of supply [37–41], or the environmental and social sustainability of energy technologies [42,56]. On the other hand, multidimensional studies include those adopting the energy trilemma [8,28,43–46]; in addition to energy security [33,47–49] and energy sustainability [30,31,34,51], as used in their broad definitions. The energy trilemma concept stems from the wider concept of the triple bottom line that emphasises a balanced approach to the economic, environmental, and social aspects for sustainability [57]. Energy sustainability challenges are context-specific and priorities could vary between developed and developing countries [50,58,59].

It is not only important to consider multiple dimensions for evaluation, but also to be able to identify trade-offs between them. This allows one to design alternative strategies that could maximise synergies and improve all objectives [37,53]. In this context, ESI can have a role in exploiting those synergies across energy systems, as it provides an opportunity for more collaboration among stakeholders in planning and decision making to have a cohesive energy strategy.

Some of the techniques that had been used to highlight the trade-offs were:

- cross impact analysis, scatter plots and influence diagrams of the degree of interrelation between the different dimensions [33].
- a balance score associated with the trilemma index [43].
- a ternary diagram to plot each of the energy trilemma dimensions [45].
- dashboard of indicators without aggregation [48].
- a radar chart to plot each of the energy sustainability dimensions [50].
- multicriteria decision analysis techniques [51].
- scenario analysis coupled with MCA [36,52].

On the other hand, the trilemma dimensions have been assessed separately using life cycle analysis, risk assessment and cost minimisation models [46] and have been presented in separate matrices [28] without making any relationship between them.

3.3. Multivectoral

Evaluation of ESI should also be multivectoral so that the multiple energy vectors of the WES are considered and the interdependencies involved upon integration are accounted for. As evident from the examples in section 2, coupling energy vectors would create additional interactions and interdependencies between energy systems (see Fig. 1). Other examples include using hydrogen to power vehicles, with electrolysers offering grid balancing and storage services while increasing the electricity demand and affecting the gas network [20]. Also through integration, energy systems with low storage capacities could access the benefits of storage available in other systems. Hence, sharing of assets is another way in which ESI can reduce whole system costs [2]. A framework that can capture such integration links and their impacts is necessary for the evaluation.

Most of the existing frameworks tend to focus the evaluation around the electricity system, while a few include other systems such as gas, heat and transport [28–30,37–41]. However, those studies do not capture the interactions and interdependencies between the different energy systems as in the case of ESI. They simply expand the boundaries of the evaluation to show indicators specific for each respective system separately. Other studies consider hybrid energy systems with multiple feed and multiple product streams of energy [31,32]. However, the focus of those studies is on the generation technology level, and thus they do not consider interactions beyond that point, particularly at the network level which is of interest in the scope of ESI.

3.4. Systemic

Evaluation of ESI should consider the whole energy supply chain from generation to end-use, through networks, storage, markets and policy. It is important to reflect systemic properties of the WES, particularly features emerging from interactions between the different system components upon integration. For instance, energy security is considered a property of the whole system rather than its individual components [29,60], and a result of the interactions and interdependencies across the whole system [12,37]. However, previous studies tend to focus on security from the supply side, particularly in terms of primary energy resource availability and energy generation diversity [37,47]. Similarly, flexibility has a different connotation in a WES context, where it reflects the capacity of energy vector conversion and shifting energy between different systems. Consequently, resilience defined as the adaptive capacity of the energy system would be enhanced by this form of flexibility [61].

In the scope of ESI, the whole system would be more than its parts due to the emergence of system features or performance at the WES level, resulting from interactions within the system [13]. This is highlighted by the requirements of future systems to provide resilience, and flexibility due to the uncertainties involved in the energy transition [15,60]. Such features will arise as a result of the interaction of the different components of the integrated energy system. Therefore, evaluation should be able to reflect those features and properties at the whole system level. In this context, a systemic approach to evaluation would support accounting for interdependencies across different components and pathways within the energy system [37,48].

A systemic approach was applied to the evaluation of energy security considering the contribution of different components of the whole system, namely the supply, conversion and distribution, and demand subsystems [29]. On the contrary, some framework, although multidimensional, would focus only on a particular component of the energy system, such as power generation [62,63], demand subsystem [64], or energy policy [65]. Furthermore, a systemic approach is adopted for sustainability assessments of different energy systems considering their own supply chain stages or lifecycle phases. For instance, a systemic approach was proposed for the evaluation of biofuel systems to consider the interactions [35] and sustainable management

[66] of its supply chain at different levels. Similarly, a systemic approach was proposed for the evaluation of waste-to-energy [67] and hydrogen [68] systems throughout their lifecycles.

Moreover, frameworks were proposed for energy security with systemic properties defined at different system levels (such as adequacy of generation and grid, and flexibility of supply and demand) [33], and within different time horizons (stability, flexibility, resilience, adequacy and robustness) [37]. On the other hand, a systemic approach was used to evaluate the environmental sustainability of energy supply technologies regarding the impact on the climate, water, land and economy as system environments [42]. Additionally, the market structure, business environment, policy framework and the society were considered as variables affecting the energy system security [8,38].

3.5. Futuristic

Evaluation of future energy pathways is important to anticipate the impact of different energy policies and technologies on the energy transition and the impact of the transition on the performance of the WES [49]. Therefore, evaluation frameworks specifically targeting future energy systems should be sufficiently generic to be valid for energy systems totally different from existing ones [41]. This is particularly essential for the evaluation of ESI given the magnitude of the expected changes to the energy system discussed in section 2.

Although several evaluations were conducted on future scenarios for the energy system [46,48,51], these have not considered major changes or reconfigurations that would totally transform the system. Future scenarios evaluated in those studies were focused around the different technological composition for electricity supply, while leaving out the potential impacts of structural changes in the energy system [41]. Other future changes include the use of smart systems and renewable fuels such as hydrogen and biofuels [69]. A few exceptions were found where the performance of decentralised energy systems [34], the extent of decentralisation and digitalisation [36], the impact of decentralisation and electrification on energy security [37], and the readiness of the energy system for the transition [8] were considered. However, none of those studies have specifically considered the impact of ESI on the WES performance.

3.6. Systematic

The evaluation framework should be systematic in terms of procedural derivation and interpretation of evaluation criteria and indicators. This is important for replicability under different circumstances as there is no definitive set of indicators. Indicators must be context-specific to accommodate for different conditions and priorities. This is evident by the multifaceted concept of energy security, which is manifested in different ways according to the different context in which it is being used [29]. This characteristic is also important for the clarity and transparency of the evaluation, which improves its validity and credibility [70]. Thus, systematic evaluation frameworks should be inherently comprehensive and flexible to cover the different aspects involved in different situations [3,4].

Most frameworks reviewed are noted as systematic with a few exceptions. Frameworks indicated as systematic are those that present the lead up and derivation of the appropriate evaluation criteria or indicators they used. This could be through systems analysis techniques [29,31,32,35–37], experts interviews or surveys [34,48,53], or a literature review with selection principles to filter indicators [8,43,44,50]. Some of the systematic frameworks also conduct additional analysis of the results beyond quantification of indicators [33,41,52]. On the other hand, frameworks not indicated as systematic just list the indicators used without transparent justification.

3.7. Applicable

The evaluation framework should be applicable in practice to prove its usefulness and contribute to decision making. While most of the frameworks reviewed were applied to systems using existing data or with future scenarios, a different approach was taken in Ref. [28] by developing an ideal set of indicators for policymakers for the separate trilemma dimensions without relying on existing data. However, the indicator set presented was not tested due to data being unavailable, which is one of the main challenges for evaluation. Hence, it is important to be able to get relevant data from energy models resembling future scenarios.

In summary, there are a number of gaps that make existing frameworks incapable of evaluating the performance of future integrated energy systems. None of the reviewed frameworks simultaneously exhibit the six characteristics identified for the evaluation of ESI. These characteristics represent the WES domains and the changes to the energy system discussed in section 2, which are necessary to account for in the evaluation. While it is common to find *multidimensional*, *systematic* and *applicable* evaluation frameworks, existing frameworks mainly fail in reflecting *systemic* attributes emerging at the whole system level from the *multivectoral* interactions and interdependencies across energy systems. Moreover, existing frameworks generally neglect major structural and functional changes to the energy system in a *futuristic* evaluation.

4. Proposed evaluation framework for integrated energy systems

In order to address the identified gaps and consider the required characteristics for evaluating the performance of integrated energy systems, a novel methodological framework is proposed. Section 4.1 describes the underlying concepts and methods used to develop the proposed framework. Section 4.2 explains the procedure whereby the framework can be applied to evaluate integrated energy systems. Section 4.3 describes the validation of the proposed framework in a group interview with experts.

4.1. Framework concept and methods

The proposed framework is based on two main conceptual and methodological approaches (Fig. 3). The first is a SoS approach for problem structuring and systems analysis. This approach primarily addresses the requirement for the evaluation to be multidimensional, multivectoral and systemic. The energy system under study is modelled as a SoS and is analysed accordingly, through conceptual system modelling and Model-based Systems Engineering (MBSE). Within those, concepts related to system architecture and system requirements are useful to the framework to be futuristic. The second is an indicator-based approach for the evaluation. After structuring the problem, criteria and indicators are systematically derived, quantified and interpreted for the holistic system evaluation using Multi-Criteria Analysis (MCA). Criteria and indicators reflect the energy system interactions and emergent properties related to ESI. The proposed framework is then applied to case studies under various future scenarios to further investigate trade-offs and synergies and to demonstrate applicability.

4.1.1. System-of-systems approach

Systems thinking is taking more ground in energy systems research due to the need for deeper understanding of the increasing complexity involved [71]. Complex systems have been the focus of other fields with similar challenges, providing insights for understanding future energy systems [72]. System-of-Systems Engineering (SoSE), a subfield of systems engineering, has developed to understand and design complex and interdependent systems, with a focus on the boundaries and interactions between different systems [73]. A SoS is defined as an integration of independent systems that act jointly towards a common goal, through

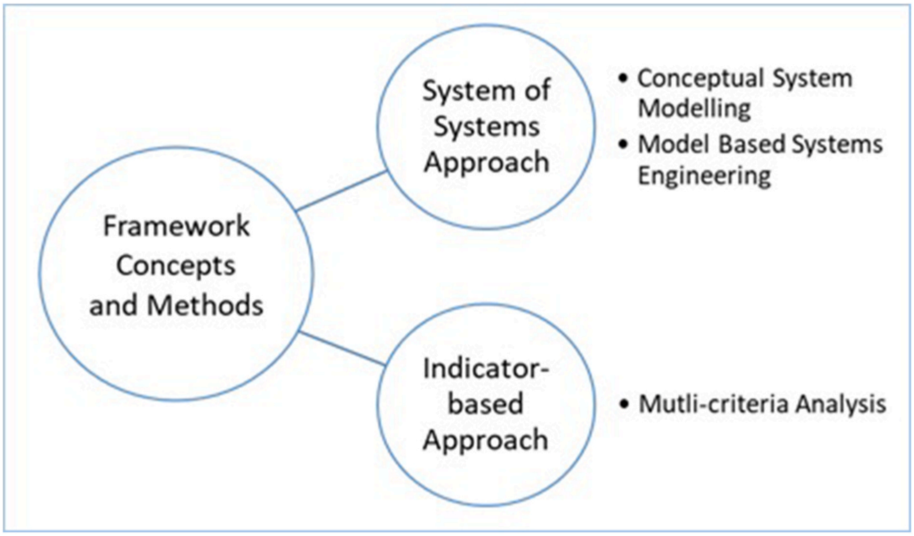

Fig. 3. Evaluation framework concepts and methods.

synergies, to collectively offer emergent functionality that cannot be provided by the Constituent Systems (CSs) alone. A SoS has distinctive characteristics of autonomy, independence, distribution, evolution, interdependence, and interoperability of its CSs, in addition to emergence as a result of synergistic collaboration of the CSs [73].

Systems analysis is considered as both a conceptual and a methodological approach to problem structuring in this framework. The strength of systems analysis is in providing a holistic approach to problem solving for complex systems [31]. In the proposed framework, the specific method chosen for systems analysis is a SoS approach. The SoS approach is chosen because it meets the requirements for the evaluation to be multidimensional, multivectoral and systemic. The integrated energy system is therefore modelled as a SoS with all the properties and analytical approaches which a SoS enables.

The SoS approach can capture the complexity and variety involved in integrated energy systems, since it can support multidisciplinary understanding and evaluation of systems, help understand the way a system is performing by exploring interdependencies, deal with complexity and consider dynamics of change. It can also enable the provision and validation of emerging behaviour, and prevent unintended consequences by considering the interactions between the CSs and with the system environment [74–76]. Such an approach is recommended in the evaluation of complex and interdependent fields such as infrastructure [77], water management [78] and sustainable development [79]. By using a SoS approach, a broader, integrated and more holistic approach to performance evaluation is enabled. This approach will better capture the value of flexibility and resilience across the whole system, describe the system interactions, and relate indicators to each other and to strategic goals and objectives.

ESI is based on a whole systems thinking that aims to find innovative solutions beyond one energy system, to make use of possible interrelations between different energy systems to collectively achieve a greater outcome [80]. In fact, an integrated energy system lends itself to a SoS approach since its comprising subsystems can be characterised by the following SoS features [13].

- Managerial independence, by various utility companies
- Operational independence, through various metrics and operational criteria
- Evolutionary independence, where each is continuously upgraded and has its own lifecycle
- Geographic displacement, where an energy system is normally geographically spread
- Emergent behaviour, resulting from interacting components
- Having a collective purpose as a SoS, such as improving overall efficiency, reliability and resilience, and reducing overall costs and emissions

4.1.1.1. Conceptual system modelling. The future changes to the energy system are expected to transform the system and alter its architecture, where the whole system must evolve to recognise the new interfaces created by new interactions, while satisfying the system requirements. A system architecture generally includes principles and guidelines governing the system structure, functions, the relationships between its components and with its environment, and how the system will meet its requirements [81]. System requirements refer to the functions and capabilities that the system needs to fulfil or acquire, and are mainly related to the needs of stakeholders [82].

Therefore, the early stage of SoSE that is the conceptual model development, which aims to identify system requirements and potential architectures, is considered useful to satisfy the requirement for the evaluation framework to be futuristic as described earlier. In the conceptual model development stage, system concepts, constraints, tradeoffs and requirements are considered. Tasks involved in this stage include translating capability objectives into requirements, understanding the CSs and their relationships, obtaining information from different stakeholders, and assessing actual performance against capability objectives [83,84].

There are two types of system requirements: (i) Functional requirements that relate to the system performing a function and are usually described by action verbs such as do, provide, deliver and produce; and (ii) Non-functional requirements that represent a constraint to another system requirement, including quality, implementation and solution-specific requirements. For example, this could be meeting a standard, complying with a legislation, using a particular technology, or ensuring a specific performance level, in addition to size and operations constraints [85]. This distinction is useful for the system modelling process and the derivation of evaluation criteria described in section 4.2.

4.1.1.2. Model-based systems engineering. MBSE is the formalised application of modelling to support system design, architecture, analysis, verification and evaluation. MBSE is a rigorous, iterative process to develop conceptual models that coherently represent a system and its operating domain. This includes the structure, behaviour, properties, functions, requirements, interactions, interconnections, data and communication. MBSE techniques are used to produce structured models of complex systems comprising input from different stakeholders, to support understanding of critical components, interfaces and processes of these systems. This allows different stakeholders to consider the system in their perspective of interests, without losing internal consistency across the range of viewpoints [86].

MBSE is supported by the Systems Modelling Language (SysML), which is a general-purpose graphical modelling language for designing, analysing and verifying complex systems. SysML facilitates standard and rigorous, yet flexible modelling of systems, as a result of the breadth of the diagrams included, allowing users to represent systems using appropriate vocabulary and conventions of the relevant domain. This makes SysML a good choice for modelling SoS [86]. The exact use of SysML diagrams in this framework is further discussed in section 4.2.1.

4.1.2. Indicator-based approach

The proposed framework uses an indicator-based approach for evaluation. In this framework, evaluation criteria and indicators are systematically derived from the conceptual system model developed and are examined in a MCA. This approach is influenced by the SoS approach described earlier to match the other required evaluation characteristics.

Indicators are a typical means used to facilitate evaluation and aid decision making, as they can convey a complex message in a simplified informative manner, and have an international recognition [35]. Indicators are trusted for highlighting problems, identifying barriers, and providing insights into the dynamics of the energy system. However, indicators must evolve over time to fit different conditions, priorities and capabilities [29]. In this context, systems thinking can provide theory for the changes and emergence of system characteristics, which would make relevant evaluation criteria seem redundant later [76]. On the other hand, a limitation for the use of energy indicators as policy instruments is their partial view and simplification of complexity, which would hide multiple dynamic vulnerabilities of the energy system, such as security [37]. In this regard, combining a plenitude of indicators with a SoS approach can resolve this limitation by capturing the dynamics and complexity involved, and identifying system-wide vulnerabilities, requirements and emerging properties.

Identifying principles for selecting the appropriate indicators sits at the heart of the process of developing an indicator set. A rigorous and transparent selection process of indicators allows for the conceptual validation and increases the credibility of the evaluation framework [70]. Selection principles commonly used in literature include measurability, analytical robustness, scientific reliability, validity, policy relevance and sensitivity to changes, exhaustiveness, comparability and data availability [70,87]. Few indicators might not be sufficient for the proper evaluation, and too many indicators would be difficult to handle [88]. In this regard, a systemic approach provides a good conceptual structure to tackle the challenging task of identifying a coherent set of essential indicator, but requires extensive knowledge of the whole system.

MCA is a formal approach for evaluation using criteria and indicators [36]. It is a universal and versatile tool for evaluation that can be utilised as a generic assessment tool for different sustainability issues [88]. In line with the holistic SoS approach, MCA can be applied as an evaluation technique that can capture the diversity of perspectives and complexity involved [26]. It provides a multidisciplinary, participatory, and transparent framework for policy evaluation [89], and is well suited for supporting decision making when several considerations are of interest, such as in energy policy and planning [90]. MCA has been applied to different problems related to energy. However, studies have focused on energy systems with one energy vector, despite systems with multiple energy vectors being considered suitable to be examined by MCA due to its ability to capture synergies between multiple systems [90].

MCA can be used either to close down a discussion by aggregation and ranking, or to open it up by a disaggregated set of indicators [91]. Upon quantification, indicators can be aggregated into a weighted index or displayed as a set of disaggregated measures. Indices can be easy to interpret and would provide a uniform scale for comparison [50]. However, indices are not always robust and different indices addressing the same concept can show inconsistent evaluations [55,89]. Indices can also mask trade-offs by compensation of bad performance in one dimension by good performance in another [54]. On the other hand, presenting indicators in a disaggregated form such as a dashboard, enables decision makers to realise trade-offs between the different indicators when comparing different scenarios. Nevertheless, the use of dashboards could be daunting if a large number of indicators is presented [50]. In this framework, indicators are presented in a disaggregated form such as a dashboard as it better presents trade-offs.

4.2. Framework procedure

The proposed framework procedure comprises three stages for the evaluation of integrated energy systems (Fig. 4). The first stage is the problem structuring stage, where systems analysis is conducted using a SoS approach to model the structure and behaviour of the system under study. This facilitates the identification of requirements and interactions within the integrated energy system, as well as the emergent properties of the whole system. SysML is utilised to develop the conceptual system model and carry out the systems analysis. In the second stage, appropriate criteria and respective indicators are assigned relating system requirements to relevant system components and functions specified in stage 1. Indicators are then grouped and analysed for the evaluation of the whole system in a dashboard form. This approach enables evaluation considering different system levels and multiple perspectives. The third stage involves comparing the findings of various future scenarios to analyse trade-offs and synergies.

4.2.1. Stage 1: problem structuring

The first stage of the evaluation framework presented in Fig. 4 involves systems analysis. The aim of this stage is to develop a conceptual system model, which includes creating context, structural and functional models of the system. The underpinning conceptual approach to systems analysis is a SoS approach, as described in section 4.1. By applying a SoS approach, an architectural framework for creating the system model can be developed. Table 3 presents the architectural framework used for this study, which is based on the System-of-Systems Approach to Context-based Requirements Engineering (SoS-ACRE) framework [92], adapted to the case of integrated energy systems. The architectural framework describes the system views that are needed as part of the systems analysis stage, which would then feed into the second stage of evaluation.

System views are divided into four system levels, namely the Context, SoS, CS and System Element levels. On each level, several views are developed to show the structure, properties, requirements and operations of the different system components. Although the system views are presented in a specific sequence from a higher system level to a lower one, the process of developing those views is iterative. One might move from one system view and one system level back to another to make the whole system model complete and consistent.

System views are developed using SysML diagrams. Diagrams of interest are both structural and behavioural and are summarised as follows [82,84,85].

- Block definition diagrams: to define the system structure, composition, relationships and properties
- Internal block diagram: to describe the internal structure and flows in the system
- Requirement diagrams: to define and describe system requirements and their relationships
- Use case diagrams: to link the system requirements to actors or CSs, showing requirements in application context

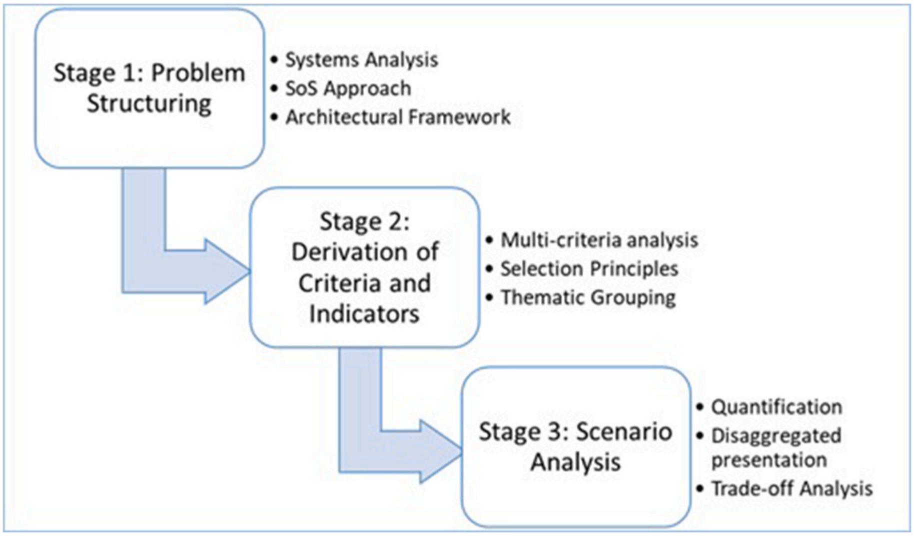

Fig. 4. Framework procedure for evaluating integrated energy systems.

Table 3
Systems analysis architectural framework.

Level	View	Diagram
Context	Context: System Boundary, Composition, Perspectives, Environment, Stakeholders	Block Definition
System-of-Systems	Structure	Internal Block
	Requirements	Use Case, Requirements
	Operations	Activity, Sequence
Constituent System	Composition	Block Definition,
	Structure	Internal Block
	Requirements	Use Case, Requirements
	Operations	Activity, Sequence
System Element	Composition, Properties	Block Definition

- Activity diagrams: to show the behaviour and interactions between and within elements and operations
- Sequence diagrams: to model scenarios and understand the logical sequence of the system operations
- Parametric diagrams: to define calculations for parameters (measures of effectiveness) used to evaluate performance

4.2.1.1. Context level. The first step in the architectural framework presented in Table 3 is setting the context and defining the SoS to be evaluated. At this level, the system boundaries are specified in order to identify what is considered inside and outside of the system, thus its CSs and the actors or stakeholders composing its environment. Block definition diagrams are used to show the composition of the system and its stakeholders. At this level also, the perspectives to be considered are identified. These could be for instance the technical, economic, environmental, political, and social.

For example, the focus of the evaluation could be the physical system architecture of ESI. In this case, the boundaries would mainly include the physical aspects of the energy system. Accordingly, the CSs would be the power, gas, heat, transport, and hydrogen physical systems involved, in addition to integration enablers or coupling components, such as CHP, P2X, HPs and EVs. On the other hand, the system environment would include stakeholders affecting or affected by the system, in other words, having some control on the system or requirements from it. This typically includes actors from policy, environment, markets and society, and therefore reflect the political, environmental, economic and social perspectives.

4.2.1.2. System-of-systems level. The second step is developing system views for the SoS level, where the structure, requirements, and operations of the system as a whole are shown, i.e. showing each CS as a black box. The structure at this level follows from the composition shown at the context level, but with a closer look at how the CSs are linked. This is carried out using an internal block diagram, showing the relationships and flows between the different CSs. Flows could be physical, commercial or informational.

At this SoS level, requirements are related to the perspectives introduced in the context level. These could be technical features that are expected from the system as a whole, such as resilience, flexibility and interoperability. For instance, the whole system resilience is resilience across CSs, since it is enhanced by operational flexibility which could be fulfilled through structural and organisational interoperability of different CSs, where interactions typically involve exchange of energy and information. Furthermore, requirements of stakeholders reflecting other perspectives can be considered as contextual objectives of the energy system as set by external actors. These could be objectives or constraints related to political concerns, environmental regulations, economic considerations, and social acceptability. Hereby, dimensions such as those presented in Table 2 can be accounted for in this framework.

Requirements are defined using requirements diagrams. Requirements are functions or capabilities that the SoS should deliver or acquire to satisfy the needs of the identified stakeholders. Requirements can also be linked together, with some requirements constraining others or being an extension to others. Use case diagrams show desired functions or features of the SoS which are linked to external actors, showing the SoS capabilities from different users' perspectives. Use cases provide context to requirements by showing how the system can be used, and help understand SoS functions, requirements and capability gaps. Based on use cases, scenarios can be produced and simulated. In this framework, non-functional requirements are represented in a requirements diagram, while functional requirements are represented in a use case diagram.

Behavioural diagrams are used to describe the operations involved and the interactions between CSs to deliver the system functionality and satisfy requirements. This includes sequence and activity diagrams. Sequence diagrams show the operations involved between CSs, while activity diagrams show behaviour within an operation. Two approaches can be taken to model the system behaviour: (i) a goal-oriented analysis, where a system view shows the operations needed to deliver a requirement. For instance, the operations undertaken to satisfy the requirement of delivering heat through the heat network after energy has been transformed from the electricity system via HPs; and (ii) scenarios-driven analysis that considers different what-ifs for the system operations. In this case, one can examine the different flows in the system and conduct a fault analysis exercise to verify the flexibility requirement of the whole system in case of a fault or a break in some pathways.

4.2.1.3. Constituent system level. System views for the structure, requirements and operations at the CS level are developed for each of the CSs, similar to the SoS level. The system views are performed to show the composition of each CS in terms of system elements and operations involved to satisfy requirements. Requirements at this level relate to the independent functionality of the CSs, in addition to the functionalities that are supported by the CSs, which the SoS has to deliver. Accordingly, requirements at this level can be associated with stakeholders, but also with other CSs and with the SoS as a whole. Block definition and internal block diagrams are used to model the structure of the CS, i.e. its composition and interrelations, while activity diagrams are used to model the operations. As described for the SoS level, use case and requirements diagrams are used to show and describe requirements for stakeholders at this level. However, based on the SoS-ACRE framework, diagrams at this level need to show the interactions between the requirements and functionalities of the CSs and the SoS.

As an example, the CS electricity system can be further broken down at this level to include primary resources, generation, storage, transmission and distribution. These elements can also be described by their operations whereby electricity is generated, stored, transmitted and distributed, to finally satisfy electricity demand, and possibly other requirements related to other CSs and the SoS to provide flexibility to the whole system. Other CSs such as P2X can in turn provide services to the electricity system such as grid balancing and storage services, while also transforming energy from the electricity system to the gas system or vice versa.

4.2.1.4. System element level. Each of the CS elements is further composed of different technologies. For instance, within the electricity system, various primary energy resources exist (gas, uranium, wind, solar radiance etc.) and accordingly different generation technologies are applied, such as gas-fired turbines, nuclear reactors, wind turbines and solar PV. Therefore, the composition of the different CSs and the properties of their system elements are viewed, using block definition diagrams. This is important when each of those technologies have different properties which impact higher levels of the system in a different way.

4.2.2. Stage 2: derivation of criteria and indicators

After modelling the system with the views described in the first stage, appropriate evaluation criteria and corresponding indicators are assigned to the different system components or functions. The first step is to specify the purpose of the evaluation. The purpose of evaluation can be governed by policy objectives or performance benchmarks that need to be met. Then, suitable criteria for the evaluation are derived from the system model based on the purpose and selection principles. Criteria can typically be objective focused (translation of objectives into criteria) or alternative focused (highlighting strengths and weaknesses of each alternative) [91]. In this framework, criteria will exploit both approaches by reflecting the system objectives and requirements identified in the first stage at the different levels. Thus, the system is evaluated against both: (i) the contextual objectives manifested as dimensions similar to those presented in Table 2; and (ii) the functional requirements identified in the systems analysis stage at the SoS and CS levels. This shows the performance of the energy systems in delivering capabilities independently and as a whole.

Furthermore, corresponding indicators that measure the state of the evaluation criteria are chosen. A thematic grouping of indicators into broader dimensions is followed as it better links them to targets. After the selection of indicators, a parametric diagram is added to the system diagrams developed in stage 1. SysML parametric diagrams show the evaluation criteria and any mathematical formulae used to quantify them. This makes the initial system model complete by representing critical parameters for achieving desired requirements, defining ways to evaluate performance and allowing the comparison of alternatives.

4.2.3. Stage 3: scenario analysis

Stage 3 of the framework presented in Fig. 4 involves scenario analysis, where stages 1 and 2 are applied in a case study to evaluate and compare the performance of the integrated energy system under a range of scenarios. Different types of scenarios have been identified in the literature for the analysis of future energy systems. In line with the WES approach followed in this paper, scenarios best fit within the framework are those used for modelling studies which typically focus on the WES, as described in Ref. [93]. These scenarios are justified by qualitative storylines and work under an identified end point. For instance, scenarios could explore the impact of employing energy systems integration under exogenous constraints such as achieving net-zero emission targets, or under different supply and demand conditions. The latter could be influenced by changes to the RES capacity or variations to the peak demand levels.

In this stage, indicators are quantified and are presented in a disaggregated form such as a dashboard. Qualitative storylines are usually combined with quantitative modelling for quantification [94]. Thus, data for scenarios are fed from existing demonstration systems, if available, or simulation models of future systems. The latter requires examining the simulation model coupled with the evaluation framework, to ensure data availability for the identified indicators and that the assumptions for modelling the WES are consistent.

Findings of different scenarios are then compared and analysed to examine whether objectives can be achieved synergistically upon ESI or whether they require trade-offs. The performance of integrated systems can be evaluated either against set targets or as improvements relative to a baseline scenario, for example one with no integration between energy systems.

4.3. Experts validation

Validation of the proposed framework is important to ensure its quality, utility and credibility. This is done following the method for scientific validation using experts elicitation [95]. Several techniques could be used to elicit the experts feedback including questionnaires and interviews. The aim of the scientific validation is to evaluate the proposed framework based on its conceptual coherence, operational coherence and utility. The three aspects are associated with the three types of validity: design, output and end-use validity. Design validity relates to the scientific foundation of the framework, while output validity relates to the reliability and credibility of the framework output, and end-use validity looks at the usefulness of the framework in serving its designated purposes [96].

A group interview with experts was conducted in the form of an online workshop for the purpose of validation, with questions provided in advance in order to elicit individual responses in addition to group responses, and a questionnaire afterwards to capture any post-workshop individual reflection. The workshop took place online due to travel restrictions caused by the COVID-19 pandemic, and a group interview was chosen to generate insights from multi-disciplinary discussions between the experts [97,98]. The participants were researchers from the EPSRC National Centre for Energy Systems Integration. Six experts were chosen to span multiple academic disciplines related to energy research including engineering, computing, mathematics and social sciences.

The workshop followed a three-fold validation process looking at the design, output and end-use of the proposed framework. The workshop was therefore divided into three parts representing different phases involved in the design (presented in section 4.1), implementation (presented in section 4.2) and application (demonstrated with examples) of the framework. Each part started with a presentation and was followed by a structured discussion. The workshop was followed with a questionnaire. The experts were also provided with a brief written description of the proposed framework ahead of the workshop for familiarity.

The participants generally showed a positive attitude towards the proposed framework during the discussions. The participants thought the framework provided a good level of accuracy, credibility, coherence and utility, and that they were somehow likely to use the framework. They all agreed that it was important that the framework allows for the following:

- Show the relationships between different system components
- Model the system at different levels
- Present the system requirements in relation to multiple stakeholders
- Link the system components and functionalities to derive
- Make informative judgements on the performance of different scenarios

Based on the experts' feedback, the strengths of the framework can be summarised as being comprehensive, flexible and transferable, and provides a structured approach and unified language for ESI understanding and evaluation. On the other hand, the downside of the framework lies in that it needs to be contextualised for each evaluation, and this could take some effort for learning the methods used, such as SysML. Another downside identified is that the framework is still dependent on the quality of the data available. Accordingly, room for improvements as suggested by the participants mainly related to the consistent, standardised application of the framework. This shall be addressed in future by development of a reference system architecture that can be used as a standard conceptual system model for the first stage of the evaluation, in addition to a functional specification of the formal relation between the evaluation framework and simulation models needed for the third stage of the evaluation.

5. Conclusion

This paper argues the need for a new evaluation framework that can holistically assess the performance of integrated energy systems towards achieving designated objectives. This is due to the major changes that energy systems integration would bring to the energy system, in the way it is structured, planned, operated, and consequently evaluated. Accordingly, the framework should adopt a whole energy systems approach to the evaluation. This enables the framework to consider the interactions between multiple energy vectors, the interdependencies across the system components from generation to end-use through infrastructure, markets and policy, and the wide range of perspectives and objectives involved in the energy system. These include the technical, environmental, economic, political and social aspects. The paper reviews existing frameworks for the evaluation of energy systems based on characteristics corresponding to the whole energy system domains and changes to the energy system. The characteristics are multidimensional, multivectoral, systemic, futuristic, systematic and applicability. The review concludes that existing frameworks are not capable of assessing the performance of integrated energy systems, lacking one or more of the identified characteristics.

An evaluation framework is proposed to address the six key identified characteristics. The proposed framework combines a system-of-systems approach for systems analysis, with an indicator-based approach using multi-criteria analysis. The framework procedure involves three stages. First, problem structuring where the energy system under study is modelled to specify the system structure, behaviour and requirements. The second stage is derivation of criteria and indicators for the holistic system evaluation relating system requirements to relevant system components and functions. Finally, results from various scenarios are compared and analysed to realise trade-offs and synergies. The framework demonstrates the six characteristics as it enables evaluation with respect to multiple perspectives and objectives at different system levels. Moreover, this framework captures future changes to the whole energy system architecture and highlights the interdependencies between energy systems. This framework can also be systematically applied to various scenarios in different contexts.

The evaluation framework presented in this paper was validated using expert elicitation in a structured group interview. Experts identified the strengths and weaknesses of the proposed framework and provided suggestions for improvement. The proposed framework is currently being applied to a case study with different scenarios representing different configurations for integrating the power, gas and heat systems at a local scale. The objectives of the case study are: (i) to ensure the applicability of the proposed framework; and (ii) to test the dashboard approach presented in stage 3 of the framework in terms of comparability between scenarios, conducting a trade-offs analysis, and presentation of results. This case study and the examples discussed in this paper focus on the physical energy systems and interactions. However, the methods from systems-of-systems engineering used to develop the proposed evaluation framework can be further extended to look at the information and communication aspects of the whole energy system. In fact, such methods are used in software engineering and are particularly suitable for cyber-physical interactions. At that point, future challenges related to the increased digitalisation of the system, such as cyber security, data sharing and interoperability, can also be assessed.

It should be noted that the developed framework can be used for evaluating decisions during the planning and operation of integrated energy systems. As an example, in the future control rooms of integrated energy systems, the control engineers from each of the power, gas and district heating systems, need to control, manage and plan the integrated energy system in a collaborative way. In this way, if a congestion, blockage or any shortage of supply occurs in any of the systems, then it would be possible to use the developed framework to inform decision-making at the managerial level about the effectiveness of adjustments made with other coupled systems to support the operational security of the affected system. This example shows that the evaluation framework has taken the advantage of the interactions and interdependencies between different systems offered by the coupling components, i.e. CHP, P2X, etc., in order to provide a basis for making well-informed decisions in terms of carbon emissions, cost and security, namely the dimensions of the energy trilemma.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank the experts that participated in the validation workshop during the challenging time of the COVID-19 lockdown.

This research was funded by Newcastle University as part of activities for the EPSRC National Centre for Energy Systems Integration (EP/P01173/1).

References

[1] IET. Future Power System Architecture - Main Report. 2016.

[2] Hanna R, Gazis E, Edge J, Rhodes A, Gross R. Unlocking the potential of Energy Systems Integration. 2018.
[3] O'Malley M, Kroposki B, Hannegan B, Madsen H, Andersson M, William D, et al. Energy Systems Integration : Defining and Describing the Value Proposition. Nrel/Tp-5D00-66616 2016:9. doi:https://doi.org/10.2172/1257674.
[4] Mancarella P. MES (multi-energy systems): an overview of concepts and evaluation models. Energy 2014;65:1–17. https://doi.org/10.1016/j.energy.2013.10.041.
[5] Hosseini SHR, Allahham A, Walker SL, Taylor P. Optimal planning and operation of multi-vector energy networks: a systematic review. Renew Sustain Energy Rev 2020;133:110216.
[6] Abeysekera M, Wu J, Jenkins N. Integrated energy systems: an overview of benefits, analysis methods, research gaps and opportunities. HubNET Position Pap Ser 2016. https://orca.cf.ac.uk/133441/1/HubNET%20Position%20paper-Multi%20Energy-Revised%20version.pdf.
[7] Ruth MF, Kroposki B. Energy systems integration: an evolving energy paradigm. Electr J 2014;27:36–47. https://doi.org/10.1016/j.tej.2014.06.001.
[8] Singh HV, Bocca R, Gomez P, Dahlke S, Bazilian M. The energy transitions index: an analytic framework for understanding the evolving global energy system. Energy Strateg Rev 2019;26:100382. https://doi.org/10.1016/j.esr.2019.100382.
[9] IET. An Overview of Britain's Changing Energy Sector. 2016.
[10] Farid AM, Jiang B, Muzhikyan A, Youcef-Toumi K. The need for holistic enterprise control assessment methods for the future electricity grid. Renew Sustain Energy Rev 2016;56:669–85. https://doi.org/10.1016/j.rser.2015.11.007.
[11] Energy Systems Catapult. Energy Systems Architecture Methodology: Enabling Multi-vector Market Design. 2017.
[12] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;45:785–807. https://doi.org/10.1016/j.rser.2015.01.057.
[13] Mittal S, Ruth M, Pratt A, Lunacek M, Krishnamurthy D, Jones W. A system-of-systems approach for integrated energy systems modeling and simulation. In: Proc. Conf. Summer comput. Simul., society for computer simulation international; 2015. p. 1–10.
[14] Guelpa E, Bischi A, Verda V, Chertkov M, Lund H. Towards future infrastructures for sustainable multi-energy systems: a review. Energy 2019;184:2–21. https://doi.org/10.1016/j.energy.2019.05.057.
[15] Kondziella H, Bruckner T. Flexibility requirements of renewable energy based electricity systems - a review of research results and methodologies. Renew Sustain Energy Rev 2016;53:10–22. https://doi.org/10.1016/j.rser.2015.07.199.
[16] Jamasb T, Llorca M. Energy Systems Integration: Economics of a New Paradigm. 2019.
[17] Kroposki B, Garrett B, Macmillan S, Rice B, Komomua C, O'malley M, et al. Energy Systems Integration: A Convergence of Ideas. 2012.
[18] Wang J, You S, Zong Y, Træholt C, Dong ZY, Zhou Y. Flexibility of combined heat and power plants: a review of technologies and operation strategies. Appl Energy 2019;252. https://doi.org/10.1016/j.apenergy.2019.113445.
[19] Hosseini SHR, Allahham A, Taylor P. Techno-economic-environmental analysis of integrated operation of gas and electricity networks. Proc IEEE Int Symp Circ Syst 2018;2018–May. https://doi.org/10.1109/ISCAS.2018.8351704.
[20] KPMG. Energising the North. An evaluation of the economic contribution of the energy sector to the North of England. 2017.
[21] Lei Y, Hou K, Wang Y, Jia H, Zhang P, Mu Y, et al. A new reliability assessment approach for integrated energy systems: using hierarchical decoupling optimization framework and impact-increment based state enumeration method. Appl Energy 2018;210:1237–50. https://doi.org/10.1016/j.apenergy.2017.08.099.
[22] Erdener BC, Pambour KA, Lavin RB, Dengiz B. An integrated simulation model for analysing electricity and gas systems. Int J Electr Power Energy Syst 2014;61:410–20. https://doi.org/10.1016/j.ijepes.2014.03.052.
[23] Winskel M, Kattirtzi M, Lowes R, Woodman B, Poulter H, Brand C, et al. Disrupting the UK energy system: causes, impacts and policy implications 2019.
[24] IET. Future Power System Architecture Work Package 1B Final Report-Future Stakeholder Needs. 2017.
[25] Martín-Gamboa M, Iribarren D, García-Gusano D, Dufour J. A review of life-cycle approaches coupled with data envelopment analysis within multi-criteria decision analysis for sustainability assessment of energy systems. J Clean Prod 2017;150:164–74. https://doi.org/10.1016/j.jclepro.2017.03.017.
[26] Troldborg M, Heslop S, Hough RL. Assessing the sustainability of renewable energy technologies using multi-criteria analysis: suitability of approach for national-scale assessments and associated uncertainties. Renew Sustain Energy Rev 2014;39:1173–84. https://doi.org/10.1016/j.rser.2014.07.160.
[27] Evans A, Strezov V, Evans TJ. Assessment of sustainability indicators for renewable energy technologies. Renew Sustain Energy Rev 2009;13:1082–8. https://doi.org/10.1016/j.rser.2008.03.008.
[28] Kisel E. Indicators for Assessing the Quality of an Energy Policy. 2017.
[29] Narula K, Reddy BS. A SES (sustainable energy security) index for developing countries. Energy 2016. https://doi.org/10.1016/j.energy.2015.10.106.
[30] Dombi M, Kuti I, Balogh P. Sustainability assessment of renewable power and heat generation technologies. Energy Pol 2014;67:264–71. https://doi.org/10.1016/j.enpol.2013.12.032.
[31] Afgan NH, Carvalho MG. Sustainability assessment of a hybrid energy system. Energy Pol 2008;36:2893–900. https://doi.org/10.1016/j.enpol.2008.03.040.
[32] He C, Feng X. Evaluation indicators for energy-chemical systems with multi-feed and multi-product. Energy 2012;43:344–54. https://doi.org/10.1016/j.energy.2012.04.019.
[33] Osorio S, van Ackere A, Larsen ER. Interdependencies in security of electricity supply. Energy 2017;135:598–609. https://doi.org/10.1016/j.energy.2017.06.095.
[34] Karger CR, Hennings W. Sustainability evaluation of decentralized electricity generation. Renew Sustain Energy Rev 2009;13:583–93. https://doi.org/10.1016/j.rser.2007.11.003.
[35] Mangoyana RB, Smith TF, Simpson R. A systems approach to evaluating sustainability of biofuel systems. Renew Sustain Energy Rev 2013;25:371–80. https://doi.org/10.1016/j.rser.2013.05.003.
[36] Witt T, Dumeier M, Geldermann J. Combining scenario planning, energy system analysis, and multi-criteria analysis to develop and evaluate energy scenarios. J Clean Prod 2020;242:118414. https://doi.org/10.1016/j.jclepro.2019.118414.
[37] Gracceva F, Zeniewski P. A systemic approach to assessing energy security in a low-carbon EU energy system. Appl Energy 2014;123. https://doi.org/10.1016/j.apenergy.2013.12.018.
[38] Watson J, Ketsopoulou I, Dodds P, Chaudry M, Tindemans S, Woolf M, et al. The Security of UK Energy Futures. 2018.
[39] Glynn J, Chiodi A, Ó Gallachóir B. Energy security assessment methods: quantifying the security co-benefits of decarbonising the Irish Energy System. Energy Strateg Rev 2017;15:72–88. https://doi.org/10.1016/j.esr.2016.11.005.
[40] Augutis J, Krikštolaitis R, Martišauskas L, Pečiulytė S, Žutautaitė I. Integrated energy security assessment. Energy 2017;138:890–901. https://doi.org/10.1016/j.energy.2017.07.113.
[41] Jewell J, Cherp A, Riahi K. Energy security under de-carbonization scenarios: an assessment framework and evaluation under different technology and policy choices. Energy Pol 2014;65:743–60. https://doi.org/10.1016/j.enpol.2013.10.051.
[42] Hadian S, Madani K. A system of systems approach to energy sustainability assessment: are all renewables really green? Ecol Indicat 2015;52:194–206. https://doi.org/10.1016/j.ecolind.2014.11.029.
[43] WEC. World. Energy Trilemma Index 2019. 2019.
[44] Global WEF. Energy architecture performance index report 2017 2017;1.
[45] Heffron RJ, McCauley D, Sovacool BK. Resolving society's energy trilemma through the Energy Justice Metric. Energy Pol 2015;87:168–76. https://doi.org/10.1016/j.enpol.2015.08.033.
[46] Chilvers J, Foxon TJ, Galloway S, Hammond GP, Infield D, Leach M, et al. Realising transition pathways for a more electric, low-carbon energy system in the United Kingdom: challenges, insights and opportunities. Proc Inst Mech Eng Part A J Power Energy 2017:095765091769544. https://doi.org/10.1177/0957650917695448.
[47] Sovacool BK, Mukherjee I, Drupady IM, D'Agostino AL. Evaluating energy security performance from 1990 to 2010 for eighteen countries. Energy 2011. https://doi.org/10.1016/j.energy.2011.08.040.
[48] Cox E. Assessing energy security in a low-carbon context The case of electricity in the UK. University of Sussex; 2016.
[49] Martchamadol J, Kumar S. An aggregated energy security performance indicator. Appl Energy 2013;103:653–70. https://doi.org/10.1016/j.apenergy.2012.10.027.
[50] Iddrisu I, Bhattacharyya SC. Sustainable Energy Development Index: a multi-dimensional indicator for measuring sustainable energy development. Renew Sustain Energy Rev 2015;50:513–30. https://doi.org/10.1016/j.rser.2015.05.032.
[51] Santoyo-Castelazo E, Azapagic A. Sustainability assessment of energy systems: integrating environmental, economic and social aspects. J Clean Prod 2014;80:119–38. https://doi.org/10.1016/j.jclepro.2014.05.061.
[52] Volkart K, Weidmann N, Bauer C, Hirschberg S. Multi-criteria decision analysis of energy system transformation pathways: a case study for Switzerland. Energy Pol 2017;106:155–68. https://doi.org/10.1016/j.enpol.2017.03.026.
[53] Sovacool BK, Mukherjee I. Conceptualizing and measuring energy security: a synthesized approach. Energy 2011;36:5343–55. https://doi.org/10.1016/j.energy.2011.06.043.
[54] Larsen ER, Osorio S, van Ackere A. A framework to evaluate security of supply in the electricity sector. Renew Sustain Energy Rev 2017;79:646–55. https://doi.org/10.1016/j.rser.2017.05.085.
[55] Narula K, Reddy BS. Three blind men and an elephant: the case of energy indices to measure energy security and energy sustainability. Energy 2015;80:148–58. https://doi.org/10.1016/j.energy.2014.11.055.
[56] Gallego Carrera D, Mack A. Sustainability assessment of energy technologies via social indicators: results of a survey among European energy experts. Energy Pol 2010;38:1030–9. https://doi.org/10.1016/j.enpol.2009.10.055.
[57] Habib MS, Tayyab M, Zahoor S, Sarkar B. Management of animal fat-based biodiesel supply chain under the paradigm of sustainability. Energy Convers Manag 2020;225. https://doi.org/10.1016/j.enconman.2020.113345.
[58] Mainali B, Silveira S. Using a sustainability index to assess energy technologies for rural electrification. Renew Sustain Energy Rev 2015;41:1351–65. https://doi.org/10.1016/j.rser.2014.09.018.
[59] Shaaban M, Scheffran J. Selection of sustainable development indicators for the assessment of electricity production in Egypt. Sustain Energy Technol Assessments 2017;22:65–73. https://doi.org/10.1016/j.seta.2017.07.003.
[60] Hoggett R. Technology scale and supply chains in a secure, affordable and low carbon energy transition. Appl Energy 2014;123:296–306. https://doi.org/10.1016/j.apenergy.2013.12.006.
[61] Molyneaux L, Brown C, Wagner L, Foster J. Measuring resilience in energy systems: insights from a range of disciplines. Renew Sustain Energy Rev 2016;59:1068–79. https://doi.org/10.1016/j.rser.2016.01.063.
[62] Rovere EL La, Soares JB, Oliveira LB, Lauria T. Sustainable expansion of electricity sector: sustainability indicators as an instrument to support decision making.

Renew Sustain Energy Rev 2010;14:422–9. https://doi.org/10.1016/j.rser.2009.07.033.
[63] Onat N, Bayar H. The sustainability indicators of power production systems. Renew Sustain Energy Rev 2010;14. https://doi.org/10.1016/j.rser.2010.07.022.
[64] Narula K, Sudhakara Reddy B, Pachauri S. Sustainable Energy Security for India: an assessment of energy demand sub-system. Appl Energy 2017;186:126–39. https://doi.org/10.1016/j.apenergy.2016.02.142.
[65] Cosmi C, Dvarioniene J, Marques I, Di Leo S, Gecevičius G, Gurauskiene I, et al. A holistic approach to sustainable energy development at regional level: the RENERGY self-assessment methodology. Renew Sustain Energy Rev 2015;49: 693–707. https://doi.org/10.1016/j.rser.2015.04.094.
[66] Ahmed W, Sarkar B. Management of next-generation energy using a triple bottom line approach under a supply chain framework. Resour Conserv Recycl 2019;150. https://doi.org/10.1016/j.resconrec.2019.104431.
[67] Chong YT, Teo KM, Tang LC. A lifecycle-based sustainability indicator framework for waste-to-energy systems and a proposed metric of sustainability. Renew Sustain Energy Rev 2016;56:797–809. https://doi.org/10.1016/j.rser.2015.11.036.
[68] Afgan NH, Veziroglu A, Carvalho MG. Multi-criteria evaluation of hydrogen system options. Int J Hydrogen Energy 2007;32:3183–93. https://doi.org/10.1016/j.ijhydene.2007.04.045.
[69] Sarkar M, Sarkar B. How does an industry reduce waste and consumed energy within a multi-stage smart sustainable biofuel production system? J Clean Prod 2020:262. https://doi.org/10.1016/j.jclepro.2020.121200.
[70] Niemeijer D, de Groot RS. A conceptual framework for selecting environmental indicator sets. Ecol Indicat 2008;8:14–25. https://doi.org/10.1016/j.ecolind.2006.11.012.
[71] Pfenninger S, Hawkes A, Keirstead J. Energy systems modeling for twenty-first century energy challenges. Renew Sustain Energy Rev 2014;33:74–86. https://doi.org/10.1016/j.rser.2014.02.003.
[72] Bale CSE, Varga L, Foxon TJ. Energy and complexity: new ways forward. Appl Energy 2015;138:150–9. https://doi.org/10.1016/j.apenergy.2014.10.057.
[73] Nielsen CB, Larsen PG, Fitzgerald J, Woodcock JIM, Peleska JAN. Systems of systems Engineering : basic concepts , model-based techniques , and research directions. ACM Comput Surv 2015;48:1–41. https://doi.org/10.1145/2794381.
[74] Hall JW, Tran M, Hickford AJ, Nicholls RJ. The future of national infrastructure: A system-of-systems approach. Cambridge University Press; 2016.
[75] DeLaurentis D, Callaway RK. A system-of-systems perspective for public policy decisions. Rev Pol Res 2004. https://doi.org/10.1111/j.1541-1338.2004.00111.x.
[76] Williams B, Imam I. Systems concepts in evaluation: An expert anthology. CA: EdgePress of Inverness Point Reyes; 2007.
[77] iBUILD. Closing the Gap: Local infrastructure business models to support inclusive growth. 2018. https://doi.org/10.1016/B978-0-12-801265-9.00013-5.
[78] Pires A, Morato J, Peixoto H, Botero V, Zuluaga L, Figueroa A. Sustainability Assessment of indicators for integrated water resources management. Sci Total Environ 2017;578:139–47. https://doi.org/10.1016/j.scitotenv.2016.10.217.
[79] Bell S, Morse S. Measuring Sustainablility: Learning from Doing. 2003.
[80] Mendes G, Ioakimidis C, Ferrão P. On the planning and analysis of Integrated Community Energy Systems: a review and survey of available tools. Renew Sustain Energy Rev 2011;15:4836–54. https://doi.org/10.1016/j.rser.2011.07.067.
[81] Ingram C, Payne R, Perry S, Holt J, Hansen FO, Couto LD. Modelling patterns for systems of systems architectures. 8th Annu. IEEE Int. Syst. Conf. SysCon 2014 - Proc. 2014:146–53. https://doi.org/10.1109/SysCon.2014.6819249.
[82] Geyer P, Buchholz M. Parametric systems modeling for sustainable energy and resource flows in buildings and their urban environment. Autom ConStruct 2012; 22:70–80. https://doi.org/10.1016/j.autcon.2011.07.002.
[83] Lane JA, Bohn T. Using SysML modeling to understand and evolve systems of systems. Syst Eng 2013;16:87–98. https://doi.org/10.1002/sys.21221.
[84] Compass. Guidelines for Architectural Modelling of SoS. 2014.
[85] Holt J, Perry SA, Brownsword M. Model-based requirements engineering, vol. 2. IET; 2012.
[86] Stephen Topper J, Horner NC. Model-based systems engineering in support of complex systems development. Johns Hopkins APL Tech Dig (Applied Phys Lab 2013;32:419–32.
[87] Patlitzianas KD, Doukas H, Kagiannas AG, Psarras J. Sustainable energy policy indicators: review and recommendations. Renew Energy 2008;33:966–73. https://doi.org/10.1016/j.renene.2007.05.003.
[88] Van Cauwenbergh N, Biala K, Bielders C, Brouckaert V, Franchois L, Garcia Cidad V, et al. SAFE-A hierarchical framework for assessing the sustainability of agricultural systems. Agric Ecosyst Environ 2007;120:229–42. https://doi.org/10.1016/j.agee.2006.09.006.
[89] Munda G. Multiple criteria decision analysis and sustainable development. Mult. Criteria Decis. Anal. 2005;78:953–86. https://doi.org/10.1007/b100605.
[90] Løken E. Use of multicriteria decision analysis methods for energy planning problems. Renew Sustain Energy Rev 2007;11:1584–95. https://doi.org/10.1016/j.rser.2005.11.005.
[91] Trutnevyte E, Stauffacher M, Scholz RW. Linking stakeholder visions with resource allocation scenarios and multi-criteria assessment. Eur J Oper Res 2012;219: 762–72. https://doi.org/10.1016/j.ejor.2012.01.009.
[92] Holt J, Perry S, Hansen FO, Hallerstede S. Report on guidelines for sos requirements. 2012.
[93] Hughes N, Strachan N. Methodological review of UK and international low carbon scenarios. Energy Pol 2010;38:6056–65. https://doi.org/10.1016/j.enpol.2010.05.061.
[94] Trutnevyte E, Barton J, O'Grady Á, Ogunkunle D, Pudjianto D, Robertson E. Linking a storyline with multiple models: a cross-scale study of the UK power system transition. Technol Forecast Soc Change 2014;89:26–42. https://doi.org/10.1016/j.techfore.2014.08.018.
[95] Cloquell-Ballester VA, Cloquell-Ballester VA, Monterde-Díaz R, Santamarina-Siurana MC. Indicators validation for the improvement of environmental and social impact quantitative assessment. Environ Impact Assess Rev 2006. https://doi.org/10.1016/j.eiar.2005.06.002.
[96] Bockstaller C, Girardin P. How to validate environmental indicators. Agric Syst 2003;76:639–53. https://doi.org/10.1016/S0308-521X(02)00053-7.
[97] Saunders M, Lewis P, Thornhill A. Research methods for business students. Pearson education; 2009.
[98] Bryman A. Social research methods. Oxford university press; 2016.