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AN EVALUATION FRAMEWORK FOR WHOLE ENERGY SYSTEMS SCENARIOS

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ABSTRACT

ESI is expected to create new interactions and interdependencies within the WES including power, gas, heat and transport. This makes existing evaluation frameworks incapable of assessing the performance of future integrated WESs, particularly due to multi-vector integration. Accordingly, this paper proposes an evaluation framework that addresses the gaps existing frameworks exhibit regarding the evaluation of such systems and capture their complexity. The framework starts with system analysis using a SoS approach to model the system under study in a way that facilitates its evaluation. This approach enables evaluation considering different system levels and multiple perspectives. The next step is MCA where appropriate evaluation criteria and a comprehensive set of indicators are derived and interpreted. These are related to system objectives and requirements and are linked to the different system components and functions. The framework could then be applied to case studies under various scenarios to realise trade-offs or synergies. This should serve as evidence for informing decision-making on the future system and the potential benefits of ESI.

Keywords: Energy systems integration, energy transition, systems engineering, system-of-systems, multi-criteria analysis, scenario analysis

NONMENCLATURE

Abbreviations	
ESI	Energy Systems Integration
WES	Whole Energy System
SoS	System-of-Systems
MCA	Multi-Criteria Analysis
SysML	Systems Modelling Language
SoSE	System-of-systems Engineering
CS	Constituent System

1. INTRODUCTION

The energy system is expected to undergo a transition to achieve the energy policy objectives of decarbonisation, acceptability and security. The future energy system would need extended functionalities to flexibly manage the changes and uncertainties in energy supply and demand patterns, driven by electrification, decentralisation and digitalisation [1]. One route for this transition is ESI, which aims to capture and exploit interactions and diversity across multiple energy vectors and pathways, including power, gas, heat and transport. ESI is perceived as one possible solution to drive the transition effectively, as it provides the required flexibility by connecting and coordinating energy vectors across infrastructures, markets and space [2].

Despite ESI being theoretically promising for providing the required flexibility and achieving the policy objectives, more quantified evidence of its benefits as a feasible and effective pathway is still needed. However, existing evaluation framework are incapable of assessing the performance of future integrated WESs, particularly due to interdependencies involved in multi-vector integration. Hence, this paper proposes a framework for evaluating the performance of such systems towards achieving the energy policy objectives.

2. ENERGY SYSTEMS EVALUATION

An extensive literature review was conducted to realise the gaps that existing frameworks exhibit with the evaluation of ESI. Accordingly, six characteristics were identified as insightful for such evaluation. Existing frameworks were rendered not fit for the evaluation lacking one or more of these characteristics.

A *multidimensional* evaluation is necessary to consider the multiple perspectives involved in ESI, initially addressed separately, as evaluation could mean different things to different stakeholders. It is therefore

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important to account for different stakeholders' objectives such as energy security and sustainability [3]. 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. In this context, ESI can have a role in exploiting synergies across energy systems, as it provides an opportunity for collaboration among stakeholders in the planning and operation of the WES.

Evaluation of ESI should be *multivectoral* as to consider the WES comprising different integrated energy vectors and account for the interdependencies involved. Having a more interlinked energy system means that solutions in one system can affect the others. Existing frameworks tend to focus on the power system and even those that consider both the power and gas systems, don't capture the interactions between the two, but they simply expand the boundary of the evaluation [4].

Furthermore, evaluation should reflect *systemic* properties of the WES, reflecting features emerging from interactions between the different system components upon integration, such as flexibility and resilience. For instance, energy security is considered a property of the whole system rather than individual components within [5]. However, previous studies tend to focus on security in terms of primary energy resources availability and energy generation diversity [3]. Evaluation of ESI should rather consider the whole chain of energy from supply to demand, through infrastructure, markets and policy.

Moreover, the framework should be *futuristic*, i.e. to be able to accommodate major changes to the energy system, such as ESI, which would alter the way the system is planned, operated and evaluated. Additionally, the 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. It is also important for the clarity and transparency of the evaluation, which improves its validity and credibility [6]. Finally, the framework should be *applicable* to prove its usefulness and contribute to decision-making. The main challenge for conducting evaluations is typically the unavailability of data [7]. Hence, it is important to be able to get relevant data from energy models resembling future scenarios.

3. EVALUATION FRAMEWORK

To address the identified characteristics required for the appropriate evaluation of ESI, a methodological framework is proposed. Through a stepwise procedure, the framework uses concepts from systems engineering to structure the problem, and (combined with MCA) derive, apply and interpret appropriate criteria and a comprehensive set of indicators for the evaluation of the system under study.

In the first stage, systems analysis using a SoS approach is conducted to model the structure and behaviour of the system under study and facilitate the identification of requirements and interactions within, as well as the emergent properties of the WES. SysML is utilised to semi-formally model the system and carry out the first stage. In the second stage, appropriate criteria and respective indicators are assigned for the holistic evaluation of the WES governed by MCA. The third stage involves scenario analysis where several future scenarios are compared to realise trade-offs or synergies.

The underlying concepts behind the proposed framework are explained in the next subsection before describing how the framework works in practice, focusing on stage 1 where the novelty mainly lies.

3.1 Concepts and Definitions

First, the SoS approach is employed in the framework to address the needs for the evaluation to be multidimensional, multivectoral and systemic. SoSs are defined as integrations of independent systems that act jointly towards a common goal to collectively offer emergent functionality that cannot be provided by the CSs alone [8]. A SoS approach can capture the complexity and diversity involved in ESI, as it can support multidisciplinary understanding and evaluation of systems, help understand how a system is performing by exploring interdependencies, and consider dynamics of change. It can also enable the provision and validation of emerging behaviour [9,10].

Such approach is recommended in evaluation of complex interdependent fields such as infrastructure, water management and sustainable development. This is to adopt a more holistic approach to evaluation that could reflect 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. While the SoS approach is not common in energy systems evaluation, the new paradigm of ESI can drive analyses in the energy field into this direction [11].

Second, the future changes to the energy system, of which ESI is the focus of this study, are expected to transform the system and alter its architecture. A system architecture is defined as the highest-level conception of a system in its environment. This includes principles and guidelines governing its structure, functions, the relationships between its components and with its environment, and how it will meet its requirements. Requirements refer to the functions and capabilities that a SoS and its CSs need to fulfil and acquire [12].

The current energy system architecture in the UK has created gaps hindering the prospects of integration [1]. These gaps are stressed with the increased decentralisation, electrification and digitalisation of the energy system. Therefore, the WES architecture must evolve to recognise the new interfaces created by new interactions. This would require flexibility and adaptability to changes to physical energy flows, data flows and commercial value flows. The new system architecture should also provide levers to policymakers to deliver policy objectives [1].

The concepts of system architecture and requirements sit within the scope of SoSE. The early stage of SoSE of relevance to this study is the conceptual development. Tasks involved in this stage include translating capability objectives into requirements, understanding the SoS CSs and their relationships, obtaining information from the different stakeholders, and assessing actual performance against capability objectives [13]. SysML, a general-purpose graphical modelling language, is used to develop the conceptual system model and support the systems analysis stage.

The second pillar of the framework is MCA, which is the systematic use of criteria and indicators for evaluation. In line with the holistic SoS approach, MCA can be applied capture the diversity of perspectives and criteria involved. It provides a multidisciplinary, participatory and transparent framework for policy evaluation, and is well suited for supporting decision making when several considerations are of interest. MCA has been applied to different problems related to energy. However, studies have focused on energy systems with one energy vector, despite the suitability of MCA for ESI due to its ability to capture synergies between multiple vectors [14].

Indicators are a typical means used to facilitate evaluation and aid decision making, as they can convey a complex message in a simplified informative form. However, indicators must evolve over time to fit different conditions, priorities and capabilities [15]. Another limitation for the use of indicators is its partial view and simplification of complexity, which would hide dynamic vulnerabilities of the energy system [5]. These limitations can be addressed by the SoS approach that provides theory for the changes and emergence of system characteristics [9], combined with a plenitude of indicators governed by MCA to capture the systems dynamics and vulnerabilities at different levels.

3.2 Stage 1: Systems Analysis

The first stage of the evaluation framework is systems analysis. The aim of this stage is to develop a conceptual model, which involves creating context, structural and functional models of the system. To get started with this stage, an architectural framework is developed and is presented in table 1. An architectural framework provides a consistent guideline for creating system views that are needed for the systems analysis. This is done using the different SysML diagrams. 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.

2.2.1 Context Level

The first level in table 1 is the context level, where the context is set and the SoS to be analysed is defined by specifying its boundaries. This allows identifying its CSs and the actors or stakeholders composing its environment. For instance, CSs could be the power, gas and heat systems, in addition to integration enablers, such as power-to-x, electric vehicles and heat pumps. The system environment would include stakeholders

Table 1 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 Structure	Block Definition, Internal Block
	Requirements	Use Case, Requirements
	Operations	Activity, Sequence
System Element	Composition, Properties	Block Definition

affecting or affected by the system. This typically includes actors from policy, markets, society and the environment, and as such respectively reflect the political, economic, social and environmental perspectives. Block definition diagrams are used to show the composition of the SoS and its stakeholders.

2.2.2 System-of-Systems Level

The next level described in table 1 is the SoS level, where system views representing the structure, requirements, and operations of the whole system 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 done using an internal block diagram.

Requirements are defined using requirements diagrams and are put in context using use case diagrams. This is where desired functions or features of the SoS are linked to external actors, showing the SoS capabilities from the different perspectives introduced in the context level. These are functions or capabilities that the SoS should deliver or acquire to satisfy the requirements of the identified stakeholders.

Behavioural diagrams (sequence or activity) are used to describe the operations and the interactions between CSs to deliver system functionalities. Two approaches can be taken here. A goal-oriented analysis, where a system view shows the operations needed to deliver a requirement. Otherwise, a scenarios-driven analysis considers different what ifs for the system operations.

2.2.3 Constituent Systems Level

Similarly, at the CS level, the structure, requirements and operations should be viewed for each of the CSs. This means showing the composition of each CS in terms of system elements and operations involved to satisfy requirements. Requirements at this level can be from stakeholders, but also from other CSs and from the SoS as a whole. Requirements are thus related to the independent functionality of the CS, in addition to the functionalities the SoS has to deliver supported by CSs.

2.2.4 System Element Level

Each of the CS elements is further composed of different technologies. Therefore, their composition and properties are viewed. This is important when technologies have different properties that impact higher levels of the system differently.

3.3 Stage 2: Multi-criteria Analysis

The second stage of the framework is MCA, where appropriate evaluation criteria and corresponding indicators are assigned to the different system components or functions. Suitable criteria are derived from the system model to reflect the system objectives and requirements identified in the first stage at different levels. Thus, the system is evaluated against both the contextual objectives and against system requirements identified at the SoS and CS levels. This shows the performance of the systems in delivering capabilities as a whole and independently. Further, corresponding indicators that measure the state of the evaluation criteria are chosen. Upon quantification, indicators are presented in a disaggregated form such as a dashboard. This allows realising trade-offs between the different indicators when comparing different scenarios [10].

The system model developed in stage 1 is further extended by creating parametric diagrams that show evaluation criteria and any mathematical formulae used to quantify them. This makes the initial model comprehensive by representing critical parameters for achieving desired requirements, defining how to evaluate performance and allowing the comparison of alternatives.

3.4 Stage 3: Scenario Analysis

Stage 3 of the framework involves scenario analysis, where stages 1 and 2 are applied to case studies under different scenarios. Findings are then compared and analysed to examine whether the objectives can be achieved synergistically upon ESI or do they require trade-offs. Finally, results and indicators are presented graphically or in a dashboard to convey the evidence to stakeholders and decision-makers.

4. OUTLOOK

The framework has been trialled on a test scenario for the case study of Findhorn EcoVillage in Scotland, with an integrated power and heat systems coupled by a heat pump. The system models are not presented in this paper due to space restrictions. Evaluation criteria and respective indicators were identified linking systems requirements with different system components and functionalities. The next step is to quantify the indicators by relating the system model developed in SysML to the simulation model running the same scenario, where relevant outputs of the simulation model will be inputs to calculate the indicators. Upon quantification, the indicators will be analysed as per the MCA guidelines. Finally, the framework will be applied on different scenarios to compare findings and realise trade-offs among the different objectives and requirements.

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