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MODEL OF ENERGY SYSTEMS AND STRUCTURES TO ANALYSE GLOBAL EFFECTS (MESSAGE)

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Abstract: Complexity science facilitates the understanding of the operation and behaviour of complex systems, such as energy systems. As an initial step, it is necessary to select suitable modelling approaches and methods for analysing a given energy system. In this process, systems thinking (as opposed to thinking in isolated parts) comes to the fore, particularly when making decisions that affect the entire energy sector, but also in wider engineering practice. Models of energy systems and structures enable systematic and analytical comparison between different energy transition scenarios. Therefore, special emphasis is placed on understanding multi-objective design theory and multi-objective modelling. This approach promotes the development of sustainable and resilient energy system architectures. When analysing the future prospects of energy systems, both driving forces and barriers emerge. Consequently, an integrated assessment of global effects is also a key part of the analysis. As a novel approach, the paper draws a parallel between musical composition and engineering modelling (Model of Energy Systems and Structures to Analyse Global Effects = MESSAGE), using Ravel's Boléro as an illustrative example. The incrementally developing structure of Ravel's Boléro serves as an analogy for the staged evolution of energy systems. Systematic comparison demonstrates the need to enable objective evaluation of alternative solutions, thereby supporting the selection of optimal design options and models. Overall, the MESSAGE framework serves to assess energy system development and global impacts in an integrated way. In the energy sector, systems thinking and modelling/simulation are essential for coordinating tasks, solving problems effectively, and managing processes in an oriented way. The complexity of tasks, problems, and challenges emphasises the importance of dialogue in energy decision-making.

Keywords: energy system, emergent system, complexity, functional optimisation

1. INTRODUCTION

One of the key characteristics of (complex) systems – including energy systems – is the law of requisite variety (Ashby, 1958). Ashby explores how the concept of variety relates to control, drawing parallels with Shannon's information theory. His famous assertion: "Only variety can absorb variety." has become a cornerstone in the study of complex adaptive systems, organizational resilience, and intelligent control mechanisms. Energy systems are directed (purpose-driven) and controllable systems (Buda, 1982), and additionally:

- multi-actor, networked systems,
- exhibiting emergent behaviour,
- adaptive and capable of learning,
- integrating social, technological, economic and environmental factors.

This integration is essential to ensure long-term sustainability. Complexity science is an interdisciplinary field that offers synthesising approaches to understanding how complex systems function, including their behaviour, structure and evolution. These complex systems consist of many interacting elements and often display properties that cannot be directly inferred from the behaviour of individual components – this is known as emergence. Emergence is a key concept in complexity science, referring to the appearance of new, complex behaviours or patterns within a system that cannot be explained by the dynamics or responses of its individual components. Besides energy systems, examples of emergent systems include ant colonies, flocks of birds, and the human brain.

An independent entity with its own properties, goals and behavioural rules can perceive its environment, make decisions and act (generating interactions). Although entities follow simple rules, these can lead to complex, system-level behaviour. If musical compositions are also viewed as entities with attributes and relationships, it becomes evident that they possess an inherent drive

and capacity for change. In this way, their interaction with the environment can also be examined, and it becomes possible to illustrate how freedom of design can exist within constraints. Based on these considerations, the aim of this paper is to highlight the analogy between musical elements and energy systems, thereby illustrating the influence of global impact components.

2. SYSTEM ANALYSIS AND MODELLING POSSIBILITIES

In closed systems, open subsystems may emerge. The results of necessary analyses are synthesised by the system researcher. Weaver (1948) demonstrated the necessity of synthesis, distinguishing between simple, complicated, and complex problems, and recognised that complex systems require a different scientific approach.

Later, Bertalanffy's work (1968) became one of the theoretical pillars of complexity research. He essentially laid the foundations of systems theory, examining how different systems – biological, social, or technical – operate under common principles. McKittrick (1998) highlighted the limitations of modelling by critically analysing the application of general equilibrium models, particularly regarding functional forms. Complementing these insights, Stirling (2010) argued that complexity is not a problem but an opportunity in decision-making. He emphasised that diversity and openness foster flexible and sustainable solutions. The following characteristics of complex energy systems reinforce these arguments:

- the system generates spontaneous structures
- past decisions influence future possibilities
- new behavioural patterns emerge from interactions among elements
- technology and social behaviour co-evolve
- the system can adapt to a changing environment

Bale et al. (2015) explored the applicability of complexity science to understanding energy systems and their transformation. Achieving sustainable, secure, affordable, and low-carbon energy supply requires methods that account for the social, technological, economic, and environmental complexity of energy systems. This approach is particularly useful in uncovering interactions between technology and human behaviour.

Modelling of complex systems – especially energy systems – can be conducted through:

- simulating the behaviour of individual actors (agent-based models)
- capturing temporal changes in relationships and interactions (dynamic network modelling)

However, both the advantages and limitations of modelling must be considered.

Advantages:

- reflects real-world complexity
- capable of handling uncertainty and non-linear behaviour
- helps identify emergent patterns

Limitations:

- computationally intensive
- difficult to validate and calibrate
- results may be challenging for decision-makers to interpret

Energy systems – as complex systems – through their phased development, optimisation, control, integration, maintenance, and reframing, demonstrate analogies with musical compositions when they are viewed from a different perspective. A prime example is the gradually unfolding structure of *Boléro* (URL1) by French composer and pianist Maurice Ravel (1875–1937). The gradually building structure of this piece offers a vivid metaphor for modelling energy systems in phases, hinting at a paradigm shift in energy thinking.

The composition exhibits an incrementally developing structure: each instrument enters sequentially, aligning precisely with the previous one, as if part of a mechanism. The piece is essentially a single melody with varied instrumentation, lasting around 16 minutes. It creates a

symbiotic unity by combining theme repetition (systematic invariance) with eclectic orchestration (systematic variability), thereby increasing dynamics and volume. The simplicity of form and richness of orchestration together create a gradual unfolding. The tempo is steady, and the emergence of unexpected moments demonstrates systemic impact. This example illustrates how rules can coexist with freedom, and how minimal complexity can yield maximal effect. It is simultaneously traditional, conventional, and timelessly modern – qualities also inherent in energy systems.

This can be conceptualised as a communication system: message sender – message – message receiver. Through this musical metaphor, one can illustrate how energy travels from the producer through transmission systems to the end user, and the impact it generates there.

However, contingency must be considered (Torrance, 1981; Csizmadia-Nándori, 2003): initial boundary conditions are contingent (variable, uncertain, context-dependent), such as the quality of energy sources, technical conditions, or disruptive factors. Contingency and order imply both energy loss and the possibility of diversified transmission.

The metaphorical description of energy system stability, integration, and resilience is provided by engineering drive types. According to Zsáry (1990), drives may be:

- friction-based drives (e.g. friction wheel, flat belt, V-belt) – relying on surface contact and friction
- form-fit drives (e.g. gear, chain) – relying on geometric interlocking

These connections symbolically illustrate the transition from an energy “force-fit” (fossil-based and/or weather-dependent, centralised) operation to an energy “form-fit” (alternative-based, potentially decentralised) logic. This transition is not merely technological; for example, the conceptual sketch of an open drive arrangement reflects a structural mode of thinking, where system elements do not connect through tension and friction, but organise themselves through emergent complexity (Figure 1). Such a structure enables energy flow to adapt to the circumstances rather than being forced. Modelling highlights how energy systems become more structured while retaining flexibility and adaptability – the key to future energy logic. The figure presents a conceptual model that helps in understanding how, within energy systems, the two perspectives are complementary and jointly determine their dynamic behaviour.

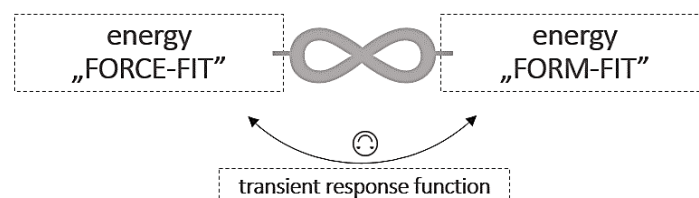


Figure 1 | Conceptual “Transmission Logic” in energy thinking

The behaviour of a system is time-dependent; a transitional function connects and interprets both perspectives. In the temporal behaviour of energy systems, it is necessary to allow for the possibility that, through the suspension of external forces, which hold the system together, subsystems and elements may (temporarily) become independent of one another. At the same time, it must also be ensured that the connections between these subsystems and elements can persist over longer periods. These are not mutually exclusive, but rather complementary principles, recognising that in real-world engineering systems, relational qualities often emerge in a combined and tightly interwoven manner.

The system operates as a driving intelligence. Each system element functions as an energy node where the form, quantity, and quality of energy may change. The transformation scheme is based on a transitional function, considered a time function, describing system behaviour until reaching equilibrium or stability or a steady state after an input stimulus.

Moreover, energy transition is a strategic priority in the EU, regulated by a wide range of legislative instruments. The “Fit for 55” package (URL2) provides the legal foundation for energy transition.

3. SYSTEM DYNAMICS AND GLOBAL EFFECT

Ravel adjusted the system components with controlled precision, similar to an engineering control system capable of optimising a specific process. An analogy to this structured, sequential progression – characteristic of Ravel's approach – can be found in the evolution of energy networks. New energy sources must be integrated gradually, while the stability of the system must be continuously monitored.

Ravel's composition inspires engineering thinking, demonstrating how complexity can emerge from "monotony" when the structure is designed with intent, deliberation, and careful planning. The same phenomenon appears in the modelling of energy systems and infrastructures: starting from simple base models, complex behaviours and systemic effects can be uncovered with global indices and characteristic parameters. This structured comparison is presented in Table 1.

Table 1 | Structured comparison – musical composition and engineering modelling

MUSICAL ELEMENT	ENERGY SYSTEM MODELLING ANALOGY	GLOBAL EFFECT
repeating main theme, single melody	standard base model (e.g. energy consumption patterns)	general applicability and implementation
gradual inclusion of instruments (layer-by-layer orchestration)	integration of new system elements (e.g. new technologies)	emergent complexity (structured chaos)
unchanging rhythm	structured system control (e.g. demand–supply optimisation)	consistent operation
dynamic intensification	changing system characteristics (e.g. network load)	approaching critical thresholds (instability)
climax and abrupt closure	system transition (e.g. energy paradigm shift, supply network reconfiguration)	effective crisis management

The internal strength of a process derives from behaviour and action aligned with a specific goal. Consequently, the global effect manifests as a process that is dynamic and rich in interactions. Individual factors reinforce or weaken one another, accelerate or delay, complement or cancel out, normalise or distort, and mutually influence each other.

Global effects and emergent behaviour in music and energy systems:

- By the end of Boléro, polyphonic texture and volume "erupt" as a global effect.
- In energy systems, local changes (e.g. new technologies, geopolitical tensions) may trigger global instability or reconfiguration.

The characteristics of energy systems – symbolised by 'friction-based' and 'form-fit' drives metaphors – are summarised in Table 2. These systems should not adhere to the general principle of relying solely on weather-dependent elements, but rather consider the full spectrum of energy sources and carriers. As a result, they are characterised by varying levels of coherence, integration, and technological development.

Table 2 | Comparative characteristics of energy systems

TRANSMISSION LOGIC COMPONENT	FRICTION-BASED APPROACH Energy "FORCE-FIT" (reduced, integration-focused, reliant on external forces)	FORM-FIT APPROACH Energy "FORM-FIT" (structured, system-integrated approach)
energy potential, opportunities	fossil + renewables, but operated in parallel, not synchronised	integrated portfolio: primary + supplementary + backup/reserve sources in synergy
system stability	intermittent instability, dependence on external conditions (imports, geopolitics), sensitive to load fluctuations	high stability through decentralisation, digitalisation, predictive control, dynamic load capacity
efficiency / losses	variable, fragmented structure, not necessarily optimised	stable, optimised operation (AI-based)
system scale	centralised, infrastructure-heavy	decentralised, modular, scalable
control mechanisms, system intelligence	frequent intervention, reactive control	rare intervention, real-time monitoring, adaptive and predictive control, automated
usage flexibility	passive "consumer" role (no real-time cooperation)	active "prosumer" role (demand-side management)
role of energy storage	marginal (optional battery units)	central element (hybrid storage systems)
innovation potential, tech maturity	ad hoc developments, dependent on subsidies	advanced energy management, including quantum computing

The causal mechanism is active, driven by the need to ensure energy supply (location, time, quantity, type, price). It also takes into account overarching EU standards, such as the elements of the “Clean Energy for All Europeans” initiative. In this way, it facilitates the formation of energy communities and supports active consumer participation in the energy market (URL3). Furthermore, energy storage is essential for integrating weather-dependent energy sources (URL4). The characteristics listed in Table 2 highlight that while the systems are operable, their operation cannot always be simultaneously energy-efficient and environmentally oriented. In this context, intentionality (evaluating multiple possible states) also plays a role, particularly in relation to the key factors and challenges of the transition. It should be noted, however, that the following list does not imply any prioritisation.

Key factors for transition:

- application of technological/infrastructural breakthroughs
- social acceptance
- economic incentives
- political support

Challenges:

- maintaining supply security
- geopolitical tensions
- technological bottlenecks (infrastructure, Technology Readiness Level)
- raw material shortages (geopolitical concentration, recycling)

4. CONCLUSIONS

Energy is increasingly understood as a service, users do not purchase energy itself, but rather comfort, lighting, temperature, etc. The purpose of the energy system is therefore to fulfil tasks enabled by energy. Accordingly, the fundamental purpose of the energy system is to perform tasks through the provision of energy. A business model based on functional energy delivery fosters energy efficiency, while also recognising the environmental and societal dimensions of sustainability. The system exhibits non-linear behaviour (characterised by unpredictability within an underlying order) which can be effectively modelled through analogical methods. This approach allows for the evaluation of global effects within the MESSAGE (Model of Energy Systems and Structures to Analyse Global Effects) framework.

Ravel's *Boléro* has a “mechanical” yet organically developing structure, analogous to a well-managed energy system. It is not concerned with melody, but rather rhythm, timbre, and intensification – just as energy systems are not solely defined by energy sources and carriers, but also by the role of flexible regulation, storage capacity, and the balance between load and capacity. *Boléro* is able to express its message dynamically within constraints, mirroring the variability and adaptability of modern energy systems. The musical tension's escalation corresponds to rising energy demand, which can only be effectively managed by an adaptive, decentralised, and intelligent system.

Thus, *Boléro* is not merely a musical composition, but a conceptual model: behind its repetitive structure lie functional optimisation, regulatory flexibility, and the potential for technological synergy.

This “combined” perspective does not imply a fossil vs. weather-dependent dichotomy, but illustrates the level of structural complexity, coordination, and adaptive capacity.

The ‘friction-based’ model (“force-fit”) reflects “industrial” logic (deterministic operation and hierarchy) whereas the ‘form-fit’ model (“form-fit”) is dominated by cyber-physical systems, digital twins (interactive via real-time data, integrated with AI), and self-organising networks.

5. SUMMARY AND OUTLOOK

There is a distinctive relationship between the structure of energy systems and their anomalies. The homogenising effect of centralised logic gives schematic configurations. The focus of system

development reflects the dominance of centralised control, indicating that the system is constructed according to a central logic and a prevailing paradigm. A key feature of this approach is the pursuit of functional optimisation, which is itself a consequence of technological determinism. The operation of a system and its processes must always be designed to fulfil its intended function as effectively as possible, while minimising the presence of redundant components, errors, and resource waste. Ideally, such inefficiencies should not even be conceptually discernible.

A musical composition paralleled to the energy system (Ravel's *Boléro*) remains unchanged in orchestration, yet its emotional impact evolves. The same principle applies to an energy model: the alteration of a single parameter (e.g., a technological breakthrough) may trigger a global reconfiguration. The combined effect (manifested through a chain of interlinked impacts) is the outcome of modelling and simulation within the MESSAGE (Model of Energy Systems and Structures to Analyse Global Effects) framework. Ultimately, this leads to the integration of energy nodes.

National energy systems are currently being composed in the manner of *Boléro*. However, the instruments and the orchestra are global, technologically heterogeneous, and dynamic—while the conductors are the engineers.

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