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Systemic Innovation in the European Energy Sector: A Collective Outlook

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Abstract

Applying the principles of systems thinking in the evolution of energy systems is a crucial approach to meet the long-term horizons of goals in the energy sector. Through a participatory approach, this paper outlines what we view as the trends shaping the current development of the energy sector; the challenges we must face as a result, and the transitions required to tackle them. Furthermore, we discuss how systems thinking can address these challenges through changing not the components, but rather their relationships and structures. Contributing to the emerging stream of literature applying more holistic approaches to energy transitions, in contrast to more linear systems modelling. We provide innovative insights into how future energy systems could be designed to become more regenerative, resilient, empowering, whilst technologically- and economically feasible; to overcome the challenges of carbon lock-in effects and carbon capture, the rebound effects of efficiency strategies, and social sustainability for just transitions.

Keywords: Energy transitions; systems thinking; socio-technical systems; Energy-as-a-Service; rebound effect.

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1 Introduction

Achieving a sustainable energy system requires more than the integration of renewable energy technologies and efficiency measures. Simply pursuing energy efficiency oftentimes leads to increased use through rebound effects and therefore mitigation of emissions cannot be taken for granted (Owen, 2012; Block & Lemmens, 2015; Giampietro & Mayumi, 2018); and the integration of renewables can shift the environmental burden from the point of combustion to that of material extraction. Therefore, novel approaches are required to provide a new lens on innovation in the sector, anticipating the downstream effects of developments, and including wider perspectives in doing so.

This paper explores the current trends shaping the development of energy systems throughout the European Union, discusses current systemic challenges, and provides an outlook of possible transitions to overcome said challenges. To achieve these transitions, we believe that a participatory systems thinking approach is beneficial, one which adopts futures thinking, widening the spheres of participation, and addressing root issues rather than already manifested problems (Ravetz, 2020). This is in part due to the tremendous complexity of existing energy systems which cannot be simply forecasted, as this fails to account for the changes in underlying changes in socio-technical systems (Laimon et al., 2022; Moallemi & Malekpour, 2018, Koskinen, Gilmore, Gui, 2022).

Concurrently, as modern energy systems are widening in terms of active stakeholders, more interests and perspectives need to be accounted for to ensure a just and equitable future and transition thereto. Therefore, basing our reasoning on the combination of principles of systems thinking and foresight, we take a participatory approach to develop a collective outlook on what pathways we see to achieve long-term sustainable energy transformation.

1.1 Background

Energy systems include much more than transforming one energy form into another. They subsume natural resources, technological processes, economic and social institutions, and have been central to economic progress (Yeager et al., 2012). Societal development is linked to their energy systems, especially to energy abundance, versatility and cost, a linkage visible from space (Henderson, Storeygard, & Weil, 2012). The perception of turbulent times and unprecedented changes are shaping the way we navigate the highly dynamic changes in energy systems around the world. However, the transitions we experience are not so different from those earlier in human history.

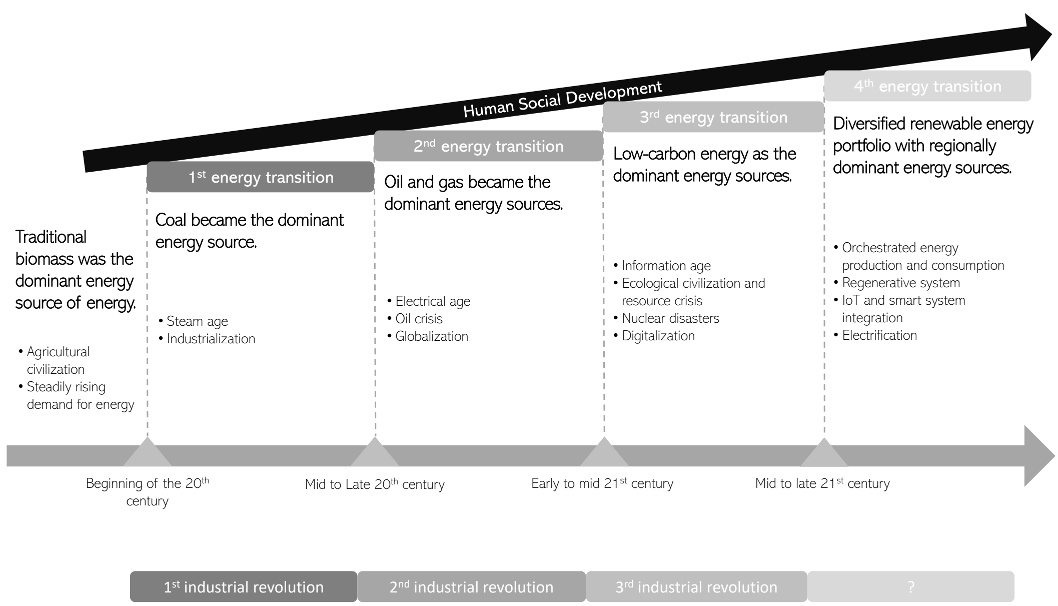

Figure 1. Schematic illustration of consecutive energy transitions occurring in recent human history (adapted from Gu et al. (2022) with historical data from Ritchie & Rosado (2020)).

Traditional energy systems constrained premodern economies, but the industrial revolution changed this through the proliferated use of fossil fuels and automated processes. This presented movement presented a sudden reduction in relative cost of energy which made it steadily more affordable and accessible. Consequently, the overall demand for performance rose, leading to higher energy consumption (i.e., increased usage, new technology as an opportunity, economic growth, and reinvestment in the form of consumption of other consumer goods). This so-called rebound effect i.e., Jevons paradox (Giampietro & Mayumi, 2018) is a consequence of changing technological components without including the interdependencies and feedback loops within the energy system. A typical example of Jevons paradox is one of traffic, wherein one attempts to solve road congestion by increasing the number of lanes, however, this intervention leads to an induced demand and thereby the system, road in this case, returns to a steady state of congestion. In the context of energy systems, this can oftentimes be seen when efficiency savings are consumed by either increased consumption of energy, or indirectly by accosting the savings for consumption in another area (Sorrell, Gatersleben, & Druckman, 2018).

Over the past two centuries, the development of an industrial-age fossil-fuel centric energy architecture transformed demographics, economies, and society. This proliferation of the energy system has created irreversible and severe lock-in effects. The energy system, including its infrastructure, is perfectly designed to meet the needs of these large-scale, cost-efficient and centralized operations. The fossil fuel industry became capital-intensive, integrated into capital markets, and has therefore garnered significantly vested socio-economic interest for its continued operation and growth.

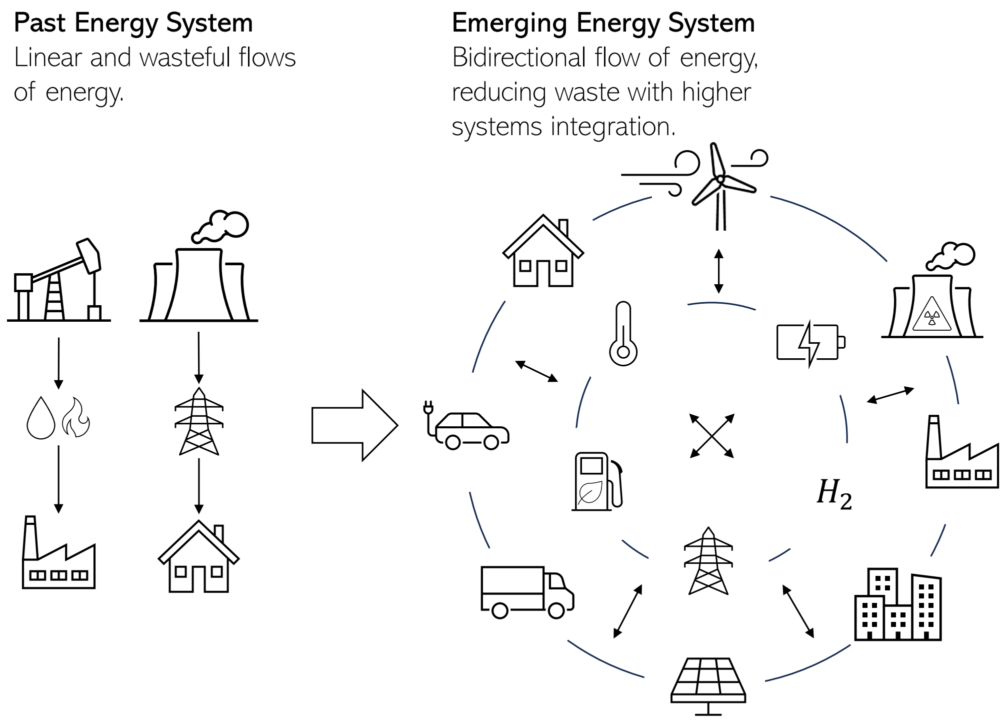

Figure 2. Representation of the changing nature of energy systems from linear to increasingly complex systems (adapted from European Commission, 2020a).

A typical linear representation of an energy or electricity system (see fig. 2) typically presents a process stemming in power plants and oil rigs, reaching the point of consumption via centralized infrastructure. A more holistic view, however, shows not only the changing landscape, but also the complexity of the system such as the bidirectional flow of resources and the multi-dimensional systems and actors which permeate the system. Although both perspectives on these systems are heavily simplified, the emerging energy system requires dealing with a greater level of complexity (Doh, Budhwar, & Wood, 2021).

1.2 From Systems Thinking to Systemic Innovation

Systems thinking began as a way of dealing with well-defined systems, and has as progressed with, turned more towards diffused and subjective boundaries (Midgley & Lindhult, 2021). Systems thinking concerns the relationships between components rather than the components themselves and considers the whole greater than the sum of its parts (Axelsson, 2022). This is because of the emergence of phenomena stemming from these relationships which can be either positive or negative in the grand scheme of things. Systemic innovation, or what Midgley (2001) earlier referred to as systemic intervention, carries a plethora of meanings (Midgley & Lindhult, 2021): From change-making on a systems level, to getting people to think in terms of systems and getting them to view opportunities and challenges from '*the big picture*' (ibid). Systems thinking on the other hand, is a broader perspective, language, and set of tools (Monat & Ganon, 2015). The perspective is a holistic one with both theoretical and methodological implications which contribute to systemic innovation (Midgley & Lindhult, 2021). This notion of holism requires us to think about systems in both time and space, studying what has led the system to reach this point and what might force it to change going forward, and including more perspectives in doing so (Monat & Ganon, 2015). In contrast to this stands a reductionistic perspective which attempts to narrow down the study or system in question in order to understand one function or component at a time. Although systems introduce boundary considerations of what is internal and external (Midgley, 1992), it is important to consider the interdependencies and exchanges between systems. For instance, heat may be used to produce food in colder environments, as parts of this food ends up as waste, it may be transformed back into the energy system as biofuels for mobility purposes, thereby creating an energy system which transcends otherwise demarcated system boundaries between food, transport, and energy. As such, we may critique and rethink boundaries to include new elements or complementary systems, or even exclude others. Boundary criteria of energy systems can follow for instance geographical and sectoral factors (Cherp & Jewell, 2014). However, it must be recognized that any system boundaries are drawn from a perspective or combination thereof (Midgley, 1992). Furthermore, there is a question of scale, most systems, especially energy, are of different scales, from local to global, and micro to macro, and to each demarcation there are both internal and contextual factors to consider (Geels et al., 2017).

Some streams of literature paint a picture of a dichotomy between systems- and linear thinking as functional opposites (Monat & Gannon, 2015). However, we find that it is best viewed as a complementary extension of an analytical way of thinking. This view captures the benefits of both approaches, as neither should be overlooked when it comes to infrastructural development, especially in the energy system. Furthermore, this view allows for the consideration of new paradigms to step in as new problems emerge to which both linear- and systems thinking may fall short. As such, systems approaches to these challenges are not an ends nor a panacea, but a much needed advancement.

Then there are the tools that support the operationalization of this discourse and way of thinking. Archetypical models include that of the iceberg, which delineates between different layers which uphold the events and patterns that are directly visible from the more hidden systems and models that govern the world (Monat & Ganon, 2015). A future looking framework, concerning systems in time is that of the three horizons (3H) (Hodgson & Midgley, 2014). The 3H framework describes the current system H1 and as time progresses and contexts change, it grows outdated and ill-fit. It also helps explain that some solutions and systems are not permanent in a transition, but rather serve a purpose supporting the transitioning to a more sustainable system (Curry & Hodgson, 2008). However, solutions on H2 can either propagate the already prevalent system leveraging lock-in effects, or serve as the bridge for H3 (Curry, 2015). Exemplifying this in the context of energy systems, we use the example of natural gas and its accompanying infrastructure. Natural gas is characterized as the best of the worst when it comes to fossil fuels, it is dispatchable, storable, and relatively low emission if managed correctly. These are characteristics much needed in an otherwise renewable energy system. As such, for certain regions, natural gas serves as the backbone of green transitions (Landry, 2020). This presents two possibilities, further increasing systemic demand for natural gas as a stabilizing energy source, strengthening the grasp which the fossil fuel industry has on energy systems, or allowing a somewhat smooth transition into alternative energy carriers such as biofuels and hydrogen. As such, increased reliance on natural gas can either further increase dependance on fossil fuels or create a bridge for new fuels such as bio-based gases and hydrogen.

Operationalizing systems thinking further, we find more sophisticated methods such as Systems Dynamics Methodology, housing tools such as Causal Loop Diagrams, used to map causal relationships, identify balancing- and reinforcing feedback loops, and potential leverage points where small interventions may lead to great system effects (Laimon et al., 2022). One such place where small interventions may lead to cascading changes, lies in deeper layers of the unconscious, intrinsic values, discourse, and worldviews which govern the way in which we think and behave (Inayatullah, 2008). Causal Layered Analysis (CLA) is a theory and methodology which delineates between these deeper levels (ibid). Building off of this, Heirani et al (2023) extends the CLA framework to the context of energy systems, by adding additional nuance between layers, described as: The *functional* problems requiring immediate resolution; the internal *structural* issues of the energy system; the *contextual* problems stemming from the external environment; below which, lies the *worldviews* which encompasses culture, values, and discourse; lastly, are the *myths*, *metaphors*, and *visions* which uphold the rest (Heirani et al., 2023). Each of these layers, support those above, together they help explore the different layers of causation and uncover root problems by navigating them. In addition to these boundaries and layers, there are levels, further described below. Utilizing tools such as these can support systemic innovation by unraveling complexities and uncertainty.

1.3 Multi-level Perspective

Energy systems are highly regulated multi-level structures (Almpanopoulou et al., 2017; Schewe, 2006; Ahlborg, 2015), and socio-technical systems which can be described through the Multi-level Perspective (MLP) (Geels, 2019). The MLP distinguishes between the socio-technical system and the emerging niches such as grassroots initiatives and innovations, and the landscape developments that shape the playing field, exerting pressure on the regime pushing it to adapt (Geels, 2004). This perspective aids us in understanding the bigger picture and provides a dynamic perspective on systemic innovation (Smith, Voß, & Grin, 2010; Geels, 2004).

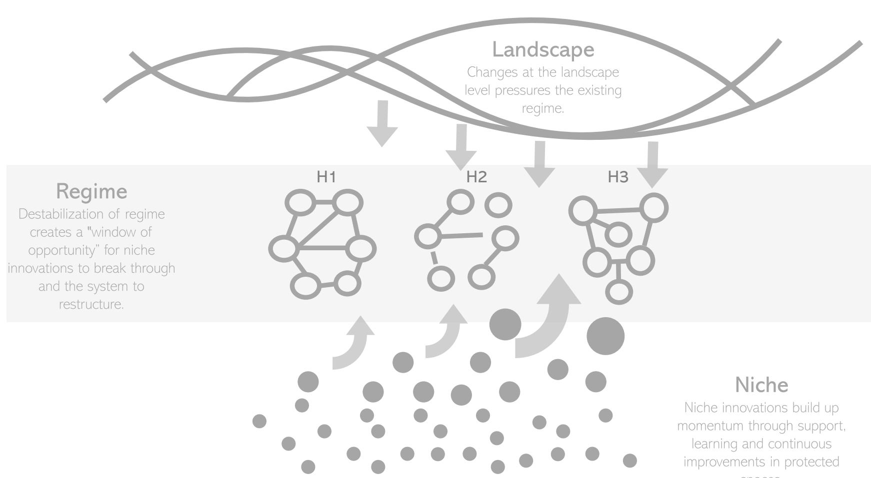

Figure 3. The Multi-level Perspective adapted from the Systems Innovation Network (n.d.).

Landscape developments is a catch-all concept for, to the system, external macro-level trends which pressure the system, and events which impose shocks. These circumstances or events provide an opportunity for niche innovations to enter as a new solution and become part of the system (Geels, 2019). However, new solutions may face resistance, and can create tensions between incumbents and new entrants. This resistance acts as opposing forces to the diffusion of innovation and may stem from societal resistance, geophysical constraints, system integration incompatibilities, or market saturation (Cherp et al., 2021).

Niches represent the protected spaces in which innovations and ideas can develop in isolation from the norms and selective nature of the socio-technical regime (Smith, Voß, & Grin, 2010). In the context of energy systems, these spaces can manifest in labs, regulatory playgrounds, or community off-grid solutions, and supported by exemptions, subsidies, or R&D funding, amongst others. Here, technologies and solutions can foster *proof-of-concept* or *readiness-level* advancement without direct market pressure or otherwise regulatory constraints. They may be discredited and dismissed at first, however, it is oftentimes there that solutions fit for the third horizon are found (Curry, 2015).

The socio-technical regime encompasses multiple domains, broadly categorized as policy, market and user preference, technology, industry, science, and culture. Viewing the energy system through the lens of a socio-technical regime reveals a tendency towards incremental, linear, and predictable changes as they are influenced by lock-in effects and path dependency (Geels, 2004; 2010). We thereby view our demarcation of the energy system as the inert socio-technical regime, where pressure is exerted from landscape developments and emerging niches can break in (*ibid*).

This perspective comes with its challenges, it requires navigating systems of multiple scale, complex interdependencies, and multi-level governance to name a few (see e.g., Smith, Voß, & Grin, 2010; Geels, 2011; 2019). As such, the confounding dimensions of scale, levels, and layers contribute to the complexity of this outlook. In applying this perspective on energy systems, we view the socio-technical regime as the energy system of Europe. This perspective does not impose any strict geographical boundaries as these are heavily diffused, but it does provide a focal point representative of the challenges of a modern, transitioning energy system. The purpose here is to embody a holistic demarcation rather than a traditionally reductionistic one (Monat & Ganon, 2015). We embrace and acknowledge the complexity rather than simplifying it away, considering the interconnectedness and plurality of landscape developments shaping energy systems of today (Chapter 2); the systemic challenges given these developments (Chapter 3); and an outlook on the required systemic changes and combination of niches to overcome these challenges (Chapter 4). The energy system challenges described in this paper are of a global nature, however they can be observed in different characteristics and maturity around the world, making them to an extent universal. As such, the solutions to these systemic challenges require unified efforts and solutions tailored to local contexts.

1.4 Research Design

Through an iterative, participatory, and open approach, this paper attempts to articulate the challenges faced in the green energy transition, combining knowledge and viewpoints to place knowledge in a context for action (Hodgson, 2014; Laimon et al, 2022). Compared to siloed approaches, participatory processes support the breaking away from path-dependency (Wiener, Gattringer, & Strehl, 2020); openness provides additional perspectives and insights representative of a widening stakeholder community (Bourgeois, Karuri-Sebina, & Feukeu, 2022); which all supports challenging the so-called official future (Inayatullah, 2006).

The starting point to this process was to understand the broader context driving change in the energy sector. This understanding was established through a year-long process of horizon scanning to identify landscape developments, trends, and weak signals covering changes occurring on all three levels of the MLP (Vähäkari, et al., 2020). The assessment of these developments and rising challenges through horizon scanning are critical to support long-term policy making (European Commission, 2020b). In line with our predominantly European perspective, we draw from the European Commission's Megatrends Hub (2022) which provides a set of well-defined landscape developments. The materials of the Megatrends Hub were reviewed to elicit what their implications on the European energy system may be. This overview is built upon with additional nuance and insight through our collective and continuous work in scanning and monitoring developments through: In-person meetings and conferences; working with stakeholders in utility companies and transmission grid operators; and reviewing relevant sources such as public- and private reports, scientific publications, scenarios and forecasts, and industry news outlets (Hines et al., 2019).

Based on the identified developments, we iteratively framed and processed a set of challenges to which modern energy systems face today and tomorrow. Finally, we ideated potential solutions and transitions to address the challenges. These challenges and potential transitions are the outcome of additional workshops and literature reviews.

A popularized version of this paper was designed and distributed to collect feedback, comments, and insights from a wider set of perspectives. The paper was distributed using a network of systems thinkers with over 20 000 members as well as publicly through social media channels. Following this distribution, we held an open online interactive workshop. During this workshop, we presented the paper and asked the participants (N=17) to reflect, comment and add upon the initial set of trends, challenges, and transitions we had previously laid out. Participants of the workshop were mostly from Europe, with some ranging from Canada to India; they were characterized by diverse roles, some industry professionals, various experts, and system innovators. Follow up workshops addressed the themes of demand-side management and a just transition with a similar constellation of participants, building upon our identified challenges and ideating solutions. This iterative approach gave us the opportunity to discuss challenges and adjust our outlook with more perspectives and insights which are presented below.

2 The Context Shaping Energy Systems of Today

Global megatrends affect different regions differently, however, on an aggregated level they provide a sound understanding of the pressures forcing systems to change. Insight into these developments and their effects also highlight the complexity of change which is often simplified away in long-term analyses (Bardazzi & Pazienza, 2023). Drawing from the European Commission's Knowledge for policy Megatrends Hub (2022), we reviewed the overarching developments that pressure current energy systems to change.

Technological developments are advancing at an accelerating rate, with implications for both the accommodation and integration of new technology in the energy system. Whilst the costs of new energy technologies are declining (Ansari & Holz, 2019), emerging industries such as data centers are introducing novel power demand (IEA, 2024). Aggravating resource scarcity is imposing not only limitations on the resources we use for power generation such as wind and water, but also the critical materials for production of new infrastructure and technologies, yet fossil fuel reserves remain high (ibid). There is automation of processes, predictive maintenance, and demand for new skills which is changing what humans in the system are tasked with (Joint Research Centre, 2024). The energy transition is creating an enormous shift in labor markets which heavily influences political decisions (Ram et al., 2022). Decommissioning of old infrastructure puts one pool of workers out of a job, whereas there is a surge in demand elsewhere, creating an imbalance of competence, requiring workers to either reskill or relocate. Where skills are transferable, such as in grid development and operation and maintenance it creates a competition for competence since new grid infrastructure must be developed simultaneously as the old requires reinvestment and maintenance (SVK, 2023; Swedish Energy Agency, 2023). New technological solutions also require more advanced skills to maintain and operate, creating a diversification of education and learning as workers may require up- or reskilling in later stages of life. For more complex tasks, it is not enough anymore to only be specialized in one aspect, but managing the increasing complexity requires additional skills and competencies that need to be integrated in energy related educational programs. To this end, migration is poised to become an increasingly important aspect of driving this transition (OECD, 2023). Concurrently, an oftentimes overlooked driver of change to energy systems are the massive demographic shifts which are altering both the labor pool and energy consumption behavior (Bardazzi & Pazienza, 2023). Such change also brings with it widening inequalities in terms of energy poverty and who has access to clean energy and its health benefits. Coupled with growing interconnectedness, reliance on a functional energy system is creating new vulnerabilities and criticality of grid infrastructure. Concurrently, as urbanization continues, cities are growing bigger and more complex pressuring urban energy systems (Ansari & Holz, 2019). New entrants in the energy system such as aggregators are creating new governing systems; increased consciousness of issues and abilities to organize are causing an increased influence from civil society. Together these forces become a driver of increased participatory approaches and public consultations to ensure a just transition.

Climate change is affecting energy systems across multiple dimensions; first and foremost is the fact that the global energy system is the largest contributor to environmental pollution; secondly, local changes such as weather patterns affect both the demand- and supply side of energy. Concurrently, the global energy system faces both a slow increase in energy supply and rapid increase in electricity demand (IEA, 2023) due to the economic and population growth of emerging economies, alongside the electrification of more developed regions, pressuring systems around the world. As such, stakeholders of the Global South and East are becoming increasingly influential in the global energy system. This influence is acquired through the extraction and export of critical materials, growing populations containing a tremendous workforce, and subsequent economic growth. Efforts are made by foreign interests to capture value from this growth by e.g., purposely creating fossil fuel lock-in which has drastic effects on the future of energy systems in developing economies (Carter & Costello, 2023).

All of which is occurring against the backdrop of energy crises, geopolitical tensions, growing share of renewables, and environmental threats which form a changing security paradigm where sovereignty and solidarity may face tensions and conflicts. The recent shock of Russia's invasion of Ukraine and its aftermath spearheaded a new European focus to reduce reliance on Russian gas and bolster energy security (European Commission, 2022c). Before which was the Covid-19 pandemic which caused tremendous ripples in energy demand spurring economic recovery packages supporting energy efficiency improvements and renewable investments (Zakeri et al., 2022). However, such a shock also gave insight into the self-cannibalization of renewables profitability and therefore incentive to further invest (Mauritzen, 2021).

The impacts of these developments will vary depending on region, and there are also complex interdependencies between these developments that give rise to new challenges (Önnered, Komazec, & Elvin, 2024). Understanding the specific challenges occurring on a regional scale requires case-by-case studies with a more defined grasp of the socio-technical regime in question. The pressures exerted by these developments are creating a window of opportunity for change where niches may emerge. However, such solutions need to adhere to three fundamental values of the energy system. Known as the energy trilemma, system solutions must be sustainable, affordable, and secure (Gibellato et al., 2023). These principles guide policy development through the World Energy Council, International Energy Agency, and the Sustainable Development Goals. Below, we outline these influential factors and how they are affected by the above-mentioned developments.

2.1 Energy Trilemma

The energy trilemma serves as design criterion or constraint that connotates a trade-off between the different dimensions of sustainability, affordability, and security (World Energy Council, 2024).

Climate change is a long-running development which exerts pressure on the energy sector (Geels, 2004). Following growing demand, the global energy sector has developed in a non-sustainable way, becoming the largest cause of the climate crisis. This crisis extends beyond decarbonization and ambitions of net-zero, as environmental sustainability includes aspects such as biodiversity, air- and water quality, material extraction, and other planetary boundaries (World Energy Council, 2024). These aspects put into question seemingly renewable or green sources of energy such as wind-, solar- and hydropower; and gives rise to debates between the green and clean(er) sources of energy such as natural gas and nuclear power. The perceived solution to sustainability of many sectors is to undergo electrification and sector-coupling, creating synergetic effects between industries and shifting their processes from different types of primary energy to electricity. This imposes novel challenges for the electricity system and reduces the overall redundancy of the energy system, though it is a necessary transition, it imposes tremendous strain on electricity around the globe and introduces other issues of sustainability such as extraction of critical metals, and social sustainability (Heath et al., 2022; Jenkins, Sovacool, & McCauley, 2018).

Referred to as availability, affordability, accessibility, acceptability (Cherp & Jewell, 2014), and more recently equitability as an encompassing term (World Energy Council, 2024), this aspect concerns the social dimension of the energy transition. It thereby involves addressing the needs of the many and facilitating an equitable and inclusive transition, to ensure that clean energy is physically and monetarily accessible to the population, globally and locally, and that developments do not disproportionally affect certain groups. Yet, we are witnessing emerging economies being exploited for their natural resources (African Energy Chamber, 2023) and coerced towards fossil-fuel dependency (Carter & Costello, 2023). Within the European frame of reference, issues pertain the affordability and transparency during price volatility for household consumers. Another prevalent issue is in effect of infrastructure development where marginalization may occur both in terms of distribution of externalities and unjust distribution of benefits. Reaching a future which satisfies these criteria whilst simultaneously being just in the transition thereto, requires novel approaches which manage to understand the complexity of the social dimensions of energy systems and their transitions. Energy, however, is not an end in and of itself, rather it is a means to achieve societal benefit by enabling mobility, sustenance, sound, warmth, and light (Erker, Stangl, & Stoeglehner, 2017). Hence, it may be more pertinent to also consider how these outcomes can be better achieved through systemic innovation in these other systems or in the intersection thereof.

The last dimension of the trilemma concerns energy security. However, we consider resilience above security as it serves as an expansion of the concept (Jesse, Heinrichs, & Kuckshinrichs, 2019). Following recent global events, the need for resilient energy systems has become widely apparent and of utmost priority (Zakeri et al., 2022). These geo-political tensions affect the global energy market and thus energy security (Wang et al., 2022). A development which has shown that security takes precedence over sustainability. Resilience typically means to rebound after a disturbance; however, it can also be seen as an evolving process (IEA, 2015) that goes beyond the short-term engineering perspective of resilience, which views it as the recovery to a previous steady state (Chelleri et al., 2015). As an evolving process, resilience also concerns adaptation to changing circumstances and system transformations when tipping points are crossed (ibid). Meaning that for each hit that the system takes, it adapts to tackle future disturbances better. This in turn allows the system to be secure over time, as the environment changes. A resilient energy system encircles more than only its technical components, it applies to the social, economic, and technological system which is energy. As such we must view resilience through the frames of boundary judgements, stakeholder prioritization, and longer time horizons (Helfgott, 2018; Jesse, Heinrichs, & Kuckshinrichs, 2019).

3 Current and Emerging Challenges

Based on these developments and principles, we provide a non-exhaustive account of what we view as the most pressing for the long-term development of energy systems. We focus on challenges of a systemic nature rather than solely technical or political ones. As such, addressing these challenges will require a great deal of research and collaboration, however, these challenges can be equally viewed as opportunities (Dator, 2018), especially when viewed from a systems perspective.

3.1 Overcoming the Carbon Power Structure

Awareness of the environmental impacts of fossil fuels has led to a significant shift towards renewables and other low-carbon technologies, particularly in power production through solar- and wind power[1]. However, any ambitions of offsetting fossil fuels through renewables are oftentimes just adding to the total energy production (York & Bell, 2019). As such, the share of fossil fuel in the energy mix appears to be decreasing, whereas it in absolute terms remains the same or even grows. A demand for renewables must also be met with measures to reduce the burning of fossil fuels in absolute terms (Cherp et al., 2021). Else, we will simply increase our consumption rather than offsetting fossil fuels and thereby do very little to combat the climate crisis. Whilst ambitions of decarbonization are oftentimes met by strategies of electrification, decarbonization of energy intensive sectors, particularly heat and transportation, still poses considerable challenges. These challenges arise in part from the deep lock-in effects of such infrastructure. Lock-in effects arise from a broad range of factors such as learned behavior, economic returns, and hurdles of procuring new investment. On the other end is the ability of other systems such as electricity to carry this shift in energy carrier. In the pursuit of decarbonizing energy systems, it is imperative to understand that we must avoid shifting environmental burdens from one sector to another, e.g., from the point of combustion to the point of resource extraction.

The carbon power structure is not only infrastructure, but also the power to influence, control, and lobby to retain their current position of power. Another facet of the socio-technical regime in which the fossil fuel industry holds its ground, is through marginal pricing schemes, whereby the profitability of renewables relies on fossil fuels to operate in the margin. With marginal pricing structures, achieving a fully renewable energy system becomes problematic (Blazquez et al., 2018). Since they operate with a minimal marginal cost, they would struggle to become profitable without fossil fuels driving up the prices. Hence, diffusion of renewables is reaching a point where they will

1. The socio-technical feasibility for hydropower has already been saturated in many parts of the world and is therefore not a core strategy for continued decarbonization but rather an underlying prerequisite for many countries.

no longer be financially viable and thereby struggle to offset fossil fuel power plants without other measures or market reforms.

Transitioning towards a more sustainable state of the energy system requires the alignment of interests of energy producers and consumers, overcoming stakeholder barriers, managing resistance from influential actors, and ensuring high-quality service provision with these new models and technologies. Effectively addressing resistance coming from incumbents and allowing for new entrants necessitates strategic communication, stakeholder engagement, and the development of business models that support such operation. Achieving this requires changes across multiple domains such as new business models, procurement processes, behavior, and responsibilities (Sovacool, 2016; Franco et al., 2022).

3.2 Maintaining Resilience with the Integration of Renewables.

Resilience and transitions are two forces oftentimes in direct opposition of one another. A resilient system can be viewed as one which strives to retain its current form and function (Walker & Salt, 2006). Whilst transitions are imposing deliberate changes that affect energy systems' ability to maintain their function (Johansson, 2013). However, to ensure long-term resilience, any system must adapt to changing circumstances and be able to maintain its function whilst undergoing this change. Therefore, we need to manage any turbulence and uncertainty during a transition to reach a better steady state (Curry, 2015; Chelleri et al., 2015).

The combination of changes occurring within the wider energy system is introducing new issues to manage to retain secure operation (Johansson, 2013). One such issue, known as "Dunkelflaute" represents longer periods of overcast and calm winds impeding renewable power generation. In combination with climate change increasing the risk of such events, there is a growing need for long-term storage solutions to smoothen out supply over such extreme weather events (Ruhnau & Qvist, 2022). Beyond such issues as plannability and intermittency, deeper structural problems related to resilience are festering. Going from large synchronous generators providing system inertia and stability, towards a much greater share of power electronics which are reliant on a functional grid to synchronize is changing the physical behavior and characteristics of the power system. These changing characteristics are causing long-term issues for continued integration (SVK et al., 2023). This also concerns the lock-in effect of certain fossil fuels which provide back-up functions and other system supply-side services to bolster system stability. Whilst renewable technologies such as roof-top solar has the potential for island mode operation, technical support thereof remains low (Sweco, 2023).

One of the core principles of resilience, redundancy, entails reducing single point of failures, bottlenecks, and maintaining back-ups and support services (Sharifi & Yamagata, 2016). Since the integration of renewables is also requiring large-scale electrification, this large-scale transformative trend is causing a significant loss of redundancy and diversity of the energy system at large. Thereby making the power grid a critical point of failure which would bring cascading effects onto all other sectors, impeding transportation, heating and cooling, food production, and many other social functions and services. Resilience is always a question of determining what should be resilient, against what, and for when (Jesse, Heinrichs, & Kuckshinrichs, 2019; Helfgott, 2018). However, this also brings into question ethical questions such as for whom the system is resilient and whom may be the beneficiary of developments (Helfgott, 2018).

3.3 Ensuring a Just Transition

Further turbulence and uncertainty of these transitions stem from the acceptability of the transitions themselves. Many energy outlooks are standing on the brink of an unprecedented development in required power- and transmission capacity to accommodate the immense increase in electricity demand (European Commission, 2023). With such rapid development, there are bound to be societal resistance ultimately leading to project delays and withdrawals affecting both grid development and renewable energy production (Sataøen et al., 2015). Although big picture ideals and ambitions are commendable, achieving them with an unfair distribution of benefits, costs, and decision-making creates energy injustices (Sovacool, Hess, & Cantoni, 2021). Reinforced by structural and ideological tendencies, energy injustice is a systemic issue rather than a localized one (Lee & Byrne, 2019). Monetary benefits of infrastructure development create unjust outcomes as they become unfairly distributed when compared to the distribution of negative effects (Sokołowski & Heffron, 2022). Another facet of this challenge is the process of development itself, calling for due process, recognition and inclusion of otherwise marginalized stakeholders, and restorative justice at the end of life for infrastructure (Sovacool et al., 2016; Heffron & McCauley, 2017).

Securing the energy transition for all parts of the world becomes a challenge as demand for critical materials increases (Lèbre et al., 2020). Likewise, the sustainable transitions of some regions can have externalities unaccounted for and affect local communities disproportionally. There are social sustainability arguments advocating for caring about the communities that have emerged around these centralized facilities (United Nations, 2016). Such that rather than being decommissioned, facilities can be upcycled for different purposes such as thermal storage (see e.g., Kayayan, 2023). Thereby keeping the local economy alive by upskilling the existing workforce to work with these more sustainable technologies. Finding other areas of utilization for the skills prevalent in the fossil fuel industry can be challenging (Carvalho, Riquito, & Ferreira, 2022). There are, however, opportunities in similar areas such as upcycling as previously mentioned, as well as Carbon Capture and Storage (CCS) implementation for use cases based on renewables or bio-energy (Vergragt, 2012).

3.4 The Integration of Carbon Capture

The promise of CCU can be found in many long-term scenarios for sustainable development (see e.g., Harpprecht et al., 2022; Koskinen, Gilmore, & Gui, 2022). However, the integration thereof poses many systemic challenges beyond simply technical and economic ones.

Different strategies for carbon capture and storage (CCS) have been extensively promoted by the fossil fuel industry with frontrunners such as clean coal, blue hydrogen, and carbon capture use and storage (CCUS) (Asayama, 2021). Taking a systems approach, Janipour et al (2021) show how such approaches can lead to new lock-in effects leading to more fossil fuel extraction, thereby prolonging and exacerbating the problem. These lock-in effects are bolstered by increasing sunk cost and incentivizing further investments in fossil fuels. Continued investments in fossil fuels and subsequent CCS reduces the investments in other low-carbon technologies, impeding innovation therein, and further hindering an eventual transition away from fossil fuels (Janipour et al., 2021).

An alternative approach to integrating CCS in the energy system is to couple it with renewables and direct air capture (DAC) (Breyer, Fasihi, & Aghahosseini, 2020). However, considering the intense power requirements of CCS processes, it is more advantageous to simply offset the fossil fuel in the first place. This means that as long as there are fossil fuels in the system, investments in DAC are ineffective in addressing the issue. Hence the challenge is finding ways of achieving carbon capture (to offset the industries that cannot decarbonize, not the fossil fuel industry), in a way that is gross-zero on a systems level and not to use it for 'enhanced oil recovery' in the fossil fuel industry (Asayama, 2021). As such, we propose that CCS be combined with renewables, whereby the energy system can become regenerative, further expanded upon in section 4.4.

4 Outlook

Overcoming these challenges, turning them into opportunities, requires a multitude of changes across the board. In this chapter, we outline and argue for the changes required on the regime-level that we identify as being crucial to overcoming the challenges whilst managing the trilemma of energy systems. These are framed as: The balancing of centralized and decentralized systems and their actors; viewing energy-as-a-service; changing values to accommodate demand-side-management; and changes which allow for stabilizing and regenerative Power-to-X systems solutions. Combined, these transitions provide us with several avenues to design and envision more sustainable and prosperous energy systems. However, getting there is no easy feat and will constitute a transition on its own. Laid out hereinafter is the accumulation of the overarching trends shaping the energy system along with the transitions that we view as critical to power a sustainable energy transition alongside the sustainable transitions of energy intensive industries. Together, they come to describe an energy system that is clean, accessible, and reliable in the many years to come, for the many people.

In this future system, there is a fundamental shift required in expanding from a profit-centric model to one that is also purpose driven. Drivers should revolve around the preservation of primary energy resources, reduction of energy waste, and the minimization of carbon emissions whenever feasible. These changes must be integrated vertically, ensuring that stakeholders at all levels experience the advantages of sufficient energy consumption. Through this approach, we can sustain societal prosperity without perpetually increasing our energy consumption. The role of incumbent organizations is changing, determining this future is for them to co-create with the rest of the system. In doing so, they can choose to either further entrench their current positions or embrace new solutions and become stewards thereof. In the case of the latter, there should be more support for grassroots initiatives, and greater consideration of emerging threats, externalities, and distribution of benefits. The support systems that currently maintain the delicate balance of a functional electricity grid need to be redirected toward more regenerative purposes rather than solely fueling industrial processes or direct waste. Much like the industrial revolution was driven by coal and the steam engine, further advancements in energy generation and management can positively transform the future of society.

"The best solution is a diversity of contextual solutions" – Workshop participant.

Different countries have different geographical prerequisites for local production; varying political states that influence how markets evolve; and varying local capabilities and technologies. Therefore, there is no one solution that can be implemented anywhere to solve all energy problems. However, ensuring that these solutions are implemented across the board is elementary to achieve a just and sustainable transition at a greater scale.

4.1 Balancing Centralized and Decentralized Systems and Actors

Renewables brought with them a trend of decentralization, users could become prosumers and utility companies had to find ways of integrating these actors in electricity grids and markets. This decentralization involves shifting to user-generated systems like (rooftop) solar panels, small-scale wind turbines vertical and horizontal, and utilizing waste heat from local industrial parks. By localizing these energy resources and incorporating waste heat recovery, communities can capitalize unique energy generation opportunities, reducing their dependence on distant power plants and promoting self-sufficiency. This serves as an opportunity to leverage the shorter lead times of distributed generation and distribution to make the transition more agile. Addressing the challenge of a just transition, it is increasingly important to consider the effects, benefits, and how stakeholder communities are approached. One such approach is to go beyond public consultation and consider the community as a primary stakeholder of a development rather than just the local municipality and directly affected landowners. In doing so, resistance can be met proactively by tailoring incentives to the needs of local communities and providing them with an actual stake in the project. These local solutions can be customized to suit the specific needs and characteristics of local communities, considering social, environmental, and cultural factors, rather than solely prioritizing economic optimization.

Our future energy system will need to be more adaptive and faster to evolve than the prior inert system. This becomes possible by leveraging the shorter lead times and acceptance of decentralized solutions. However, in the interest of economies of scale and market dynamics (see Blazquez et al., 2018), large-scale centralized solutions are also required, capturing the benefits of both approaches as they are not mutually exclusive. The development of transmission grids serves as a crucial backbone for distributing renewable energy, addressing the intermittent nature of renewable energy sources, and providing centralized support for system stability.

4.2 Energy-as-a-Service

Servitization of the energy sector is a trend well under way (Park, 2022). The last few years the emergence of as-a-service business models have surfaced with examples thereof ranging from energy-savings, resilience, security, efficiency, and energy to name a few (Park, 2022; Önnered, 2023). Energy-as-a-Service (EaaS) introduces novel business models and value propositions that are important for systems innovation in the energy sector. One key aspect is the shift from the traditional energy supply model to pay-for-performance models. Consumers pay for desired energy services or performance levels rather than the quantity of energy consumed. This change shifts the responsibility of efficiency improvements from the consumer to the distributor, thereby promoting efficiency improvements on the systems level. Such system level improvements could be realized by repurposing waste heat for district heating, food production, or industrial symbiosis creating the foundation of the circular management of energy (Önnered, 2023). In such a system, there would be a greater incentive to conserve primary energy through the use of district heating networks, heat pumps, and sector coupling, allowing low-grade heat to be used to heat homes, produce food, or fuel industries. Additionally, EaaS is an enabler of demand side management by providing the system operator or aggregator with control over the demand to adjust consumption based on wholesale prices and use the flexibility as a support service providing substantial economic benefits (Iria & Soares, 2023). It promotes collaboration among different stakeholders, including energy providers, technology developers, financiers, real estate owners and consumers. By fostering partnerships and knowledge sharing, we anticipate EaaS to drive innovation and accelerate the adoption of sustainable energy solutions. Potentially, EaaS could serve as a solution for the renewable energy paradox as laid forth by Blazquez et al. (2018).

4.3 From Supply to Demand Side Response

Managing the frequency of electricity systems is a constant challenge of balancing energy demand with supply. As systems become more dominated by weather-dependent generation, they also become non-dispatchable and intermittent. Such characteristics require other supply-side flexibility, storage mechanisms, international trade, and demand side management (Ruhnau & Qvist, 2022). However, we oftentimes fall into the trope of discussing how supply should be able to account for these changes. Less focus is put on how the demand side of the energy system plays an important role in this transition. It is, however, becoming increasingly acknowledged that without demand flexibility, future energy systems will not be able to secure operation (SVK, 2021; Sousa & Soares, 2023). Likewise, future energy demands need to be adjusted to the availability of renewable resources in the longer term (Lund et al., 2014). Thus, we need to do more than upscale the system of today for the demand of tomorrow, but we need to make the current system work better as a whole, to better suit the context of tomorrow.

These trends take us towards a greater flexibility amongst end users through e.g., aggregators allowing households to partake in balancing markets (Lopes et al., 2019) and integrated systems actively controlling consumption based on market and system dynamics (Khan & Masood, 2022). In our view, this transition is inevitable and will require a shift in cultures and values as it constitutes not only a technological change but a behavioral one (see also, Franco et al., 2022). It will reduce the burden of material extraction, decrease the need for new infrastructure, thus mitigating the environmental and social impact of a future energy system. Designing a system without this behavioral change will be costly, inefficient, and wasteful.

4.4 Regenerative System

Demand side response is not only needed in times of scarcity. There is a strong trend of increasing times of negative pricing on the wholesale electricity market (ACER, 2023; 2024). Such instances of abundance results in low to negative prices and curtailment (i.e., decoupling generation resulting in waste of electricity) of generation to protect the grid from over-generation (Singh & Colosi, 2022). This development is thereby causing stability issues, wasting energy, promoting wasteful consumption, and affecting the profitability of the renewable energy industry. Coupling this trend with an urgent need to decarbonize the energy system reveals a systemic opportunity.

Using renewable energy for the purposes of CCS whilst coal- and oil power plants are in operation, is an inefficient approach to address decarbonization. However, in times of abundance, where societal needs are saturated, the case for using renewable energy for CCS becomes much more attractive as it synergizes with renewables (Chen, Wu, & Lee, 2021). However, this would require the CCS facilities to become an integrative part of large-scale renewable energy production such that this abundance can circumvent market forces and the rebound effect. This requires Power-to-X policies such as Denmark's direct lines which enables the direct connection of power production to consumption (Energistyrelsen, 2023). However, this is currently oriented towards hydrogen production and a few other industrial purposes, rather than CCS. Provided that economic incentives and regulatory mandates would tip this utilization towards CCS, this would form a truly additive carbon offset which can be sold as certificates or turn renewable energy sources' CO2e footprint into the negatives taking us from curtailment to capture (Singh & Colosi, 2022). Pursuing carbon dioxide removal technologies decoupled from fossil fuels, thereby circumventing the direct lock-in effect of CCUS with fossil fuels (Asayama, 2021). Going from loss to profit, from waste to regeneration, and from finite to renewable.

However, considering the focus on security, we anticipate that the primary demand responses during negative prices will come from mechanisms such as hydrogen production and battery storage. Nonetheless, these use cases ultimately contribute to decarbonization in one form or the other. Hydrogen can substitute coke in industrial processes (Harpprecht et al., 2022), and storage solutions can mitigate the need for fossil fuel reserve capacity. Nonetheless, optimal use cases will require case-by-case consideration. However, in combination, these different mechanisms for demand side response will create balancing loops that mitigate the volatility from which they profit. This means that the best time to act is now, leveraging foresight to invest in truly additive offsets for a regenerative energy system.

5 Conclusions

Electricity consumption has been a historically stagnant trend as improved efficiency has been met by growing demand. However, this historical trend is at a turning point for many nations towards a rapid increase in electricity consumption (EMBER, 2024). This situation creates both challenges and a window of opportunity, and a necessity to reconsider many aspects of the system. To overcome the lock-in effects of short-term solutions to secure energy accessibility we need to adopt a more forward-looking and holistic perspective (Zakeri et al., 2022; Laimon et al., 2022). Achieving these necessary transitions cannot be realized through only the linear integration of technological solutions, but rather through innovation on a systemic level. As such, we call for an increased understanding of complexity and anticipatory thinking in line with the Inner development goals, and education for Sustainable Development Goals (UNESCO, 2017) to address SDG7, clean energy for all. This paper contributes to an emerging stream of literature taking a more holistic and emergent approach to systems analysis in the energy sector to navigate the complexity and the interrelatedness between different (policy, market and user preference, industry, science, and culture) components of the energy sector. We provide initial fruitful insights and ideas that exemplify the value of applying systems approaches in creating actionable futures; contribute with a participatory approach better able to deal with the uncertainty and plurality of the future (Moallemi & Malekpour, 2018; Rosa et al., 2021); and contributes with guiding vision (Späth & Rohracher, 2010). These outlooks are concepts that call for a great deal of research and additional perspectives.

Any systems inquiry imposes boundaries, ours has been demarcated by a Eurocentric perspective, however, complemented by diverse participation (Hines et al., 2019). Our view on challenges and changes is limited by our expertise and perspectives, this is to say that there are many more challenges to account for in the nuances of the energy transition. Concurrently, the boundaries of what is considered the energy sector are being diffused, following the trends of sector coupling, decentralization, and electrification amongst others, which calls for further participatory and cross-sectoral approaches to achieving sustainable and just transitions. Likewise, there are limitations to a holistic and future oriented approach, as they deal with an immense uncertainty and complexity, meaning that the future cannot be accurately predicted, nor any complex system precisely modelled, but they can and should be explored. As such, this should be viewed as a complement to more traditional approaches (Moallemi & Malekpour, 2018).

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