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ABSTRACT

Economic development, technological innovation, and policy change are especially prominent factors shaping energy transitions. Therefore explaining energy transitions requires combining insights from disciplines investigating these factors. The existing literature is not consistent in identifying these disciplines nor proposing how they can be combined. We conceptualize national energy transitions as a co-evolution of three types of systems: energy flows and markets, energy technologies, and energy-related policies. The focus on the three types of systems gives rise to three perspectives on national energy transitions: techno-economic with its roots in energy systems analysis and various domains of economics; socio-technical with its roots in sociology of technology, STS, and evolutionary economics; and political with its roots in political science. We use the three perspectives as an organizing principle to propose a meta-theoretical framework for analyzing national energy transitions. Following Elinor Ostrom's approach, the proposed framework explains national energy transitions through a nested conceptual map of variables and theories. In comparison with the existing meta-theoretical literature, the three perspectives framework elevates the role of political science since policies are likely to be increasingly prominent in shaping 21st century energy transitions.

1. Introduction

The ways societies use energy have changed over the course of history, are changing at present, and will certainly change in the future. These long-term changes, energy transitions, are shaped by economic development, technological innovation, and policies among other factors. At the same time, governments around the world are called on to steer energy production and consumption so as to solve, not aggravate, international security, poverty, climate change and other global challenges [1]. Yet, such calls can only be meaningful if they are based on a systematic understanding of national energy transitions an understanding, which remains elusive despite a large and growing literature on the topic.

One difficulty in explaining energy transitions is the disciplinary diversity of required scholarly approaches. Existing reviews of the vast transition literature identify relevant knowledge from economics, sociology of technology, political science, geography, history and other disciplines [2–7]. A consensus of these reviews is that since a single theory of transitions may not be feasible due to their complexity, they should instead be analysed using *several* theories [3,8,7]. But what are these theories, which disciplines should they represent, and how can they be integrated? The existing literature does not provide consistent answers.

This inconsistency largely results from the fact that the existing reviews significantly vary in their scope and method. For example, some of them focus on *energy* transitions [9,4] while others cover *low-carbon* transitions [3] and yet others extend to *sustainability* transitions [10,7]. While these concepts are overlapping (energy transitions may

Abbreviations: ACF, Advocacy Coalition Framework; CCS, carbon capture and storage; IAM, Integrated Assessment Model; MLP, multi-level perspective; SNM, strategic niche management; STS, science, technology, and society/science and technology studies; TIS, technological innovation system; TM, transition management

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be ‘low-carbon’ or ‘sustainable’), they are clearly not identical,[1] and therefore are not necessarily explained by the same theories. With respect to their method, the existing meta-theoretical reviews range from inductive accounts of history of thought [4,6] to bibliographical studies centered on several influential papers [5], to deductive analyses based on the nature of the problem in question [9,11,6].

Our paper aims to advance understanding of energy transitions by proposing a meta-theoretical framework based on several scholarly traditions. We make three choices about the scope of phenomena which we analyze. Our first choice is about the boundaries of energy systems which we limit to **the energy sector**, i.e. to conversion and use of energy by people. Economic and population growth as well as other factors outside of the energy sector clearly influence energy transitions, but we choose to consider them as external driving forces rather than central foci of our analysis (see for example Section 3.1 on energy demand). Similarly, the wider effects of energy transitions on societies are outside of the scope of our analysis.

Secondly, we follow Grübler et al. [12] who define an energy transition “as **a change in the state of an energy system** as opposed to a change in individual energy technology or fuel source”. This definition contrasts complex and pervasive systemic transitions on decadal scales with more trivial and shallower[2] shifts in individual energy technologies in specific markets that may occur in matter of a few years. The wider scientific consensus is that mitigating the risks of the climate change and addressing other sustainability challenges would require such deeper transitions involving many different technologies and encompassing national and global scales [1,6]. However, deep and wide energy transitions do not necessarily lead to ‘clean’, ‘modern’, ‘low-carbon’ or ‘distributed’ energy systems. Indeed, most historical examples of such grand transitions involve fossil fuels and more recently nuclear energy [14]. We include such transitions in the scope of our analysis because we believe that the mechanisms of energy transitions depend more on their scale and depth than on their normatively evaluated direction or effects.[3] Though it sets us apart from some transition studies which are primarily interested in ‘green’ technologies, it is in line with most long-term scenarios of climate change mitigation, which typically envision deploying a wide range of technologies ranging from carbon capture and storage (CCS) and nuclear power to hydrogen, biomass, renewables, and energy efficiency [15].

Our final choice is to focus on **national** (rather than sectoral or local) energy transitions. With all their complexities, national energy transitions relate to relatively well-defined national economies, laws and regulations, natural resources, and infrastructure. These factors are accounted for in national statistics and plans available for empirical analysis that can validate or refute theoretical explanations [4,16]. Moreover, since nation states have the most obvious mandate to govern energy systems, it is at the national level where some of the most significant decisions to steer energy systems to avoid dangerous climate change are and will be made [17].

These are not the only possible choices in studying energy transitions. For example, illuminating studies were conducted in analyzing the rise and fall of individual energy technologies [18–20]. On the other end of the spectrum, Perez [21] framed the expansion of electric production and steel making as part of a wider technological “surge” also involving changes in finance, lifestyles and politics. Similarly, many contemporary scholars are interested in social ‘transformations' accompanying changes in energy systems [22]. Other research looks beyond national systems to study changes at the local [23], sub-national such as states in the USA [24], sectoral such as pulp and paper industry [25,26] or supranational such as Nordic region [27] or the European Union [28] scales. We hope that by creating an analytical framework for decadal-scale changes in relatively well-defined national energy systems our analysis will support and supplement these other important streams of research.

We use a deductive method of identifying scholarly approaches relevant to understanding national energy transitions based on the concept of co-evolution of natural, technological and social systems [29–31,21]. In Section 3, we argue that national energy transitions involve co-evolution of distinct systems delineated by (a) energy flows and markets, (b) energy technologies embedded in their socio-technical context, and (c) political actions affecting formulation and implementation of energy policies. We further show how scholarly analysis of these distinct systems gives rise to the techno-economic, the socio-technical and the political perspectives on national energy transitions. In Section 4, we compare the three perspectives to the frameworks in existing meta-theoretical studies, summarize fits and misfits of each perspective, and propose a general method for their application following the framework approach developed by Elinor Ostrom and her colleagues. This framework is illustrated in Section 4.4 using an example of comparing electricity transitions in Germany and Japan. Section 5 concludes the paper and proposes a further research agenda.

2. Literature review

The majority of publications on energy transitions use existing theories for analyzing empirical cases of transitions (e.g. [32]) or exploring transition scenarios (e.g. [33]). Other studies propose new theories of transitions [34–36]. In addition, several meta-theoretical studies review the state of knowledge on transitions. In searching for relevant literature, we aimed to identify key peer-reviewed English-language publications of this latter type. Our search focused on academic journals hosting the debate on energy transitions (*Research Policy*, *Energy Policy*, *Energy Research & Social Science,* and *Global Environmental Change, Environmental Innovation and Societal Transition, and Technological Forecasting and Social Change*). Section 2.1 summarizes the insights from these reviews while Section 2.2 discusses existing proposals for integrating transition theories as well as approaches for analyzing co-evolving natural, technological and social systems.

2.1. Existing reviews and categorisations of approaches to transition studies

Economists and historians have been interested in long-term changes in human use of energy resources since at least the 1960s (e.g. [37]). Studies of *past* transitions have often been motivated by the aspiration to anticipate potential *future* transitions. First quantitative scenarios of future energy transitions were developed in the 1970s and combined forward-looking projections of economic and population growth and resource availability with empirical observations on how energy conversion and use changed historically (e.g. [38]). These scenarios were based on engineering and economic theories, such as technological substitution [39], which Marchetti and Nakicenovic [40] extended to energy sources [4].

A review by Grübler [4] highlighted the importance of this pioneering research as well as pointed out other contributions from economic history and theory [41,42], history [43] and social studies of technology [44]. Grübler’s paper was published in the special issue of *Energy Policy* on energy transitions. In the editorial to this issue, Fouquet and Pearson [45] argued that aggregate long-term changes in energy use by entire societies need to be understood as combinations of changes in the use of individual energy technologies.

Such technological change was explored in several strands of studies developed separately from both macro historical analyses and forward-looking models. A particular boost to these studies was given by the

[1] Low-carbon transitions may occur outside of the energy sector (e.g. in urban planning, industry, agriculture and forestry). ‘Sustainability’ transitions may also include changes in food systems, distribution of wealth, human rights, governance and conflicts.

[2] While there is no universal agreement how large a change would constitute a transition, scholars have developed a robust understanding of the relationship between the speed, the scale, and the depth/complexity of change (see e.g. [12,13]).

[3] For example, in Section 3.4 we illustrate our approach in case of the transition from nuclear to renewable power in Germany, which is largely carbon-neutral.

growth of wind power in some countries in the 1990s. A seminal paper by Jacobsson and Jonsson [46] conceptualized this change as an outcome of technological innovation that can be either facilitated or hindered by social factors. Jacobsson's and Jonsson's central focus was on combining the idea of an *innovation system* [47] with that of a *technological system* [48]. The resulting concept of *technological innovation system* (TIS) further elaborated by Jacobsson and Bergek [49] and Bergek et al. [50] has become influential in studies of transitions. A parallel strand of transition research, which Grübler [4] called "the Dutch school", emerged in the 1990s from Science, Technology and Society (STS)[4] studies and evolutionary economics. It adopted a quasi-evolutionary approach based on sociological theories combined with a detailed understanding of specific technologies and a macro-view of historic changes. In the late 1990s and the early 2000s, this tradition gave prominence to a set of influential concepts and frameworks such as the multi-level perspective (MLP) [35,53] (see [6] on an intellectual history of the MLP).

A proliferation of transition theories in the 2000s was accompanied by several meta-theoretical reviews [10,54,55,6] culminating in two special issues of *Research Policy* on sustainability transitions in 2010 and 2012. In the editorial to the 2010 special issue, Smith et al. [6] explained the history of innovation studies for sustainable development as a process of "linking broader analytical frameworks to successfully larger problem framings" (p.7). They discussed the progression from (neoclassical) environmental economics to the concept of cleaner production focused on individual firms, to studies of structure and performance of national, sectoral, regional or technological innovation systems and eventually to a "quasi-evolutionary conceptualization of transitions in societal functions", which the MLP aspired to provide. In the editorial to the 2012 special issue, Markard et al. [5] provide another meta-theoretical review of the field based on a bibliometric analysis of papers citing selected prominent sources (including the already mentioned Jacobsson and Jonsson [46] and Geels [35]). They identified four "frameworks" for transition studies: (1) transition management, (2) strategic niche management, (3) multi-level perspective, and (4) technological innovation systems.[5] Rooted in evolutionary economics and STS, all these frameworks shared the concepts of a socio-technical system, a socio-technical regime, and a niche.

Multi-theory frameworks for analyzing energy transition have also been proposed outside of the scholarly communities focused on technological innovation. Grubb mapped three "domains of transition" onto three domains of economics: behavioral, neoclassical and evolutionary/institutional, pointing out specific insights from macro-economics and ecological economics that are missing from most socio-technical approaches [8,9]. Meadowcroft [56] pointed out the relevance of political science, stressing the need to analyze political processes of problems framing and goals formation, rather than only innovation to achieve these goals.[6] In 2011, Meadocroft [11] proposed to incorporate analysis of interests, ideas and institutions into studies of energy transitions, a call also reiterated by Schreuer [57] and followed by Kern [58] and other scholars.

Three similar 'analytical approaches to sustainability/low-carbon transitions'[7] were described in two recent papers by Turnheim et al. [7] and Geels et al. [3]. The first analytical approach, 'quantitative systems modelling/Integrated Assessment Models (IAMs)', focuses on quantitatively exploring complex long-term changes, but has difficulty adequately representing local-level phenomena, technological innovation and inertia, and realistic behavior of social actors. The second analytical approach, 'socio-technical transition analysis', similarly to the MLP, views technological change as shifts in normally stable socio-technical regimes resulting from a combination of pressures from external landscapes and innovation in protected niches. The third analytical approach, 'initiative-based learning/practice-based action research', focuses on local processes such as urban sustainability experiments and is rooted in participatory and action research methodologies.

2.2. Integration of multi-disciplinary knowledge, co-evolution, and Ostrom's framework approach

An increasing number of studies combine different disciplines for transition research. Socio-technical analysis is sometimes combined with political analysis ([59,32,60,61]) or with energy-economy modelling for future scenario building [62–66]. However, only a few studies offer general blueprints for interdisciplinary integration. Exceptions include Grubb et al. [9], who describe how their three domains can be used as a policy diagnostic and design tool, and Turnheim et al. [7], who propose a systematic integration of their three analytical approaches for evaluating transition pathways.

For Turnheim et al. [7], the first element of integration is alignment of problem frames with respect to five 'analytical challenges'. The second element is bridging the approaches with respect to 'attributes of transition pathways'. In the third element, integration is achieved through a dialogue which involves multiple iterations of alignment and bridging (p. 248). Though Turnheim et al. [7] do not provide specific examples of such integration, it seems that the proposed process is designed to develop improved transition scenarios through quantitative modelling. Similarly, Geels et al. [3] illustrate how socio-technical transition analysis and practice-based action research can enhance IAMs.

This proposal stressing the alignment of *analytical approaches* does not explore the interaction (or its absence) of *actual systems and processes* involved in transitions. Such interaction is explored in the literature describing social change as co-evolution of natural, technological and social systems. Different scholars delineated these co-evolving systems differently, frequently mentioning Technology, Economy, and Institutions (Table 1). Despite different delineation of subsystems, these works subscribe to a similar concept of co-evolution, stressing that co-evolving systems are semi-autonomous (i.e. they have their own elements, boundaries and dynamics) but interacting. Though Safarzyńska et al. [67] recommend reserving the term co-evolution strictly for systems with a Darwinian mechanism of variation, selection, and differential reproduction, in this article, we follow the tradition of using this term in a broader sense, to denote interaction between semi-autonomous systems regardless of specific mechanisms of system dynamics.

Conceptualized as a co-evolutionary process, an energy transition involves two types of mechanisms: (1) those explaining the evolution of each of the subsystems and (2) those connecting these subsystems. Therefore, neither atomized studies of strictly additive subsystems, nor subsuming all systems in one is a productive approach to studying transitions. 'It is … essential to study both the relatively independent development of each stream of history and their interdependencies, their loss of integration, and their reintegration.' ([30], p. 127).

Elinor Ostrom and her colleagues developed a systematic approach for researching co-evolving systems. She started elaborating this approach in the mid-1960s with the aim to bring together economists, sociologists and political scientists interested in understanding the dynamics of socio-ecological systems. Ostrom aimed to develop capabilities of applied scientists for a 'serious study of complex, multivariable, non-linear, cross-scale and changing systems'. She observed

[4] This school was also significantly influenced by Latour's and Callon's *Science and Technology Studies* ([51,52]) abbreviated as STS as well.

[5] Markard et al. [5] mention the relevance of economic and 'socio-political' scholarship to understanding of transitions but do not elaborate on relevant theories and approaches.

[6] In particular, he demonstrated how such central concepts of transition management as 'lock-in' and 'system change' are politically constructed. For example, depending on the perspective, the CCS technology may be considered as both a system change and a lock-in the old regime.

[7] Though largely similar, the two papers have somewhat different terminology. When different terms are used, we introduce them with a '/' where the first one refers to the term used by Turnheim et al. [7] and the second one is the corresponding term from Geels et al. [3].

Table 1
Co-evolving systems mentioned in selected seminal studies.

Publication	Scope	Co-evolving systems
Norgaard [31]	Socio-economic development	Technologies, Knowledge, Organization, Values, Environment.
Freeman and Louca [30]	Technological revolutions	Technology, Science, Politics, Culture, Economy.
Perez [21]		Economic, Technological and Institutional [spheres]
Foxon [29]	Sustainable low-carbon transitions	Technologies, Institutions, Business Strategies, User Practices, Ecosystems

that scientific progress had been achieved when scholars recognized that such complex systems were 'partially decomposable in their structure' and can be represented as 'relatively separable subsystems that are independent of each other in the accomplishment of many functions and development but eventually affect each other's performance' ([68], p. 15182). This argument, echoing co-evolutionary thinking, formed the foundation of Ostrom's framework approach for diagnostic and prescriptive inquiries.

Ostrom argued that an appropriate strategy for analyzing a complex system comprising distinct subsystems was to identify and organize relevant *variables* into 'nested conceptual maps', which she called 'multitier *frameworks*'. Such frameworks unpack generic top-level variables (usually relevant to all systems of a particular type) into second- and third-tier variables (relevant only to some situations or subsystems). Interactions of such hierarchically analysed variables are described by *theories* that could 'diagnose a phenomenon, explain its processes, and predict outcomes' as well as 'enable the analyst to specify which elements … are particularly relevant for certain kinds of questions and to make general working assumptions about these elements'. In addition, Ostrom discussed *models*, analytic tools, which use certain assumptions about variables and selected theories to explore systems' behavior in a precise (often quantitative) manner [69].

Ostrom's central point is that multiple theories (often with roots in different scientific disciplines) are usually necessary to describe the evolution of a complex socio-ecological system. She strived to create analytical frameworks for analyzing such systems recognizing that 'several theories are usually compatible with any framework'. She believed that an important function of a framework was to provide a 'metatheoretic language' through which various theories (and related scientific communities) could communicate with each other ([69], p. 826). This idea echoes Turnheim's et al.'s [7] 'dialogue of analytical approaches'. We consider this approach suitable for studies of national energy transitions because (1) it deals with co-evolving systems, (2) it specifically aspires to create a meta-theoretical framework; and (3) it is based on the experience of organizing interaction of economists, sociologists and political scientists, i.e. much the same disciplines as should be involved in analyzing energy transitions.

2.3. Summary

The existing meta-theoretical literature provides useful insights into energy transitions. It identifies relevant bodies of knowledge such as several domains of economics, sociology and history of technology, and political science. At the same time, there is uneven attention to different parts of this knowledge and virtually no guidance on its potential integration. A comparison between existing meta-theoretical studies is complicated because of their different scope (energy, low-carbon or sustainability transitions) and method (historical accounts, analysis of citations, deduction based on the structure of the problem). In Section 3, we propose structuring the bodies of knowledge represented in these reviews into three perspectives on energy transitions.

The literature discussed in Section 2.2 covers co-evolution as asynchronous change in semi-autonomous but interacting natural, technological and social systems. Ostrom's approach for the study of complex co-evolving systems offers a strategy for combined use of several theories through creating a meta-theoretical framework describing multiple conceptual tiers of variables. Such a strategy can be implemented through systematic identification of co-evolving systems involved in national energy transitions as well as variables and theories from relevant domains of social science characterizing such systems as done in Section 3. In Section 4.3 we use Ostrom's approach to propose a framework of hierarchically organized variables and relevant theories and models for analyzing national energy transitions and in Section 4.4 we illustrate this approach using the example of comparative analysis of electricity transitions in Germany and Japan.

3. Three perspectives on national energy transitions

National energy transitions have historically involved several kinds of changes. The first has been change in the **energy flows** associated with energy 'production' and 'consumption'[8] coordinated through **energy markets**. The second has been change in **technologies** used for extracting, transforming and utilizing energy. The third has been change in **policies** regulating the socio-political role of energy systems, for example to modernize a country, increase its independence, or reduce poverty. These three types of changes have occurred in three distinct types of systems (Fig. 1):

(1) **techno-economic systems** defined by energy flows associated with energy extraction, conversion and use processes involved in energy production and consumption as coordinated by energy markets;
(2) **socio-technical systems** delineated by knowledge, practices and networks associated with energy technologies; and
(3) **systems of political actions**[9] influencing energy-related policies.

The systems involved in national energy transitions *co-evolve* in the following three senses. First, they have different boundaries, elements and connections. Techno-economic systems include for example, fossil fuel deposits and streams of water, sunlight and wind, transportation of coal and oil from mines and wells to power plants, refineries and petrol stations, conversion of chemical, mechanical and light energy into electricity and transmission of electricity through grids, as well as final energy conversion in automobiles, refrigerators and light bulbs. Socio-technical systems include for example, networks of developers, manufacturers and installers of solar PV panels, maps of shale gas locations, patents for electric vehicle batteries, and household practices of using heat pumps or car sharing. Political action systems include what Easton ([70], pp. 384–385) terms 'inputs' such as demands and support for certain policies from voters, parties, lobbies and bureaucracies and 'outputs' such as energy-related laws, regulations, and international agreements as well as feedbacks between the two.

Fig. 1 illustrates (with grey rectangular boxes) that one and the same real-world object may be viewed as an element of two or more

[8] Although physically energy cannot be 'produced' or 'consumed' since it is always preserved, these terms have a clear economic sense. By using energy services, economic actors 'consume' energy depending on its costs and their means and preferences and they can also 'produce' energy by extracting or capturing it from nature and transforming it to useful forms.

[9] Easton [70] called such systems of political actions 'political systems'. We avoid using this term as it is often understood in a narrower sense as a country's constitutional and government order.

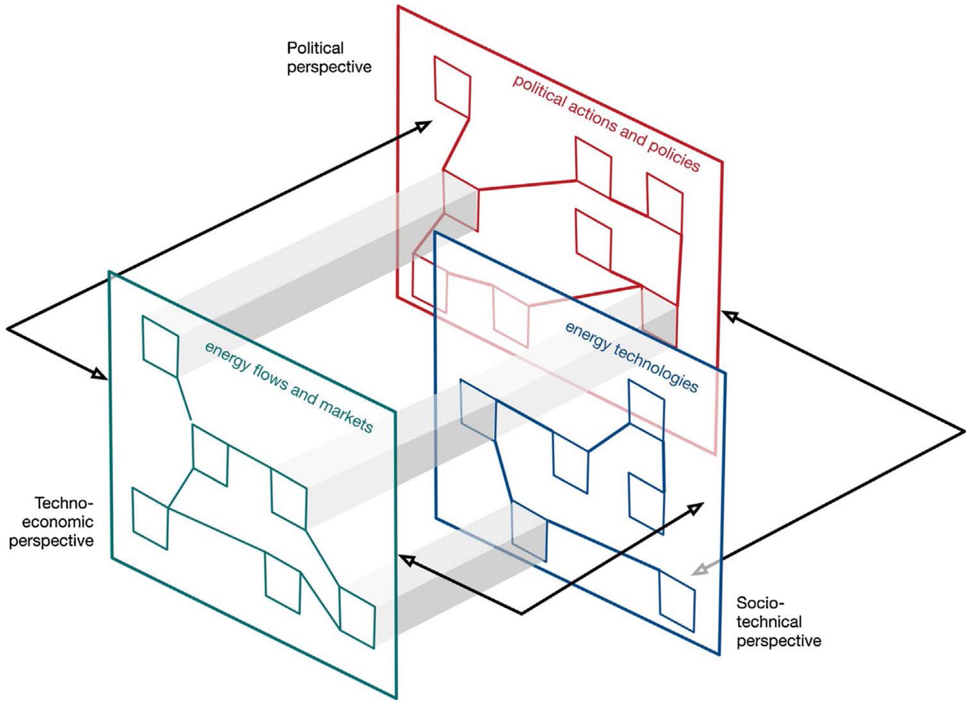

Fig. 1. Co-evolving systems in and perspectives on national energy transitions.
The grey rectangular boxes connect representations of the same real-life objects (e.g. power plants) in the three perspectives. Lines with arrows represent interaction between the three systems. Real-life transitions may involve more than one system of a particular type, e.g. socio-technical systems associated with nuclear power production and with consumer household appliances.

systems. For example, a gas-fired power plant can be viewed as an energy conversion node in a system of energy flows and markets, connected through pipelines to gas deposits and through electric grids to final users of energy. It is also a unit of economy characterised by investment in equipment and construction, rate of depreciation, marginal and levelized cost of electricity generation, profitability etc. The same power plant can also be considered as an element of a socio-technical system using certain technologies for electricity generation linked to designers and manufacturers of equipment and organizational practices of utilities and grid operators. Finally, the construction, operation and decommissioning of the power plant are linked to inputs and outputs into the system of political action, being decided, evaluated and interpreted in political debates about energy security, the price of electricity, industrial competitiveness and employment, greenhouse gas emissions, back-up capacity for wind and solar power and other wider political topics.

Second, each of the three systems can evolve autonomously, independently from the other two. For example, energy flows may change because of the depletion of fossil fuel deposits, decommissioning of old power plants, or people buying larger houses that require more heating. None of these changes require political or technological shifts. Socio-technical systems may change because of invention or diffusion of new technologies, independent of the changes in energy flows or policies. Finally, policies may change because of changed perceptions of energy security or other political shifts, not necessarily in sync with energy flows or technology change.

Third, the co-evolving systems affect each other as shown with arrowed lines in Fig. 1. Politically motivated taxes and subsidies may influence the use of existing and diffusion of new technologies. Increasing energy imports may trigger political interest in domestic energy resources. Technological innovation may stimulate new energy uses and therefore increase energy demand.

Thus, national energy transitions involve co-evolution of techno-economic, socio-technical, and political actions systems. As explained in Section 3.1, Section 3.2, and Section 3.3, the three types of systems are in the focus of three distinct scholarly fields, which we call the perspectives on national energy transitions, each with its specific disciplinary roots, concepts, variables, and theories explaining change and continuity in the relevant systems.

3.1. The techno-economic perspective

The techno-economic perspective focuses on energy systems defined by energy flows, conversion processes and uses coordinated through energy markets. On the one hand, these are connected to elements of natural systems such as oil or uranium deposits and the flows of water, wind and sunlight. On the other hand, energy delivers services (such as lighting and mobility) valued by people. These services are produced and distributed similarly to other economic goods, for example bought and sold in markets. Therefore, physical energy flows and conversion processes can be matched with energy ‘production’, ‘consumption’ and trade in societies, which makes it possible to represent these flows and processes in techno-economic theories and models.

Explaining stability and change of techno-economic systems involves theories from Earth sciences (e.g. geology, hydrology, climatology), engineering, and economics. The concept of supply-demand balance means that a change in any particular type of energy supply or use must be balanced by corresponding changes in other types of supply or uses (e.g. expansion of electricity generation from renewable sources must be accompanied by increasing use of electricity, or phasing out conventional sources, or increasing electricity exports). Within the techno-economic perspective, the concept of supply-demand balance is often used in conjunction with the neoclassical economic idea of market equilibrium. It asserts that under competitive markets energy supply and use are in a stable equilibrium as long as consumers are not prepared to pay a different price for energy or producers- to supply it at a different cost.

Neoclassical economics can explain not only stability of energy systems but also some of their changes. For example, resource depletion leads to increasing extraction costs and thus may prompt shifts to other resources, more efficient equipment, or reduce consumption. Population growth leads to increasing demand and thus may also trigger different supply options. More nuanced understanding of long-term changes in energy systems requires systematic historical observations and insights from evolutionary and ecological economics that go beyond neoclassical theories. For example, Marchetti and Nakicenovic [40] and Wilson and Grübler [71] analysed long-term macro trends in energy supply and rates of growth of energy supply technologies for use in forward-looking models. Starting from the

1920s, economists have documented the evolution of the cost of technologies [72] and applied these experience curves to the costs of renewables [73], nuclear [74] and other energy technologies. Scholars of economic history and ecological economics have also shown that wealthier societies use more and "higher quality" energy per capita ([34,75,76,42,77]).

Most of the above theories deal with quantitative variables and can therefore be used to create quantitative models of energy systems and long-term scenarios of their change under different assumptions. In the 1970s and the 1980s, such scenarios addressed widespread concerns about oil scarcity by portraying futures dominated by nuclear power and natural gas [38]. More complex models of the 1990s and the 2000s (e.g. [78]) came especially handy with the increasing concerns over the risks of climate change and the effort needed to stop it, which required understanding the evolution of energy systems on the global scale over the next century. Energy-economy modelers rose to this challenge by creating IAMs, which coupled the energy-economy models with climate and other Earth system models. It was IAMs[10] that most clearly rang the alarm bell that under reasonable assumptions about the availability of energy resources, economic growth, and historic patterns of renewing energy infrastructure, catastrophic climate change in this century is almost a near certainty, unless decisive policies avert it. IAMs have also been used to estimate the costs of such climate stabilization policies [15,80] as well as policies to achieve other energy goals such as universal access to modern energy [81] or reducing energy imports [82].

Although IAMs aspire to both model the effects of various policies and to provide policy advice [83], neither these models nor the techno-economic perspective in general ask or answer the question of whether (or under what conditions) real-life policy makers would be willing and capable to pursue any of these goals.[11] In the techno-economic perspective, policies appear as external, exogenous assumptions or normative targets, rather than objects for analysis, understanding and explanation.

Another limitation of the techno-economic perspective is that it cannot provide an adequate account of inertia, path dependence, and innovation in energy technologies. Though the patterns of evolution of energy demand, use of different sources, infrastructure, and technologies can be derived from historical observations, such observations are rarely good predictors of the future. Historians of technology have observed that many old technologies have lingered around for much longer [84] and many new ones entered the societies much faster [85] than economic models would have predicted.

These limitations exist because technological innovation and diffusion as well as policies originate in systems different from energy-economy systems which are the focus of the techno-economic perspective. These systems are the foci of the other two perspectives: socio-technical and political.

3.2. The socio-technical perspective

The focus of the socio-technical perspective is on technological change, especially on the emergence and diffusion of new technologies. Social scientists were interested in the spread of technological and other innovations for over a century. Tarde [86] described how social novelties emerge in one place or group and then spread (*diffuse*) to other places or groups as early as 1906. On the international level, this process is sometimes viewed in terms of world-systems theory [87]: technologies first emerge in 'core' countries and then diffuse to the 'periphery'. Other early observations were that adoption of a technology follows an S-curve, with initial development, rapid upscaling and then a plateau, and that in the periphery technologies are deployed later but their uptake is faster [88].

Beyond these general observations, the exact mechanisms of the emergence and diffusion of new technologies have been studied within evolutionary economics, sociology of technology, and STS. In contrast to the techno-economic perspective, where technology is simply a method of extracting, converting or using energy by means of particular equipment or infrastructure, the socio-technical perspective has a more complex and nuanced view of technology as a social phenomenon, i.e. knowledge and practices embedded in infrastructure and other technical artefacts, shared by human actors, and circulating in social networks, collectively known as *technological* [48] or *socio-technical systems* defined by Schot et al. [89] as:

> … a configuration of technologies, services and infrastructures, regulations and actors (for example, producers, suppliers, policy-makers and users) that fulfils a societal function such as energy provision.

The socio-technical perspective includes two major strands of research relevant to energy transitions. One strand, what Markard et al. [5] call 'technological innovation systems (TIS) studies', has its primary roots in evolutionary economics [50,47,46]. *Innovation systems* are subsystems of socio-technical systems which participate in the generation and spread of novelties, for example through learning. Innovation systems may be structured along sectoral, technological or national boundaries [10].

Another strand of research within the socio-technical perspective is what Turnheim et al. [7] and Geels et al. [3] call 'socio-technical transition analysis', and which 'adopts a broad sociological frame, combined with a practical interest in historical methodologies' ([7], p. 243). The roots of this research are closer to history and sociology than to evolutionary economics and it blends historical macro-perspectives with actor-based micro-economic and institutional foundations [4]. The central conceptual unit is a *socio-technical regime*: a shared set of rules and routines embedded in socio-technical systems to ensure that they can provide the relevant social function [89]. Regimes are stable and resilient, i.e. able to adjust to pressures from the external environment or internal failures and disruptions. To survive or expand, regimes may foster innovations but they may also block those innovations that threaten their stability. This explains *technological lock-in*, when beneficial innovations are hindered because they are incompatible with a dominant regime [90].

Socio-technical transition analysis is specifically interested in innovations that occur outside dominant regimes and are capable of overcoming lock-in. Such innovations occur in *niches*: socio-technical systems with more fluid boundaries, actors, rules and practices, which are less stable, but more capable of radical innovation than systems functioning within established regimes. Novel technologies which initially cannot compete within dominant regimes (e.g. because they are too costly or too complicated) emerge in such protected niches, where they may mature and become competitive. The strategic niche management (SNM) approach in particular emphasizes the need to foster such innovative niches to facilitate technological innovation [91].

One of the most influential frameworks in socio-technical transition analysis, the MLP [35,53], points out that because of regime resilience, niches do not automatically displace incumbent regimes even when they become more effective in fulfilling a relevant social function. For a niche to replace an incumbent regime, the regime first must be destabilized, for example by external (*landscape*) pressures. Regime destabilization can occur along several distinct pathways [92], most of which represent non-linear rapid change.

The socio-technical perspective offers several explanations for technological change through learning and diffusion facilitated by TIS.

[10] In the last two decades, IAMs have become increasingly sophisticated and influential, especially in the work of the IPCC, and other bodies which need long-term outlooks of global energy development, for example, the IEA's World Energy Outlooks, the Global Energy Assessment [1] and the UN Secretary General's Sustainable Energy for All (SE4All) initiative [79].

[11] This was obvious already to the founders of IAMs who observed that their parent disciplines of engineering and economics did not provide means to analyze the world of politics where energy policies are conceived, negotiated, adopted and implemented ([38], p. 24).

The MLP is also capable of explaining technological lock-in and disruption through regime stability/destabilization and niche innovations. One limitation of this perspective is that it largely focuses on changes involving significant novelty. This leads to overlooking changes in deployment of already existing technologies requiring only incremental innovation or no innovation at all (e.g. consumer acquiring more cars or appliances, natural gas replacing coal). There is also insufficient attention to the decline of old technologies, what Turnheim and Geels [20] call 'the flip-side of energy transitions', that may or may not be directly connected to the introduction of novelties. Both types of changes are potentially significant for energy transitions, particularly their effect on climate.[12]

The second limitation of the socio-technical perspective is its representation of the political and the techno-economic. The literature within this perspective often follows an aspiration articulated in seminal publications by historians of technology Hughes [93] and Bijker [19] to develop theories of socio-technical change as a 'seamless web' where there is no a priori distinction between the technological, the socio-economic and the political. This aspiration runs contrary to the idea of co-evolution by subsuming techno-economic, socio-technical, and political systems into a single system. Bridging the gap between the socio-technical and the political has been a particularly prominent goal of socio-technical transition studies. For example, Smith et al. ([6], p. 448) asked 'just how independent are policies from what is going on in the socio-technical realm?' remarking that 'as long as policy remains an external force … the conditions for these policies to be put in place continues to be obscure'. Many socio-technical transition scholars have chosen to deal with this obscurity by studying political phenomena through the lenses of socio-technical theories and methods. For example, in the quote above, Schot et al. [89] explicitly consider regulations and policymakers as elements of a socio-technical system. This has led to criticisms that socio-technical transition studies neglect the political [56] and the economic [9].

Our argument is that techno-economic and political entities and processes are neither independent of nor subsumed into socio-technical systems. Rather they make up semi-autonomous systems with their own dynamics which co-evolve along with socio-technical ones. Therefore, all three perspectives, techno-economic, political and socio-technical, are needed to explain national energy transitions.

3.3. The political perspective

The central focus of the political perspective on national energy transitions is on change in policies which affect energy systems. Policy change is studied within several domains of political science with different ontological assumptions and epistemological practices [94]. Because most energy policies are adopted and implemented by governments acting on behalf of nation states, the *state* is the main unit of analysis in the political perspective. In this regard, the political perspective is different from both the techno-economic and socio-technical perspectives where states may be ordinary economic actors, elements of a 'seamless web', external 'landscape' factors, or recipients of normative recommendations, but not the primary focus of analysis.

3.3.1. State-centric and state-structural approaches

While the state is a central concept in political science, its conceptualization is vigorously debated [95,96]. Scholars make varying assumptions regarding the autonomy of the state and the way it aggregates the preferences of public officials and other actors (e.g. [97]). Among different approaches to classifying these assumptions,[13] we find the typology proposed by Hall particularly helpful. Hall positions various theories of state along two dimensions: state-centric and state-structural [99]. *State-centric* approaches assume that states are autonomous actors [100] pursuing national interests [101] or state imperatives such as internal order, external independence, and economic growth [102]. In the state-centric approach, the goals of energy policies are dictated by national interests: for example, striving towards a secure supply-demand balance [103], minimizing energy imports or maximizing exports [104], ensuring reliable access to electricity, securing industrial competitiveness, and increasing employment [17].

In contrast, *state-structural* (neo-pluralist) approaches assume that states' policies reflect competing interests of domestic actors such as voters, political parties, social movements and industrial lobbies. In this strand of research, scholars focus on the 'politics of energy policies' (e.g. [105]). For example, governments may seek to maximize votes from constituencies with preferences for specific energy options.[14] Following this line of argument, political science literature sometimes hypothesizes (though without much empirical backing so far) that left-leaning governments would stimulate the promotion of renewable energy to provide widely distributed social benefits [108,110,111]. State policies may also be influenced by *special interests*. For example, Geels [112] argues that incumbent firms can resist transitions by using various forms of power and concludes, similarly to Hess [36], that 'socio-political struggles with fossil fuel companies and other incumbent firms […] will be crucial in the case of low-carbon transitions' (p.37). In this line of reasoning, the shift from nuclear to renewable energy in Germany is often portrayed as an outcome of the political struggle between on the one side the nuclear energy industry and on the other side anti-nuclear movements and renewable power owners and manufacturers ([105,113,114]). However, consistently proving that special interests affect energy transition policies has turned out to be difficult. For example, Schaffer and Bernauer [111] do not find a correlation between the share of fossil and nuclear energy or high greenhouse gas emission intensity and renewable energy policies. By comparing Japan's pre- and post-Fukushima energy plans, Cherp and Jewell [115] argue that the strength of nuclear power interests did not affect Japan's commitment to renewable energy (see Cherp et al. [116] for a similar argument about Germany).

3.3.2. Capacities, institutions, and ideas

A central concept within the political perspective is that of *institutions*, i.e. structures and rules that enable and constrain state and other political actors [117]. In one of the earlier political studies of energy transitions, Ikenberry [118] explained the responses of industrialized democracies to oil crises by their institutional capacities, defined as patterns of interaction between the state and industries and resembling the later concept of varieties of capitalism [119]. The concept of *capacity* signals that a state is not able to pursue any energy policy it desires. For example, L. Hughes and Urpelainen [120] approximate institutional capacity by the presence of a bureaucratic agency that has a mandate for implementing climate policies. Jewell [121] shows that state's capacity to launch a nuclear power program historically depended on the size of the economy, GDP per capita, and political stability.

In contrast to Ikenberry, who deliberately abstracted from party politics and struggles of different interests, other political scientists focus on how institutions aggregate interests of individual actors, thus

[12] Fouquet and Pearson [45] note that even massive introduction of low-carbon technologies does not necessary mean reduction of fossil fuel use under population and economic growth. A similar but broader point about persistence and significance of 'old' technologies is also made by Edgerton [84].

[13] For example, Almond [98] structures the debate around pluralism vs. statism.

[14] For example, German Chancellor Merkel's decision to impose a moratorium on the operation of nuclear power plants in 2011 has been widely viewed as reflecting her concerns not to lose regional elections in Baden-Württemberg and Rheinland-Pfalz with strong anti-nuclear preferences [106]. Political scientists conceptualize such behavior as 'vote-seeking' [107]. Alternatively, governments might be assumed to be *'policy-seeking'* i.e. preferring to maximize the payoff of the constituencies that support them as it is assumed in the model of public support to clean energy by Aklin & Urpelainen [108]. For a general overview and criticism of vote-seeking and policy-seeking assumptions see Strom [109].

Table 2
Three perspectives on national energy transitions.

Perspective	Disciplinary roots	Systemic focus	Examples of concepts and variables	Examples of theories	Examples of models and applications	Limitations
Techno-economic	Economic history, neoclassical, evolutionary, ecological economics; energy systems analysis	Energy flows and markets	Energy resources, energy services, energy demand, energy infrastructure, energy prices	Supply-demand balance, market equilibrium, demand convergence, energy ladder, peak resource	IAMs and long-term climate-energy scenarios	Poor representation of technology inertia, innovation, and policy change
Socio-technical	Sociology and history of technology, STS, evolutionary economics	Energy technologies embedded in socio-technical systems	Socio-technical regimes, niches, landscapes, innovation systems, core and periphery	Technological lock-in, learning, diffusion, MLP	Transition management, innovation policies	Excessive focus on novelty, strive for “seamless web”
Political	Political science, political economy, policy studies, international relations	Political actions and energy policies	National interests, policy paradigms, constitutional systems, special interests, voters' preferences, institutional capacities	Punctuated equilibrium, multiple streams, ACF, policy learning and diffusion	Design of international regimes and domestic policies	Poor representation of material factors

STS = Science & Technology Studies; IAM = Integrated Assessment Model; MLP = Multi-Level Perspective; ACF = Advocacy Coalition Framework.

shaping outcomes of political struggles [122]. In exploring the role of institutions, scholars follow three distinct streams of neo-institutionalism: rational choice, historical and sociological [123]. The rational choice tradition views institutions as mechanisms that enable collective action of self-interested actors through lowering transaction costs and increasing predictability of other actors' behavior. The above mentioned studies of the influence of voters, parties, and special interests on energy policies follow this tradition.

Historical institutionalism draws attention to somewhat different factors by seeing state 'no longer as a neutral broker among competing interests but as … capable of structuring the … outcomes of group conflict'. It contends that 'the institutional organization of the polity and economy structures conflict so as to privilege some interests while demobilizing others'. As such, historical institutionalism is especially useful for 'cross-national comparisons of public policy, typically emphasizing the impact of national political institutions' ([123], 6). Cross-country comparisons of energy transitions have observed certain effects of political institutions (such as federal vs. centralised structure or proportional vs majoritarian electoral system) on renewable energy policies (e.g. [111]). Others have showed how different configurations of political institutions and energy resources lead to different types of energy governance [124]. More generally, scholars have developed a theoretical argument for the importance of historical institutionalism for energy transition studies as a complement to sociological institutionalism [125] or to socio-technical analysis [126].

Several energy transition studies use the concept of *varieties of capitalism* [119] developed in the historical institutionalism tradition. This differentiates between two types of capitalist economies: liberal market economies and coordinated market economies. For instance, Geels et al. [3] refer to different varieties of capitalism in the UK and Germany to explain differences in energy transitions in these two countries. Ćetković & Buzogány [127] analyse the implications of varieties of capitalism for renewable energy policies in the new EU member states. Lachapelle and Paterson [128] and Mikler and Harrison [129] investigate how varieties of capitalism affect climate and energy policies.

All three streams of neo-institutionalism have been criticized for representing institutions as 'given, static and constraining' and thus not being able to explain policy change, typically attributing such change to exogenous shocks [130]. To introduce an endogenous concept of change, Schmidt [130] proposes the fourth, 'discursive' institutionalism, comparable to 'ideational' or 'constructivist' institutionalism proposed by other scholars [131,132]. Discursive institutionalism views institutions as both constraining structures and enabling 'constructs of meaning', created and maintained by agents which can change institutions using their critical discursive abilities ([130], p. 4).

Discursive, constructivist, or *ideational institutionalism* is an example of a broad class of political theories recognizing that political actors are not necessarily guided by a rationally formulated choice between clearly defined courses of action that best serve their well-defined preferences, solve objectively framed problems, or conform to established institutions. Instead, these theories see actors as driven by either incomplete (as in Simon's [133] bounded rationality) reading of reality or by the meaning of problems, preferences and solutions which they themselves construct through narratives, interactions, and learning (e.g. as in Hansenclever's [134] 'cognitivism').

An important concept illustrating this type of thinking is *policy paradigm* (a pattern of framing policy problems and searching for solutions) proposed by Hall [99] as a way to reconcile state-centric and state-structural approaches in studies of policy change. Hall argues that a policy *paradigm shift* occurs when the state and other social actors agree on a new definition of or a solution to a problem and stresses the role of learning in this process. Kern and Kuzemko [135] apply Hall's theory of paradigm shifts to explain the change in the UK energy policies in the 2000s when the concept of self-regulated energy markets gave way to more forceful state intervention. Their account views the causes of the paradigm shift as a change in 'crises narratives' [136]. In another example, Leung et al. [137] explain China's policy of acquiring overseas oil assets as resulting from a combination of on the one hand objective depletion of domestic oil reserves and rising demand and on the other hand the ideational process of securitization [138] invoking the painful but objectively irrelevant memory of the 1960s oil embargoes.

3.3.3. International influence

In formulating and implementing energy policies, states interact not only with domestic actors but also with other states. Such interaction is analysed in international relations theories, particularly the field of international political economy, born out of studying states' responses to energy crises of the 1970s [139,140]. An influential body of literature on policy change in the international context focuses on policy *isomorphism* or *convergence*, a phenomenon when different states adopt similar policies. This is explained by *policy diffusion* induced by coercion, international harmonization, regulatory competition, transnational communication, lesson drawing, transnational problem-solving, emulation, international policy promotion and independent problem solving [141,142]. For instance, Schaffer & Bernauer [111] show that EU membership influences adoption of renewable energy policies, but the presence of such policies in neighboring countries does not.

3.3.4. Comprehensive policy change frameworks

Shifts in material conditions (e.g. resource discovery or depletion, economic growth, or technological development) may affect national interests and thus trigger state action. Pressures from international institutions or examples from other countries may encourage states to adopt new energy policies. Policymakers may also respond to changing voters' preferences and shifting balance of special interests. Yet, stabilizing mechanisms may prevent policy change. In contemplating new goals, state bureaucrats may be slowed down by perceived risks of creating new (or re-creating old) problems. Existing policy paradigms and cognitive limitations may prevent new problem framing or search for new solutions. Policies transplanted from other countries may be short-lived because they are not compatible with domestic institutions or capacities. Special interests may collude with bureaucrats to manipulate or ignore public opinion.

These examples indicate why contemporary theories of policy change move away from a linear analysis of 'drivers and barriers' to a view of policy change as a cumulative non-linear process.[15] Pierson [143] points to *increasing returns*, when a policy empowers certain beneficiaries who in turn support and strengthen the policy, which further empowers its beneficiaries etc. Jacobsson and Lauber [105] illustrate this dynamic by describing how the adoption of initially modest renewable electricity policies in Germany in the early 1990s empowered their beneficiaries who subsequently lobbied for retaining and expanding such policies in the 2000s. Increasing returns create path dependence and institutional lock-in when, once chosen, a policy makes alternative policies increasingly less attractive and when existing institutions prevent policy change while existing policies prevent institutional change. It is particularly intriguing why and when this general pattern of stability is altered so that policy change is possible. Baumgartner and Jones [144] introduced the concept of *punctuated equilibrium*, where periods of policy and institutional stability are punctuated by periods of simultaneous policy and institutional change. This pattern of change is accounted in the *Multiple Streams Theory* [145], which argues that policy change occurs when necessary preconditions in material factors, interests, problem framing etc. coincide in time.

One of the most comprehensive approaches to policy change is the *Advocacy Coalition Framework* (ACF) [146], which 'absorbs many of the explanatory variables advanced by other theories' [147]. ACF views policy change as shaped by interactions of competing advocacy coalitions and exogenous shocks that might lead to policy-oriented learning constrained by constitutional rules ([117], 253).[16]

Political science and international relations theories were productive in explaining shifts in energy systems following the oil crises of the 1970s and the 1980s. The interest of political scientists in energy declined in the 1990s following the decline in oil prices and have not recovered despite calls for its renewal [139,148]. Challenges of contemporary energy transitions are more complex than in the 1970s with respect to the timescale, the sectors involved, and the type of societies affected. These challenges cannot be addressed by mimicking the classic studies in focusing on only one challenge (e.g. climate change or energy security). Moreover, it usually requires opening the black boxes of energy economics and energy technologies and therefore interacting with the other two perspectives: techno-economic and socio-technical.

3.4. Summary

Table 2 summarizes the three perspectives on national energy transitions. Analysis of co-evolution of energy flows and markets, energy technologies, and energy policies should include theories and variables from all three perspectives as well as account for their interactions. The next section compares these perspectives to existing meta-theoretical reviews as well as proposes and illustrates a meta-theoretical framework based on the three perspectives.

4. Towards a meta-theoretical framework

4.1. The three perspectives and the existing literature

Table 3 compares the three perspectives on the national energy transitions with the existing reviews summarized in Section 2. It illustrates that while knowledge domains from each of the three perspectives have been discussed in at least one existing study, none of these reviews has brought all the perspectives together.

Most of the existing studies mention economics, which is at the heart of the **techno-economic perspective**. The techno-economic perspective most closely overlaps with Grubb's et al. [9] neoclassical economics domain (see also environmental economics analytical framing by Smith et al. [6]), but according to Grübler [4] it also incorporates scholarship from economic history (e.g. [149]) , and certain strands of ecological and evolutionary economics [34,150,76,40]. The common feature of all these approaches is their focus on quantitative regularities in the evolution of energy systems, including but not limited to cost-optimization and market equilibrium.

This commonality is aptly captured in the quantitative systems modelling/IAM approach described by Turnheim et al. [7] and Geels et al. [3], also overlapping with the techno-economic perspective. However, we do not equate the techno-economic perspective with IAMs. This is because IAMs are *models*, not *theories*[17] and thus cannot be directly used for constructing meta-theoretical frameworks, at least not before the theories under the hood of IAMs are explicitly distilled.

Reviews by Markard et al. [55,5] and Coenen and Lopez [10] do not include techno-economic approaches in their classification of transition studies. One reason might be that these reviews focus on *sustainability* transitions, which may or may not include a techno-economic subsystem, central in national *energy* transitions. Another reason may be the tendency of socio-technical transition literature to 'have limited intellectual interaction with mainstream and especially neoclassical economics and sometimes even positions itself as "contrary to neoclassical economic theory" ' ([9], p. 90).

The **socio-technical perspective** closely corresponds to the scholarly tradition covered by Markard, Coenen and their colleagues [10,5,55] by Smith et al. [6] and by Grübler [4]. These researchers divide this tradition into two or more strands of research including MLP, transition management, SNM, and TIS studies. While we find this distinction illuminating, we locate this entire scholarly tradition within the same socio-technical perspective since it focuses on the same phenomena of change in socio-technical systems , shares similar disciplinary roots and uses similar concepts and variables (Tables 2 and 3). The socio-technical perspective is broader than the 'socio-technical transition analysis approach' identified by Geels et al. [3] and Turnheim et al. [7], which does not explicitly include innovation systems studies. It does, however, include their third analytical approach, initiative-

[15] A distinction between linear and cumulative theories of policy process are made by Knill and Tosun [117].

[16] Nohrstedt [147] used ACF to explain Swedish nuclear energy policy by focusing on the 1980 referendum on nuclear energy, which was initiated by the Social Democratic Party not because of its party members' views on nuclear power, but because of the upcoming electoral campaign. He also criticizes ACF for not accounting for partisan politics.

[17] See Ostrom ([69], p. 826) on differentiating between theories and models.

Table 3
The three perspectives on energy transitions compared to existing *meta*-theoretical literature.

		Techno-economic perspective	Socio-technical perspective		Political perspective
Publication	Scope of transition	Knowledge domains/disciplines discussed			
Grübler [4] 'insights and cautionary tales'	Energy	Neoclassical economics, Economic history	Evolutionary economics Innovation systems, technology diffusion	'Dutch school' (MLP and TM)	
Smith et al. [6] 'problem and analytical framings'	Sustainability	Neoclassical (environmental) economics	(Firm-based) 'cleaner production' Innovation studies	Evolutionary economics MLP	'Black box' of public policy*
Coenen and Lopez [10] 'systems approaches'	Sustainability/ competitiveness		Innovation systems	Socio-technical (MLP and TM)	
Markard et al. [5], 'frameworks'	Sustainability	Neoclassical economics*	Innovation systems studies	MLP, TM, SNM	Political science*
Grubb et al. [9] 'domains'	Energy	Neoclassical economics Macro-economics, evolutionary, ecological and institutional economics Behavioral economics	Macro-economics, evolutionary, ecological and institutional economics Behavioral economics	Macro-economics, evolutionary, ecological and institutional economics	Socio-political analysis*
Turnheim et al. [7] / Geels et al. [3] 'analytical approaches'	Sustainability / Low-carbon	Quantitative systems modeling / Integrated Assessment Models		Socio-technical transition analysis Initiative-based learning / practice-based action research	

Notes: * domains of knowledge in non-shaded cells are mentioned (e.g. as future research agendas), but not systematically discussed. MLP = Multi-Level Perspective; TM = Transitions Management; SNM = Sustainable Niche Management.

based learning/practice-based action research, which overlaps with SNM [7] and transition management.[18]

The socio-technical perspective overlaps with Grubb et al.'s [9] third domain (evolutionary and institutional economics) though it also stresses the role of theories originating in sociology and history of technology and STS rather than only in economics. Grubb et al.'s [9] first domain (behavioral economics) applies to the individual rather than the national level. Insofar as human behavior is embedded into socio-technical systems [89], it overlaps with the socio-technical perspective. However, insofar as human behavior exhibits regularities that are part of some techno-economic theories and models it overlaps with the techno-economic perspective.

The **political perspective** is less represented in the existing meta-theoretical studies though Markard et al. [5] and Grubb et al. [9] mention the importance of political analysis. This neglect of the political perspective may at least in part be explained by the fact that scholars of historical energy transitions disagree on the significance of deliberate government interventions in the past evolution of energy systems, though there is a general consensus that such interventions may play a larger role in the future energy transitions driven by climate concerns and other normative social goals [45]. One specific reason for the neglect of the political perspective in IAMs is the difficulty of quantifying political factors in techno-economic studies, especially in long-term global scenarios, which often lack the national resolution where most politics happen.[19]

The last obstacle for a recognition of a separate political perspective may be the aspiration of some socio-technical studies to construct a 'seamless web' which does not a priori distinguish between technological, social and political factors. In this respect, it is symptomatic that some socio-technical literature explicitly includes political regimes, policymakers and political strategies as parts of socio-technical systems. While highlighting important connections between the technological, the social, and the political, such representation runs the risk of oversimplifying political phenomena by reducing them to a conflict over technological innovation: for example, between on the one hand, change-resisting incumbents and on the other hand, change-seeking newcomers.[20] The former are often identified with large companies

[18] For example, Markard et al. [5] characterize transition management as 'instrumental *practice-oriented* model' noting its promise in application to *local* transitions.

[19] Instead, such scenarios represent energy transitions at the level of *global regions* such as Africa or Latin America.

[20] For example, Geels [112] analyses political strategies of incumbents using the socio-technical notion of regime resistance. This study portrays the interest of coal industry in CCS as resistance to climate change mitigation although from the techno-economic standpoint CCS is generally seen as a cost-effective and important element of mitigation [151].

Table 4
Fits and misfits of the three perspectives on national energy transitions.

	Archetypal episodes of transitions	
Perspective	Fits (strong explanatory power)	Misfits (weak explanatory power)
Techno-economic	*Growth driven* shifts between mature technologies due to resource depletion, population or economic growth.	*Politically driven* changes, disruptive technological change.
	E.g. contemporary expansion of electrical generation from thermal, nuclear and renewable sources in developing countries	E.g. early phase-out of nuclear power in Germany* (2000s–2020s); explosive expansion of wind energy in Germany (1990s).
Socio-technical	*Innovation driven* emergence and adoption of new technologies	*Growth driven* changes in the use of existing technologies, especially in case of decline
	E.g. contemporary replacement of incandescent light bulbs with LED systems	E.g. stagnation of nuclear power in Germany and its expansion in Japan in the 1990s
Political	*Policy driven* shifts in energy systems E.g. rural electrification in the USA (1930s) and South Africa (1990s). Deployment of nuclear power in response to the oil crises in the 1970s–1980s. Phase-out of nuclear power in Germany.	*Technology-dependent* dynamics E.g. lack of deployment of wind power in Germany in the 1980s and Japan in the 1990s–2000s.

Note: Examples in this table refer to the comparative analysis of electricity transitions in Germany and Japan discussed in Section 4.4.

colluding with conservative forces in governments while the latter – with reformist policies, small innovative firms, and citizens' movements. For example, Geels et al. ([3], p. 6) propose that socio-technical transition analysis can:

> provide information […] about hindering influences such as resistance from big firms, limited political will in Parliament, public opinion concerned about non-climate issues such as austerity, jobs or refugees.

To us this seems to be an excellent justification for *political* rather than only *socio-technical analysis*, because it is the scholarly tradition of political science that has developed theories and methods for explaining special interests, political will, and public concerns, which originate and extend beyond energy or other particular socio-technical systems. Meadowcroft [56,11] explains why political factors deserve serious analysis in transition studies, but it seems that his argument has not been fully accepted. His point about the importance of political power is often cited in discussing incumbent regime actors (e.g. [112]). However, his other point that the battle between incumbents and newcomers is not the only and perhaps not even the most important issue on the political arena relevant to energy transitions is cited much less often.

4.2. Fits and misfits of the three perspectives

National energy transitions are the result of asynchronous co-evolutionary processes. This means that the relative roles of semi-autonomous systems may change from one transition episode to another. For example, during certain episodes techno-economic changes may play the leading role whereas during others, technological innovation or political shifts may be the leading drivers of change. In other words, each perspective may be a better 'fit' (i.e. its variables and theories may have a stronger explanatory and predictive power) to analyse certain episodes of transition. However, each perspective also has its own 'misfits,' a term we use to capture conceptual or empirical incongruences and misalignments seen in Table 4.

4.3. Three perspectives as a meta-theoretical framework

We propose a meta-theoretical framework for analyzing national energy transitions using the three perspectives as an organizing principle for systematically mapping hierarchically-organized variables, as shown in Fig. 2 and Table 5, and theories explaining their interaction, as recommended by Ostrom et al. [68] and Ostrom [69]. These variables and theories can be used to construct case-specific explanations of specific transition episodes or situation types or more general models and scenarios. Whereas the total number of possible lower-tier variables can be large, only a relatively small subset would usually be relevant for a particular situation.

4.4. Illustrative application of the framework

A combined application of three perspectives can be illustrated by a recent comparative analysis of transitions in electricity systems of Germany and Japan [116]. In 1990, these two countries had similar electricity systems dominated by coal and nuclear power. However, between 1990 and 2010 Germany became the world's leader in renewable electricity[21] while deciding to phase out nuclear power, whereas Japan has become a nuclear technology leader while deploying only modest amounts of renewables.[22]

A **techno-economic** analysis in combination with the **political** concept of national interest (particularly energy security) explains why, in the 1970s–1980s, the two countries followed a similar path of reducing energy intensity and deploying nuclear power while heavily investing in research and development of renewable and alternative energy. The main driving factors were the increase in electricity demand combined with the 1970s oil crises and price increases. The same variables explain the divergence of their energy paths in the 1990s: while Japan faced continued rapid growth in electricity demand and increasing tensions over energy resources and imports in Asia, Germany's electricity demand stagnated and its energy security outlook improved following the end of the Cold War in Europe. Therefore, during the 1990s, Japan built the same number of nuclear reactors as in the 1980s while Germany built none. This strengthened the political power of the nuclear **socio-technical** regime in Japan and weakened it in Germany.

A techno-economic analysis cannot explain other differences between the two countries: (a) why was it the more energy secure Germany and not the less energy secure Japan that deployed more domestic renewables in the 1990s–2000s and (b) what compelled Germany to start phasing-out nuclear power in the early 2000s. Bringing climate change concerns into the picture does not explain

[21] In 2014, Germany produced more than 20% of its electricity from non-hydro renewables and was within the top five countries in terms of installed solar PV, wind and biomass-based capacity as well as investment in renewable power and fuels [152]. In addition, Germany has been a leader in innovation and manufacturing of renewable electricity equipment [153].

[22] Cherp et al. [108] review several existing explanations for this difference to show that none of them is fully satisfactory.

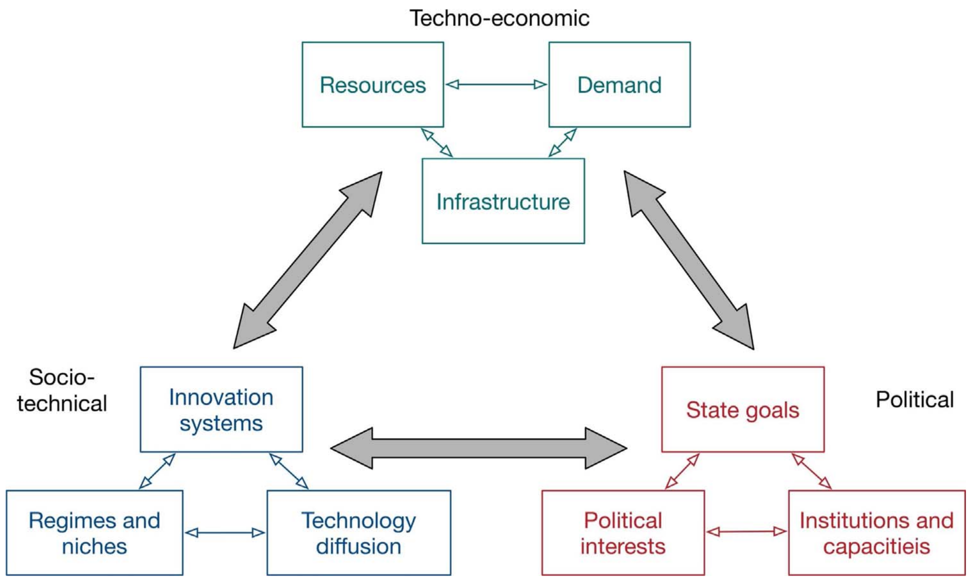

Fig. 2. Top level variables associated with the three perspectives on national energy transitions.

Table 5
Top-level and selected second-level variables in the three perspectives framework.

Techno-economic	Socio-technical	Political
Resources - Fossil fuels types, resources, reserves, extraction costs - Import and export of fuels and carriers - Type and potential of renewable resources; cost of relevant technologies	Innovation systems - Presence and structure of national, sectoral and technological innovation systems - Performance of innovation systems with respect to their functions e.g. R & D activities, knowledge stock	State goals - Type of state goals (e.g. energy security, access to modern energy, climate change mitigation, technological leadership) - Factors affecting state goals e.g. import dependence, international competition.
Demand - Types and scale of energy uses - Energy intensity - Factors driving demand growth and decline, e.g. population and economic growth/decline; industrial restructuring	Regimes and niches - Structure, resources and coordination of incumbent regimes - Structure and resources of newcomers' niches - Niche-regime interaction including external support mechanisms	Political interests - Special interests (e.g. industrial lobbies) - Party ideologies and organized social movements - Voters' preferences
Infrastructure - Existing infrastructure for extraction, transportation, conversion, and use - Age of infrastructure - Manufacturing, import and export of equipment - Cost of operation and construction of infrastructure	Technology diffusion - Global maturity of relevant energy technologies - Location on core/periphery of technology - Possibilities for technology export	Institutions and capacities - State capacity e.g. economic and other resources, political stability - Institutional arrangements, e.g. varieties of capitalism, party system, government system - International processes: e.g. policy diffusion, international agreements

these differences either, because such concerns have been similarly strong in both countries[23] and in any case they cannot explain a shift from one low-carbon option (nuclear) to another (renewables). The explanations of these differences can be found in bringing in additional variables and theories from the socio-technical and political perspectives.

According to **socio-technical** accounts, wind power diffused to Germany from Denmark [18] in the early 1990s due to similar socio-geographic conditions and a moderately favorable legal environment.[24] The rapid uptake of the technology in the 1990s resulted in actors associated with wind power gaining considerable **political** influence by the 2000s [105]. In contrast, in Japan, onshore wind power did not take off despite similar policies and promising developments in niches populated by first Danish, then German and even Japanese wind turbine companies [156].[25]

The nuclear phase-out and the strong boost to renewable energy in the early 2000s in Germany were legislated by the 'red-green' coalition government which represented not only the nascent wind power sector, but also the powerful coal industry linked to the Social-Democratic Party, SDP [105,157]. Both groups of interests benefited from the demise of the nuclear sector that competed with coal and renewables, a clear example of a **political** advocacy coalition. In Japan, such a coalition was not possible, because of the failed uptake of wind and the absence of a domestic coal sector. Moreover, the nuclear sector in Japan was politically much stronger due to its vigorous growth in the previous decade in parallel with electricity demand growth.

These arguments illustrated in Fig. 3 show that all three perspectives are needed to explain the differences in the two cases of transition. They also show how the interplay of relevant explanatory variables and theories from different perspectives varies from one transition episode

[23] Cherp et al. ([116], p. 613) cite Pew Research Center [154,155] to indicate that in 2009, 65% of Japanese considered global warming as a very serious problem and 64% were prepared to protect the environment even if it slows growth and costs jobs, whereas in Germany the relevant numbers were 60% and 77%. In 2015, 42% of Japanese and 34% of Germans considered global climate change as a very serious threat.

[24] According to Jacobsson and Lauber [105], one factor distracting German electric utilities from fiercely opposing the feed-in-tariff for wind power was German reunification.

[25] One explanation for the much slower uptake of wind power in Japan is its distinct geography with great scarcity of available land close to large power consumption centers, erratic winds, frequent lighting strikes and earthquakes.

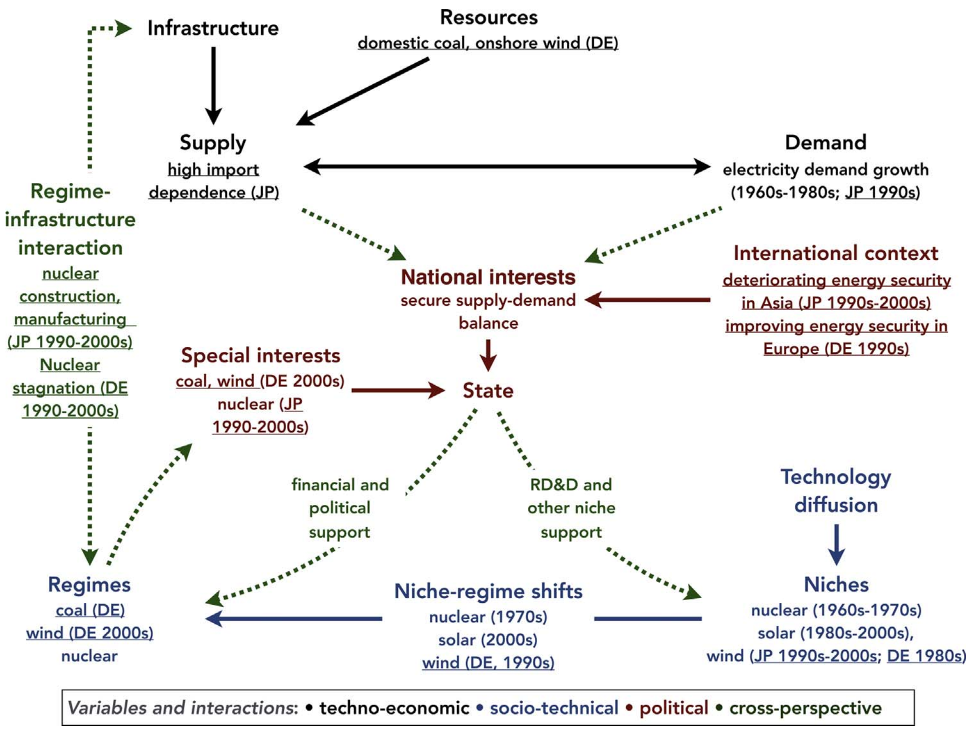

Fig. 3. Variables and processes explaining differences and similarities in the evolution of electricity sector of Germany and Japan. An illustrative example of combined use of the three perspectives.
Notes: techno-economic variables and interactions are shown in black, socio-technical – in blue, and political – in red; the green dotted lines show connections between variables across perspectives. 'DE' denotes variables relevant to Germany and 'JP' – to Japan. Variables which differ between the two countries are underlined. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to another. This lastly illustrates the concept of co-evolution: the semi-autonomous but mutually interdependent change in techno-economic, socio-technical and political action systems in both countries.

5. Conclusions

Understanding sustainability transitions presents many challenges for social science. Several existing reviews identify, classify and compare approaches to tackling these challenges. This literature identifies broadly similar fields of knowledge including different domains of economics, STS and sociology of technology, and occasionally political science (Table 3 in Section 4.1). Yet there is little consensus on how these various approaches can be integrated, despite a consensus that such integration is necessary for a comprehensive understanding of transitions.

We contribute to this literature by focusing on a specific problem of national energy transitions. National energy transitions include changes in three co-evolving systems: energy flows and markets, energy technologies, and energy-related policies, each in the focus of a specific scholarly field, framing three perspectives on energy transitions: techno-economic, socio-technical, and political, each associated with its own disciplinary roots, systemic focus, variables and theories (Table 2 in Section 3.4). In comparison with the disciplines emphasized in the existing literature, the three perspectives framework elevates the role of political science since policies might be increasingly prominent in shaping the 21st century energy transitions.

We also propose and illustrate a method for analysing national energy transitions, inspired and guided by Ostrom's framework approach. We use the three perspectives as an organizing principle for constructing a meta-theoretical framework as a nested conceptual map of variables and theories from different social science disciplines which we believe are necessary for explaining specific cases and broader classes of national energy transitions. In this regard, the exact boundaries between the perspectives are less important than their ability to identify critical variables and theories which explain their interaction and behavior (Table 5 and Fig. 3).

We illustrate the application of our framework by a comparative analysis of electricity transitions in Germany and Japan, which shows that national energy transitions may comprise distinct episodes not necessarily abiding by the same logic. The importance of various theories, and of each of the three perspectives, differs from one episode to the other and it could also vary from one comparative case to another. Nevertheless, we believe that such an analytic approach may have wider applicability. This observation leads us back to the aspiration for a middle-range theory [158] of national energy transitions. Such a theory is likely to be more feasible and useful than any 'grand theories' of broadly sketched transitions. It is possible that an initial step for such a theory should be an inventory of micro-logics explaining specific episodes or elements of national energy transitions as an interplay of variables and theories from the three perspectives, e.g. as shown in Fig. 3. The next step would be on the one hand synthetizing these micro-logics into broader theoretical constructs and on the other hand developing diagnostic tools for establishing the applicability of such logics to particular classes of situations.

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