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ORIGINAL PAPER

Electricity infrastructure and innovation in the next phase of energy transition—amendments to the technology innovation system framework

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Abstract
A new phase of energy transition makes auxiliary technologies such as energy storage and other flexibility options more important. Economic policy that aims to steer this transition needs to grasp the complex system dynamics underlying energy and society. This conceptual article gives an overview of energy technology innovation theories that exemplify the growing importance of flexibility for electricity usage. First, the article presents different conceptualizations of technology innovation and diffusion. Second, how energy systems are embedded in physical infrastructures and social power relations is shown with a brief history of electricity in contemporary industrialized societies. Third, energy innovation is discussed in context of challenges of the upcoming energy transition. Fourth, energy technology innovations are further contextualized in light of insights from political economy and energy social sciences. Finally, the discussed approaches are synthesized to amend the holistic technology innovation system approach for studying energy technology innovations such as energy storage.

Keywords Renewable energy · Sustainable energy transition · Technology diffusion · Technology innovation system · Infrastructure

O33Technological Change: Choices and Consequences, Diffusion Processes
P18Energy, Environment
P48Political Economy, Legal Institutions, Property Rights, Natural Resources, Energy, Environment, Regional Studies
Q42Alternative Energy Sources
Q40General
Q55Technological Innovation
Z10General
B52Historical, Institutional, Evolutionary, Modern Monetary Theory†

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1 Introduction

Few depictions of global capitalism are as emblematic as the double role that human-used energy plays—both as an enabler and stabilizer of contemporary global society, but also as a transformer of earth's ecosystems. Thus, socio-economic research should include the physical and material foundations of our human activities. The energy dimension is fundamental to academic research. Renewable energies become systemically important and diffuse beyond their niche (Markard 2018a) flexible supply-side options such as energy storage technologies require attention from scholars, as changes within the current energy system occur.

Sustainability transitions in, e.g., food or processing, require the attention of socio-economic research; the current energy transition comprises issues such as heating, manufacturing, housing, and transportation of goods and services (Foxon 2017). Against this backdrop, this article focuses on the role of electricity in the energy transition—a topic of increasing importance, due to its centrality for many renewable energies, the electrification of key sectors like personal transport, and the increasing use of computers and "smart" devices (IEA 2019).

In the past, many evolutionary economics concentrated on the supply side while neglecting demand in innovation process research (Dopfer and Nelson 2018). Entrenched in a pro-innovation bias, evolutionary economists and innovation researchers are increasingly adopting a transformation framework and seek to understand how (technological) innovation can benefit society, alleviate contemporary global challenges, and how policies can be framed accordingly (Schot and Steinmueller 2018).

The goal of this article is to conceptualize a research focus that incorporates elements of the next phase of energy transition where renewable energies are expected to replace fossil fuels, requiring more consideration of infrastructure, social and political power, and physical embeddedness. To do so, the article synthesizes selected approaches that bridge different fields of knowledge and concepts. There are contributions from economic geography, innovation economics, science and technology studies (STS), transition studies, political sciences, and business studies (Köhler et al. 2019; Rakas and Hain 2019).

The article starts with a brief review on innovation in contemporary capitalist and industrialized societies, stressing aspects of national innovation systems, diffusion, and specific technology innovation systems. A brief history of energy and electricity system development in capitalism follows, so as to emphasize the biophysical embeddedness of socio-technical energy systems. In the fourth section, peculiarities of energy technology innovation systems with a special focus on diffusion and social acceptance are discussed. Finally, the article closes in the fifth section with a tentative synthesis and proposes three amendments to the technology innovation system framework.

2 Systems of diffusion and innovation

Drawing on Schumpeter (1939), innovations refer to anything that can be seen as a recombination of existing things to perform a new function, or have a novel aspect in the realm of economic life.

> Technological change in the production of commodities already in use, the opening up of new markets or of new sources of supply, Taylorization of work, improved handling of material, the setting up of new business organizations such as department stores—in short, any 'doing things differently' in the realm of economic life—all these are instances of what we shall refer to by the term Innovation. (Schumpeter 1939, p. 84)

Schumpeter's definition of innovation exceeds the term "invention." While an invention can contribute to an innovation, such as the development of a new technology, innovation can also include immaterial factors such as the way of organization. Newer definitions put the use of a product or process at the center (Gault 2018). Thus, an innovation is when "[n]ew or significantly changed processes are implemented when they are brought into actual use in the operation of the institutional unit, including the making of product available to potential users."

In the following section, I briefly discuss emergence and diffusion of technology innovations with the theoretical approach of diffusion of innovation, national innovation systems, and technology innovation systems.

2.1 Innovation systems and institutions

To answer Veblen's (1898) call for this specific economic field: Innovation research is and must be an evolutionary science. Consequently, the theory of how innovation occurs in economic life was further developed by Schumpeterian and evolutionary economists like Nelson and Winter (1982, chap. 5), who introduced a dynamic theory of innovation. This implies a historical contingent nature of economic change (Arthur 1989) with path dependencies (David 1985). Technological change is context dependent, i.e., circumstances of emergence are important (Maréchal and Lazaric 2010). Dosi (1982) introduced the idea of technological paradigms that—in reference to Thomas Kuhn's scientific paradigm shifts—limit the direction of technological change. Only within this paradigm are market dynamics of costs and benefits relevant.

From this perspective, heterogeneous agents (or entrepreneurs) innovate under uncertainty and have a vision to create something new (Nelson 2018). Due to their bounded rationality (Cyert and March 1963; Simon 1991, 1955), they base decisions and evaluations on rules of thumb and routines that are heavily influenced by institutional settings and context (Shove 2004). While daily practices help to free-up resources from routine problems, their lock-in can foster unintended and unsustainable practices. Thus, structure is both enabling and constraining (Giddens 1984).

Based on this work by early evolutionary economists and guided by organizations such as the OECD (Godin 2009), economists with different academic backgrounds have helped develop an approach to economic development that focuses on the role of knowledge infrastructures and on learning by both individuals and organizations (Lundvall 1992; Nelson 1993). Freeman would later label this approach as the study of innovation systems, which initially focused on innovation systems in countries (Freeman 1989), i.e., national innovation systems (NIS) or national systems of innovation.

The innovation system approach was based on List's (1841) national economy doctrine, which was designed in opposition to Adam Smith's free-market approach.

According to List (1841), bringing the German state's economy up to speed with England's would require government interventions and strengthening infrastructure, specifically, knowledge infrastructures and mental capital (Lundvall 2016, chap. 9). Knowledge, however, can exist in tradable commodities and is somewhat transferrable and embodied in the labor force (Lundvall 2016). The innovation system is accordingly understood as an analytical tool for understanding systemic properties that enable developing, diffusing, and utilizing new products and processes (Bergek et al. 2008). Based on this reasoning, the importance of institutions that hinder or enable innovation assumes a key role alongside the networks of actors.

The NIS approach has a strong spatial dimension, because knowledge in the labor force tends to be local and tacit. Physical infrastructure, e.g., roads, grids, ports, and factories, can be replicated or moved to different regions—but only at high costs. Further, some geographical factors are always present in certain regions (sunny days, mountains, natural resources).

Edquist (2006) added another dimension to innovation system research by focusing on activities or functions, their causes and determinants. This emphasis on functions would later become one of the cornerstones for the technology innovation systems approach.

As in many innovation policies, innovation systems research has a tendency towards a "deficit model" (Pfotenhauer et al. 2019) and deficit framing in its policy recommendations, with a clear pro-innovation bias that tends to marginalize other rationales. In this understanding, there is always a societal problem that is missing a technological innovation as a solution. However, given the upcoming transformation policy frameworks that are based on global challenges, rather than only the competitiveness of national innovation systems (Schot and Steinmueller 2018), the technology innovation system approach can play a constructive role in steering transition and shifting the directionality of technology development.

2.2 Diffusion of innovation

Diffusion of innovation is one of the most researched topics in social sciences and consists of many approaches. A key extension of innovation theories arose from developments in network sciences that combine knowledge from disciplines like sociology, anthropology, mathematics, and physics. They could explain why certain, seemingly useful innovations would not diffuse in society. These insights clarified that the diffusion of innovation is not so much influenced by relatively effective top-down actors (such as the media or governments). Rather, communication amongst actors in different kinds of networks is central to how and if an innovation gets adopted on a larger scale (Rogers 2003, chap. 8). Here, it became clear that, for example, missing links between actors—or weak ties—amongst different (heterophilious) actors (Granovetter 1973) influence the diffusion of innovation.

Rogers (2003, chaps. 1 & 8) devised a terminology for the different groups of actors, along with how and at what speed they adopt innovation. Accordingly, one group of actors takes the role of opinion leaders, who can be individuals or entire organizations, and are labeled as innovators or early adopters. They are central to adoption speed, as they are trusted by actors of their immediate surrounding that aim to follow and adopt their behavior. As the distribution of these groups follows a Gaussian bell curve, only a small group of actors leads in adopting an innovation. The majority follows later. A small group, again, will always attempt to resist the adoption or is not informed about the innovation—the laggards. One way of capturing this diffusion process across an entire network is the S-shaped sigmoid curve that shows initial slow adoption, a sudden uptake, and a long stabilization period (Geroski 2000). Simplified, this curve can be represented by a logistic growth function (Fig. 1).

with L = maximum of adopted innovations, k = innovation growth rate, and x_0 = turning point of the function.

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}}$$

More complex ways to capture diffusion dynamics were prominently modeled in the later-defined Bass model (Bass 1969; Jiang et al. 2006; Mahajan et al. 1995).

2.3 Technology innovation systems

In recent years, research has investigated other innovation system types, including regions (e.g., Mattes et al. 2015), sectors (Malerba 2002; Squillace 2012), and technologies (Bergek et al. 2008). Because of the importance of flexibility options for energy transition, this article focuses on technology innovation systems (TISs). Also, the TIS literature increasingly incorporates the role of sectors, regions, and nations in their analysis.

A precursor for TIS was first discussed using the term "technology system." Here, "[t]echnological systems are defined in terms of knowledge/competence flows rather than flows of ordinary goods and services." (Carlsson and Stankiewicz 1991). The approach was later developed more coherently as TIS (Bergek et al. 2015, 2008; Hekkert et al. 2007). The systemic perspective in the TIS approach draws attention to flaws or "failures" in the innovation system, hindering (or enabling) the rate or

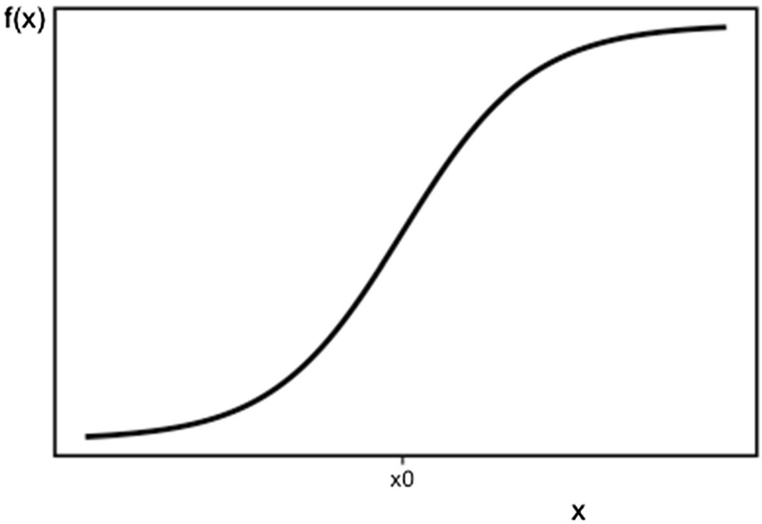

Fig. 1 Logistic growth curve

character of a specific technological development. These obstacles to development are typically identified when the flow of information and knowledge in the system is somehow blocked or interrupted.

TIS is comprised of three structural components: actors (e.g., firms, universities, intermediaries, authorities) (Bergek et al. 2008; Planko et al. 2017), networks between those actors (e.g., firm networks (Musiolik et al. 2012) or learning or political networks (Markard et al. 2015)), and formal and informal institutions (Bergek et al. 2008; Kukk et al. 2016). Following the TIS approach, these structural components regarding flexibility options such as energy storage are configured to enact innovation functions that fulfill central roles within the innovation system across the three structural components (Planko et al. 2017).

Building on the notion of system functions, as mentioned above, several innovation functions (or processes) can be identified that enable sustaining the innovation system. To date, this group of functions is loosely developed, although there has been some re-interpretation and re-formulation. Because different kinds of context factors appear progressively important (Bergek et al. 2015), external economies are no longer considered within the scope of TIS. Further, next to knowledge development, knowledge diffusion is seen as an integral innovation function (Stephan et al. 2017) that relates to other non-heterodox innovation studies (e.g., Jaffe and Trajtenberg 2002).

Ultimately, in line with Myrdal (1957), the TIS approach stresses positive or negative feedbacks with cumulative causation between the different innovation functions, with the prospect of leading to virtuous or vicious cycles (Bergek et al. 2015; Haley 2018). While this function is conceptualized sometimes as positive external economies, others conceptualize those as cumulative dynamics between functions or as positive effects from context factors. Different actors influence through certain actions, e.g., government actors through policies, interest groups through lobbying, or universities through researching different innovation functions. External economies are increasingly further specified as competing or neighboring TIS and sectors that enable or hinder a TIS development (Haley 2018). Following this general understanding, the following six innovation functions are conceptualized:

1. Knowledge development and diffusion
2. Resource mobilization (e.g., financial, human, infrastructure)
3. Market formation
4. Influence on the direction of search
5. Private and public entrepreneurial experimentation
6. Creation of legitimacy (interest groups and advocacy coalitions)

Although it was not originally designed with sustainability-relation issues solely in mind, the TIS approach is often used to help or enable such matters like diffusing clean energy technologies (Markard et al. 2015). While it is useful in that regard, it can be also applied to any other kind of technology (Kukk et al. 2016).

2.4 A multi-level perspective

Another approach that uses a longer time-frame than TIS is the multi-level perspective (MLP) (Geels 2010, 2002) a widely recognized evolutionary framework that aims to explain socio-technical transitions. However, it is used both as theory and heuristic device, making its scope and ability for causal explanation unclear (Sorrell 2018). While this approach puts a focus on socio-technical changes, examples succinctly show that systemic change arises from transitional change. Building on evolutionary economics and STS studies, MLP describes long-term technological development with an evolutionary logic, i.e., the radical variation and selection of technologies in niches—referring to ecological niches (Vandermeer 1972)—and selection and retention at the more stable regime level (Geels 2002). Examples of niches include R&D facilities or demonstration projects. Socio-technical regimes contain a "deep structure" (Geels 2011) with set of rules coordinating the reproduction of social structures. This notion is built on Giddens' (1984) structuration theory. In turn, socio-technical regimes and niches interact with a wider socio-technical landscape (Geels 2011). This landscape contains long-term macro factors such as population development, societal values, and macro-economic variables, which are an adaption of the *longue durée* concept (Braudel and Wallerstein 2009). Within these conceptual spheres, different actors such as suppliers, user groups, and societal groups interact through different financial and production networks (Geels 2011).

Thus, Geels (2018, 2010) recognizes transitional changes as regime shifts. He locates the origin of radical changes within niches (technical innovations), which then potentially change the overall socio-technical regimes.

For example, Schumpeterian patterns can be observed, where new firms with new technologies compete with incumbent ones. Conversely, substitution within sustainable socio-technical also transition happens through other channels, e.g., outsiders such as activists, and other citizens develop and deploy technologies based on normative rationales (Geels et al. 2016).

Similarly, Foxon (2011) translates MLP for ecological economics with the support of coevolutionary economics. What Geels describes as an "exogenous landscape" is enriched with coevolutionary dynamics—not only within a human sphere (economy within a broader society)—but also with nature. He thus applies Norgaard's framework of coevolution (Kallis and Norgaard 2010; Norgaard 1994) to a specific focus on technological lock-ins and innovation. Coevolutionary dynamics, which are important for transitions, are seen amongst five areas: business strategies, technologies, ecosystems, institutions, and user practices. Further, the focus on evolutionary analysis allows for both structural constraints and agency and "highlights the uncertain, path-dependent and cumulative nature of system change" (Foxon 2011, p. 2265). A second strength of Norgaard's, Kallis', and Foxon's coevolutionary approach is that the framework is not limited to local and regional effects. However, as Foxon (2011) notices himself, understandings of power remain under-theorized.

2.5 Government and policy

While the government was always seen as a central actor for energy innovations, the conceptualization of state sharpened recently. It moved from a night-watchman state that fixes "market failures" and provides public goods such as basic research towards a more enabling understanding of state where markets are socially constructed in a Polanyian (1944) sense by providing and enforcing rules (Callon and Muniesa 2005; Mackenzie 2006; Silvast 2017).

Since innovation does not always happen where it is socially desirable (Foray 2019), search directionality is the qualitative dimension of innovation which can be steered through mission-oriented policies (Mazzucato 2018a, 2015). Here, the state provides, e.g., patient capital for research and experimentation to find solutions for pressing societal challenges through state investment banks (Kattel and Mazzucato 2018; Mazzucato and Penna 2016). Another way of steering development is through public procurement and driving aggregate demand (Edquist and Zabala-Iturriagagoitia 2012) or by actively participating in research and development through government agencies such as the defense agency DARPA in the USA (Mazzucato 2015). This mission-driven and active engagement of government moves beyond previously favored approaches of mostly enabling experimentation in niches (as argued for by Maréchal and Lazaric 2010).

While it is applaudable that research is increasingly considering this active role for the government—which finds more traction in the policy arena (Mazzucato 2018b)—a more nuanced understanding of state is necessary to understand how power dynamics drive or hinder certain trajectories. Thus, it is important to recognize that states were never in control of "the economy" but are rather intertwined with their wider ecology of, e.g., companies on several levels (Jessop 2008).

Also, mission-oriented innovation polices pose a danger in that it is crowding out more critical research. If most research funds are allocated to finding (technological) fixes to selected societal challenges while providing economic growth—as it is done in the current Horizon Europe program of the European Commission—other forms of critical reflection that question the mission itself are getting less resources. These innovation biases hinder tackling more structural challenges which might challenge current power structures.

Recent approaches by transition scholars consider the power perspective more explicitly and focus on the importance of incumbents (Turnheim and Geels 2013, 2012; Turnheim and Sovacool 2019). Still, transition research received well-deserved criticism as capitalism and power relations are mostly treated as a landscape factor. However, "[c]apitalism permeates the workings and logics of socio-technical systems in ways that are critical both in the elaboration of rigorous accounts of transition trajectories and for the capacity of [sustainability transition research] to support future societal sustainability transitions" (Feola 2019). Thus, the state creates policies—also when they are mission-oriented—according to a "general will." But, this general will always neglects some interest, while preferring others (Jessop 2008, p. 9).

When the inner workings of capitalism are articulated more explicitly in innovation research, new approaches such as de-growth and post-growth that are actively dealing with socio-economic relations outside of capitalism that aim to be more in line with nature can be better integrated into the study of transition (D'Alisa et al. 2015; Kallis 2011).

3 A brief history of energy in the political economy

Every life form consumes some form of energy. Some organisms, such as plants, transform electromagnetic waves caused by the gigantic fusion reactor our planet circles around—the sun—and transform it into organic matter via photosynthesis.

Other life forms can feed upon these primary producers until we arrive at our human existence that is based, of course, on matter-energy as low entropy inputs (Georgescu-Roegen 1971).

Vast amounts of organic matter have accumulated on earth over millions of years. This useable energy stored in this matter—fossil fuel, coal and gas—was essential for the emergence of the industrial revolution (Smil 2017). Access to fossil energy resources enabled the centralization of factories and the increased control of workers via centralized work places—two cornerstones of industrial capitalism (Malm 2016). In essence, the usage of these forms of energy resources enabled new social and power relations. After WWII, capital accumulation regimes became increasingly augmented with regulation regimes targeting economic growth. This growth-centrism was formulated and disseminated by international organizations—such as the OECD (Schmelzer 2016) and the World Bank (Allan 2019)—who established it with the theoretical support provided by neoclassical economics. Other possible policy objectives, such as those pertaining to social or environmental issues, were largely sidelined, or treated as complements to the growth imperative (Allan 2019).

The increased consumption and production of fossil fuels led to a series of unintended consequences. Rising fossil fuel consumption, due to increased energy intensive activities, is causing global warming and environmental degradation that harms human well-being (IEA 2019, chap. 2; IPCC 2019). Meanwhile, the increased production of fossil fuel (Healy et al. 2019; Obi 2014; Watts 2006) is straining the environment and triggering many violent conflicts over land use and extraction rights (Mitchell 2011, chap. 10). It thus seems unsurprising that access to energy sources is a central objective of national defense sectors (Samaras et al. 2019).

Access to energy is a pre-requisite for poverty alleviation and an essential support for social provisioning and human wellbeing (GEA 2012, chap. 2). Therefore, energy security—along different dimensions (see Cherp and Jewell 2014)—becomes a central societal objective. This is why "access to affordable, reliable, sustainable and modern energy" was set as the 7th sustainable development goal (SDG) by the United Nations in 2015. In this context, the destructive impact of anthropogenic climate change—heavily driven by energy production—was globally acknowledged in the 2015 Paris agreement. While it is seen by many as a helpful call for action, others criticize our remainder within a green-growth approach (Spash 2016).

With increased industrialization, energy has been applied in many ways to facilitate automation and encouraged the search for new ways of using and harnessing energies, such as by means of electricity. This is the focus of this article. However, electricity is by far not the only energy-form that transition scholars must consider (see Fig. 2). Other forms such as industrial energy use and transportation of people and goods—two systems that are still largely dependent on the use of fossil fuels, i.e., coal, oil, and gas—come with their own sets of challenges (see, e.g., Foxon 2017).

The first commercial electric grid was switched on in New York by Thomas Edison in 1882 and financed by J.P. Morgan. Electricity grids evolved from small, decentralized projects for the few to all-encompassing interconnected grids run by natural monopolies that are used by all in industrialized countries (Bakke 2016). Successor companies of their builders are still amongst the most influential in the world (e.g., General Electric and Siemens).

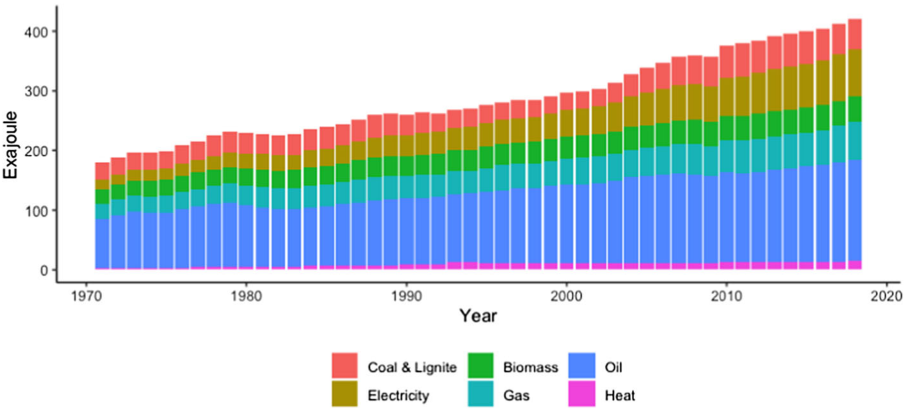

Fig. 2 Global primary energy consumption in Exajoule. Data IEA 2020

Notable advances include Nikola Tesla's alternating currents (AC) to overcome large distances and the availability of commercialization through the invention of the electricity meter (Yergin 2012). Next to the consumption of fossil fuels, electricity especially "delivers a precision unmatched by any other form of energy; it is almost infinitely versatile in how it can be used" (Yergin 2012, p. 347), and its usage is globally—mostly in the industrialized world—growing (Fig. 2). It provides constant access to light, thus allowing for a departure from pre-industrial cycles based on day-night changes and seasons. Also, it established the basis for using semi-conductors, computers, and the whole world of digitalization.

In his seminal work, Hughes (1983) defined electricity grids as large technical systems (LTS) that were composed of both technological, institutional, and organizational elements. These socio-technical systems can be considered the world's largest machines that transform enormous quantities of natural resources. Given their importance, electrical grids have for a long time been controlled or influenced by nation states and therefore developed in parallel to them. Their historic roots and evolution from local to regional and to large interconnected pan-national grids explain contemporary differences between infrastructure (e.g., 50 Hz frequency in Europe and Russia vs 60 Hz frequency in many of the Americas).

The idea for the development of a European electricity grid stems from the period between WWI and WWII, driven by techno-economic factors, such as the demand for increased grid stability, and by ideological views and visions held by grid planners, striving towards a unified Europe. For many European countries, this development of interconnection goes hand in hand with the European Union's emergence from the European Coal and Steel Community and the policy alignment of member states through the Union for the Coordination of Transmission of Electricity (UCPTE) and its successor ENTSO-E.

Like in other policy areas, the continued dominance of economic liberalization as a cultural ideology and political trend reaches the energy domain. Electricity in particular can also be a driver of this (Lagendijk 2008). Following the adoption of the Second Energy Package in 2003 and the Third in 2009, the EU is laying the foundation for an open energy market by unbundling grid operators and energy providers. This trend of liberalization has been further sustained by the establishment of the European Energy

Union and the creation of institutional mechanisms such as the Agency for the Cooperation of Energy Regulators (ACER). With the 2018 Clean Energy Package, the EU is fostering liberalization in the internal energy market, laying foundations for local energy communities and different companies to enter the market once controlled by the old monopolies. Nonetheless, policies support both the large, central infrastructure of an increasingly interconnected European grid and more decentralized solutions (energy communities, e.g., community storage). The latter are in Europe in general still grid dependent.

Also, policies motivated by the mitigation of climate change and pollution such as the Paris Agreement 2015, the German *Energiewende*, or the EU taxonomy for green finance have a structuring impact on technological innovation. While they provide legitimation for renewable energies and increasing investment in new infrastructures, the case of the German *Energiewende* exemplifies that energy innovation policy is a highly contested field. There, incumbents from the fossil fuel industry used the nuclear phase-out to replace nuclear with coal under the framing of renewable energy transition (Cherp et al. 2016) and, lately, new zoning regulation brings the diffusion of wind energy to a halt (Renn and Marshall 2020).

Historically, fossil fuels comprised a vast share of electricity production (e.g., gas, coal, and nuclear) and renewable hydroelectricity (e.g., pumped hydro or run-of-the-river). Both provided a relatively steady supply of electricity. This condition has been slowly changing since the 1990s, with the rise of wind power and solar photovoltaic. However, the unsteady supply of renewable energies requires other flexibilities as counterbalance (IEA 2018; Ornetzeder et al. 2019; Sterner et al. 2017). The simplified one can say that the grid has to stay permanently in balance to prevent blackouts. The daily fluctuations of electricity supply by renewable energies are exemplified by the so-called duck curve (Fig. 3) that depicts the total load minus the variable renewable energies (VREs) solar and wind.

The growing importance of technologies such as energy storage, conversion, and transmission heralds in a second phase of the global sustainability transition (Markard 2018a). Following the first phase, the emergence of wind and solar technologies began transforming the energy system, making complementary technologies more important. Conversely, incumbent generation technologies, such as coal power plants, are on the verge of decline, which has led to institutional resistance as policy-makers try to ease their demise through delays (e.g., of coal phase-out) (Cherp et al. 2016).

Of the different flexibility options that enable variable renewable energies (VREs), energy storage is the most discussed. Current transportation objectives, which depend on electric vehicles and electricity supply through micro-grids, are associated with energy storage—especially with batteries (Crabtree 2015). From this perspective, the anticipated future has many decentral elements, such as local generation through renewables and local consumption, i.e., security through autarky (Kalkbrenner 2019). By re-integrating energy-related activities into the daily praxis of users (or habits and routines), energy storage can be a driver for users to engage in energy transition, help form new relationships amongst energy actors, and establish new practices (Christensen et al. 2020; Kloppenburg et al. 2019).

Currently, electricity storage solutions do not render profits for users based on arbitrage-trading and time-shifting (Anuta et al. 2014; Burlinson and Giulietti 2017), as energy-only markets do not incentivize investing in energy storage (Gaudard and

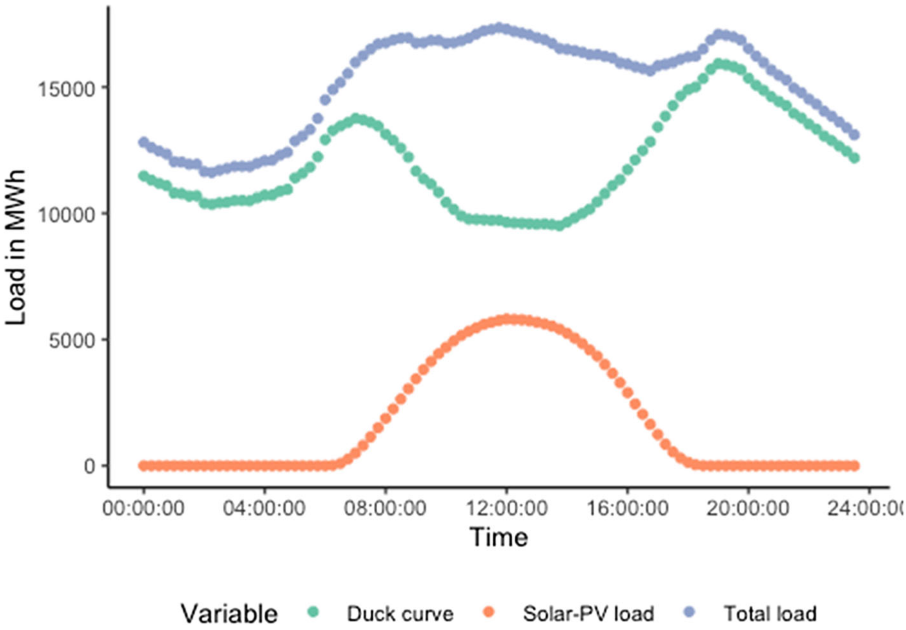

Fig. 3 Author's depiction of the duck curve based on data by German Federal Grid Agency smard.de. The duck curve depicts the gap of electricity supply due to solar PV on March 31, 2019. It consists of the total load minus the solar load

Madani 2019). This would require other revenue streams beyond those offered by the spot market, such as revenues for ancillary service and capacity provision (Waterson 2017), or new business models, such as virtual storage provided by aggregators (Castagneto Gissey et al. 2019). While virtual storage provision and other business models are increasingly established in some countries, it remains questionable if alternatives, as well as social and environmental consequences, have been sufficiently considered (Ornetzeder et al. 2019).

The current changes in the energy system through a sustainable energy transition indicate that the nature of innovating and diffusion of new energy technologies will possibly be different than for previous technologies due to the required accompanying institutional and infrastructural changes. Therefore, the following section will highlight some current research avenues that stress the complexities of energy innovation and transitions.

4 Innovation and energy

Most of the approaches presented below aim to answer the precise questions asked by Unruh (2002, 2000) about how to escape situations where countries, or the whole world (Unruh and Carrillo-Hermosilla 2006), are locked-in to using carbon-intensive energy technologies, such as coal and gas, seemingly incapable of substituting them with renewables. Carbon lock-in can therefore be specified as a particular type of path dependency, including infrastructural and technological as well as institutional and behavioral lock-ins that mutually interact with each other (Seto et al. 2016). The technical superiority of new technologies is not the only requirement for an energy transition, but rather, interactions amongst different actors with technologies play a role.

In this context, investigating flexibility options such as electricity storage requires a political economy perspective, placing a greater emphasis on features like power and institutions, but also on physical infrastructure. This is because they cannot be described as user technologies as, e.g., solar energy in the early stages but are both user technologies and supporting infrastructure that require changes on multiple levels to diffuse. As exemplified in the brief historical account in Section 3, physical/material constraints often precede socio-institutional changes and therefore techno-economic tipping points.

While energy systems and their transition were traditionally researched from engineering and economics perspectives, recently, more research is emphasizing the social dimension of energy (Miller, Richter, and O'Leary 2015). From this approach, energy systems contribute to every aspect of contemporary society and allow for its functioning. Historical research shows that there is a long account of deeply connected and intermeshed relations between energy and society (Hirsh and Jones 2014).

Adding to the brief history of energy in Section 3, many energy issues are uniquely complex compared with other (consumer) products and technologies. Therefore, the following section gives special focus to issues surrounding energy technologies. Notably, it unravels the issue of technology innovation systems and energy as well as the diffusion of energy technologies with a focus on social acceptance.

4.1 Technology innovation systems and energy

Early investigations of inducement mechanisms and blocking mechanisms for energy technology diffusion were the first studies from which TIS was developed. (Jacobsson and Bergek 2004; Jacobsson and Lauber 2006). However, the approach was explicitly reformulated to study the energy technology innovation system (ETIS) by a group of IIASA scholars to focus more on energy topics (Gallagher et al. 2012). As in the early phase of innovation studies (Schot and Steinmueller 2018), they mostly stressed the importance of R&D expenditure.

Regarding energy, globalized knowledge flows are transnational (Binz et al. 2016). However, locality and localizing effects are still central to globalized innovation systems (Schmidt and Huenteler 2016), where demand-side policies might even have negative effects on local TIS in a global innovation system (Hipp and Binz 2020). Likewise for multinationals, home or domestic markets are still critical for TIS (Crescenzi et al. 2015; Normann and Hanson 2018).

Ultimately, despite these attempts—as within STI policy (Schot and Steinmueller 2018)— sustainability issues are becoming progressively important for employing TIS (Markard et al. 2015) and have an overlapping knowledge base with economic geography (Coenen et al. 2012; Hansen and Coenen 2015). Increasingly, geographical circumstances play a fundamental role in understanding sustainable energy transition and are gaining more recognition in the literature (Bridge et al. 2013; Köhler et al. 2019; Lawhon and Murphy 2012). Regarding flexibility options, conventional energy storage technologies like pumped hydroelectric storages (PHS) or compressed air energy storage (CAES) need geological formations such as mountains and underground caverns. The development of other renewable energies such as wind and solar technologies is also heavily dependent on physical contexts and influences other flexibility options such as energy storage (Gaudard and Madani 2019).

Previous studies show embeddedness of innovation processes in different institutional arrangements and interconnection with physical energy technology infrastructure. For example, the virtuous cycle of cumulative causation for natural gas as an automotive fuel can build on existing infrastructure as a driver (Suurs et al. 2010). Carbon lock-ins (Unruh 2002) and an insufficient diffusion of renewable energy technologies are therefore closely related to the lifecycle of the innovation systems for fossil fuel technologies (Markard 2018b). Thus, the resistance and push-back of incumbents are a central element for TIS development.

Like technology diffusion processes, TISs also have life spans and undergo a lifecycle that emerges, grows, is stable for a while, matures, and then declines (Markard 2018b). This is important from a transition perspective, as certain technologies (e.g., coal) need to be phased out for a sustainable energy transition. Actors of incumbent fossil fuel technologies also shape the context around the innovation system of renewable emerging technologies.

In addition, context-dependent technologies that require local embedding diffuse slower than standardized technologies, which can be produced in series; for example, some heat-generation technologies tend to be more embedded than PV modules (Wesche et al. 2019). Additionally, technologies in very early development stages that are not ready to substitute the incumbents in the near future can still benefit from support networks (Musiolik and Markard 2011). Nonetheless, these technologies remain heavily influenced by alternatives already in place (Wicki and Hansen 2017). Thus, following Markard's (2018a) proposal for the new phase in energy transition, comparing the development of PV technologies (Shubbak 2019) is only likely to help with the first stages of a TIS, e.g., the TIS for energy storage technologies, and does not sufficiently explain successional diffusion dynamics.

An initial example that emphasizes the knowledge creation and diffusion processes already shows that sectoral configurations are particularly important for technologies such as batteries (Stephan et al. 2017). Haley (2018) re-introduces the notion of "structural tensions" as mismatches between an innovation and its wider sectoral system to deepen this approach.

Also, policy (mixes) can structure and "activate" innovation functions and "trigger structural change," innovation functions in turn influence policy; they mutually interact (Rogge and Reichardt 2016). These policies are then publicly legitimated reactions to issues in the innovation systems by the state (Rogge and Reichardt 2016; but also Jessop 2008). Legitimacy of technologies, in particular, as briefly touched upon above, is fundamental to their deployment (Markard et al. 2016) and is therefore one of the central and early researched central TIS functions (Bergek et al. 2008). This appears to be particularly important for value-laden technologies such as VRE that require for diffusion a vision for the future.

The financial system is one central field that can radically change the economy through infrastructure investment (Naidoo 2019). Currently, however, investment in a sustainable energy transition is insufficient (IEA 2020). While many are hoping for business to fill this gap, private investment is remaining low for reaching the 1.5 °C target as commercial initiatives mainly work when there is a profit to be expected. Often, however, no immediate profit can be expected from investment in energy innovations, which is why other short-term investments are more profitable (Malm 2016, chap. 15). One way forward is to qualitatively change the financial rules to steer private finance into green infrastructure investment (Naidoo 2019), e.g., by creating a common taxonomy for green finance in the European Commission (2020). Moreover, private initiatives are often small scale—a feature that is desirable to many advocates of energy transition—but often, infrastructure is needed in a scale that only public capital can provide (Jacobsson and Jacobsson 2012). An important financier of the transition is municipalities (Malm 2016; Villaraigosa et al. 2013).

Besides the issue of finance however, command and control are necessary to steer energy transitions (Malm 2016, chap. 15); otherwise, renewables remain merely an add-on, rather than a substitute for fossil fuels (Vinichenko 2018). Thus, governments remain the central actors able to block or enable the diffusion of renewable energy technology (Negro et al. 2012) and demand therefore particular attention.

4.2 Energy technology diffusion

Historically, diffusion dynamics differ between technologies. The overall duration from product invention to widespread adoption can vary from 20 to 70 years for electricity supply or end-use technologies (Gross et al. 2018). For electricity generation technologies, Gross et al. (2018) found that adoption could be subdivided into a first phase of invention-development-demonstration and a deployment-commercialization phase. The latter is the one that requires special attention in the second phase of energy transition where diffusion of renewables is scaled-up.

One explanation for the sluggishness of energy system transition is the long lifespan of energy-generation technologies (Bento and Fontes 2015; Gross et al. 2018). Economic viability and expected lifetime of incumbent and alternative systems is a highly relevant factor influencing technology substitution (Seto et al. 2016). Another explanation is that these products are not bought by end-users (households), but rather by firms, who tend to have a stricter cost-benefit rationale behind their innovation-adoption decision, thus less likely to contribute to diffusion dynamics resembling the S-curve (recall Fig. 1) (Day and Herbig 1990).

One way of researching diffusion of energy technologies is through the concept of *social acceptance*—a central approach in the energy social sciences literature. Social acceptance, a concept introduced to grasp possible resistance against new technologies and infrastructure, is an offspring of the concept of *public acceptance*. Using pejoratives like NIMBY ("not-in-my-backyard"), local resistance to projects has been investigated to ideally help foster the acceptance of these new technologies (Friedl and Reichl 2016; Wolsink 2000). By departing from this NIMBY perspective, with its clear pro-innovation bias and to take societal concerns and the complex interaction of adoption of new technologies more seriously, the concept of social acceptance was formed. Stressing the social dimension of technological innovation, Wüstenhagen et al. (2007) argue that the social acceptance of energy technologies is split into three dimensions: (1) community (local stakeholders, residents, local authorities), (2) market (customer, investors, inter-firms), and (3) socio-political (public at large, key stakeholders) (Wolsink 2018). Investigating all of these dimensions is equally important (Fournis and Fortin 2017).

Local resistance to technologies is often the response of local actors (such as businesses and employees) to declining technologies threatened by a newcomer (Markard 2018a). Studying social acceptance is becoming therefore more important in the next phase of energy transition. Up until now, social acceptance has been researched for different technologies including wind technologies (Khorsand et al. 2015; Liebe et al. 2017), infrastructure projects (Friedl and Reichl 2016; Komendantova and Battaglini 2016), and smart meters (Jegen and Philion 2017).

It is not only important for implementing renewable energy innovation but also for conventional ones like shale gas, as LaBelle (2017) shows for Poland. In addition, Devine-Wright et al. (2017) propose researching social acceptance of energy storage technologies as central technologies for the sustainable transition. A first deliberate approach to assessing social acceptance of energy storage was tested in the UK in 2017 (Thomas et al. 2019).

Essentially, the social acceptance perspective is a demand-side perspective that can be used to investigate the diffusion of (energy) technologies. It provides a clearer differentiation of demand-side factors than the already very thorough TIS literature can provide, as it considers different dimensions of social acceptance. Also, it accounts for the often-complex interactions when it comes to the diffusion of “controversial” technologies. Thus, it should be seen as a step further than the diffusion of innovation literature (following Rogers as described in Section 3) and used as an amendment to investigate technology diffusion systems. This can be seen as a first conceptualization-attempt to answer Bergek’s (2019) call for considering technology diffusion systems alongside TIS.

5 Synthesis

The vast body of literature on innovation identifies several mechanisms and phenomena of innovation development and diffusion. Both are clearly related, as the previously presented theoretical approaches show. Diffusion dynamics are context and innovation dependent but also dependent on how they are being developed. The technology innovation systems approach is one approach that successfully captures both these dynamics. It enables applied capitalism research under the premise that innovations are desirable. However, the approach tends to neglect the larger societal relations of power as well as dynamics within capitalism. While it considers the geographic dimensions and is not blind to history, it requires a stronger focus on political context and support systems for the capitalist production.

TIS in particular provides a useful holistic perspective that captures both diffusion speed and directionality of innovations depending on types of technologies, involved actors, networks, and institutions, and context factors. However, as shown above, the logics of capitalism and power relations that permeate the inner workings of TIS need to be stressed to strengthen the explanatory capabilities of the approach for researching transitions.

The brief history has shown that the energy system is deeply embedded in physical infrastructures, strongly connected with the global political economic system, and deeply structured by and structuring societal relations and culture. The upcoming changes in the electricity sector in particular show that social and political power relations are central for explaining its diffusion. Electricity grids as LTS are especially prone to inertia as they have a long history where power structures are manifested in the materiality of the physical infrastructure.

Energy TIS and the diffusion of energy innovation are a special case of innovation and diffusion and are increasingly treated in the literature as such. While the research of socio-technical energy systems can profit a lot from studying other non-energy technologies, the study of energy requires particular attention to some details: Although many elements are generalizable, the unique role of energy for society, its embeddedness into socio-institutional relations and physical infrastructure, make energy technologies special. The new phase of energy transition requires an even stronger consideration of these particularities.

Thus, researching energy flexibility options such as energy storage—both as infrastructure and user-products—benefits from amending the TIS framework. Therefore, the following three proposals for future TIS-related empirical work are proposed:

5.1 Physical-structure/nature as fifth element of a TIS

As argued above, physical nature is foundational for the development of innovation systems. While this point receives considerable recognition in economic geography and ecological economics and is already getting implicit attention in current innovation system analyses, the TIS framework should *explicitly* include physical-structure/nature as the fifth system element. This is necessary to embed the innovation dynamics within the physical system they are in.

For flexibility options such as energy storage, physical environments—such as mountainous areas—are likely to have an influence on various aspects of a TIS. This includes obvious functions such as market dynamics, but also the direction of search and legitimation and as a consequence resources availability need to be considered.

5.2 Including social acceptance in TIS to capture market diffusion complexity

The diffusion dynamics of innovative energy technologies are well researched in innovation studies. However, with the shift in the energy transition to scale-up VRE and the necessary deep structural changes in infrastructure, economy, and user behavior, the insights from the emerging study of social acceptance of renewable energies should be stronger integrated into the analysis. In TIS, this means re-evaluating the market function.

In particular, the social acceptance–amended diffusion theory from energy social sciences presented above, and the TIS framework from innovation studies, forms a conceptual duality whose combination appears beneficial for studying the next phase of energy transition. This allows for a distinction between innovation development and diffusion similar to the distinction between supply and demand. They are two distinct sides that form a duality—dualities and not dualisms in the sense of Giddens (1984)—of the same coevolutionary system; they are potentially spatially distinguishable, but always relative, since the local innovation system only overlaps with local social acceptance.

The scale-up of VRE requires an accompanying diffusion of flexibility options, such as energy storage. While VRE such as wind energy encounter various forms of resistance, for new forms of battery energy storage, this remains open. Also, grids as LTS are likely to influence the development.

5.3 Incorporating the wider political economy in TIS

The central role of state and policy in the conceptual TIS framework is receiving increasing attention. However, the wider political economy dimensions of policy intervention/state involvement require particular attention when it comes to the next phase of the energy transition. Therefore, power relations—such as between incumbents and insurgents—receive increasing attention as they determine the choice-set of other actor groups (e.g., consumers but also regulators). While networks have conventionally been considered explicitly in TIS analyses—e.g., by emphasizing the important role played by lobbying organizations—it is important to stress that power relations in networks rarely follow a top-down logic with states at top. More broadly, capitalism as a system tends to structure the inner working of the TIS (e.g., by defining worker-capitalist relations). This should be more explicitly addressed in TIS research to open up discourse on alternative economic systems beyond capitalism, as done by, e.g., degrowth scholars.

Including the wider political economy dimension for researching diffusion and innovation of new flexibility options can thus shed light on the importance of green-growth rationales and other motives for actors to engage in the field that lie outside the direct VRE-specific drivers. It improves the research on why—in the long run—certain development trajectories did or did not materialize.

6 Conclusion

This article sets out to identify the next research steps concerning the next phase of the energy transition. This phase is characterized by a scale-up of renewable energies beyond niches, by a demise of incumbent (fossil based) technologies, resistance by powerful industry and institutional actors, and the development and diffusion of new forms of infrastructure, such as storage, Thus, there is a multitude of structural factors and their dynamic interplay that our theoretical and analytical frameworks need to account for. Energy systems consisting of elements as the grid are deeply enrooted in physical infrastructure, dependent on geography and societal power relations and institutions. Clearly, past technological decisions matter for and foreshadow current and future energy system development paths. Thus, an analytical political economy perspective with a strong focus on historical materialism, physical structures, and power relations in the society is important for understanding the role of new technologies such as energy storage for the development of the energy system as a whole.

Also, researchers need tangible and managerial approaches for policy guidance, such as the innovation system approach, which illustrate how innovations and knowledge are created, diffused, and shaped, to identify pressure points for transition. Providing a theory of institutional change alongside diffusion pathways and dynamics, the proposed amendments are a useful way for further research.

As shown in this article, the second phase of the sustainable energy transition requires an evolutionary political economy perspective that accounts for the embedding in institutional, cultural, economic, and physical system structures. It requires the study of fundamental regime changes on multiple spatial, societal, and technological levels. Essentially, it must account for the deep structures and prevailing path dependencies, trajectories, and power structures within contemporary global capitalism. To do this, it requires an approach that moves beyond the supply side perspective inherent to evolutionary economics and comes to a coevolutionary understanding of political economy.

Three proposals for future empirical TIS research on the next phase of energy transition are presented: (1) inclusion of physical structure/nature as a fifth element of TIS, next to actors, networks, institutions, and technologies; (2) capturing complex diffusion dynamics in markets in TIS by including social acceptance; and (3) incorporating the wider political economy of power relations and capitalism in TIS.

As demonstrated in this article, many useful compatible theoretical approaches already exist that build on various research traditions and a plurality of methods from hermeneutics to qualitative empirical, quantitative empirical, simulations, deliberate methods, and the mixing of all the others. Evolutionary political economy should and will build on these strengths and provide guidance for the transformational challenges of our time. However, the conceptual considerations above remain theoretically and require further empirical grounding.

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