Curr Sustainable Renewable Energy Rep (2017) 4:181–190
DOI 10.1007/s40518-017-0088-y

Toward Deep-Decarbonization: an Energy-Service System Framework

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Abstract

Purpose of Review This paper reviews the historical and applied literature on energy transitions from an integrated system-level framework. We synthesize the literature using a simple energy-service system framework to highlight the main problems and possible pathways for a transition to a decarbonized energy system.

Recent Findings Recent literature suggests that the combination of demand-pull and technology-push policy instruments will be necessary to tip markets in favor of low-carbon energy alternatives. These studies illustrate that complex feedback mechanisms between the different components of an energy system, such as lock-in and push-back, complicate prescriptive policy design.

Summary The transition to a decarbonized energy system is one of the most pressing problems facing modern society. Energy systems are complex systems with many layers of feedback between social, technical, and institutional systems. Given these complexities, policy design and analysis must evolve to incorporate these feedbacks more explicitly.

Keywords Deep-decarbonization · Energy transition · Path dependency · Multi-level perspective · Energy-economy models · Energy economics

Introduction

Despite contemporary efforts to mitigate risks posed by global climate change, emissions of anthropogenic greenhouse gases have reached their highest levels in recorded history and show no immediate indication of slowing down on a global scale [1]. From a policy perspective, reducing greenhouse gas emissions can be achieved by either switching to low-carbon technologies or reducing the amount of fossil fuel energy consumed [2–4]. The scale of environmental risks, however, necessitates monumental changes in both social and technological systems to avoid significant environmental degradation [5]. This encompasses changes in energy use, innovation and development of low-carbon technologies, and broader changes in social, political, and economic institutions.

Relieving the environment of the stressors introduced by global reliance on fossil fuels requires the orchestration of a system-wide transition to a deep-decarbonized energy system. Historically, energy transitions occur over several decades as key transformational processes unfold and realign; a future transition to a decarbonized energy system is likely to be prolonged without additional assertive guidance and direction. Historical analyses illustrate the complexity of energy system transitions using a comprehensive qualitative framework, known as the multi-level perspective; however, the flexibility and comprehensiveness of this framework limits identification of the driving forces behind energy system transitions, limiting any attempt for policy prescription.

Driven by the inherent complexity of energy systems, analysts and policy makers generally rely on historical evidence and quantitative techniques for evaluating the potential impact of public policy on energy technology and fuel substitution, including the impact on broader market processes. In recent years, advances in computing power, data availability, and algorithmic design have permitted use of increasingly complex

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This article is part of the Topical Collection on *Energy Policy*

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simulation and optimization techniques in the evaluation of energy system transitions. Specifically, a general class of models known as energy-economy models augments existing historical energy transitions studies by approaching energy transition analysis using quantitative models that combine energy resource extraction, distribution, and consumption into a single framework. While these models have evolved over time to account for more realistic scenarios, quantitative approaches still fall short in capturing the full range of complex interactions between modern energy and market systems [6, 7].

Fundamentally, an energy system is a complex web of relationships between natural resources, physical infrastructure, production systems, scientific knowledge, and consumer practices. Changes in one component can influence the entire system in highly non-linear and unpredictable ways. Hence, steering the transition to a global, low-carbon energy system will require better knowledge of the correct levers to pull and by how much to pull them. The purpose of this review is to provide a unified framework that complements both qualitative and quantitative approaches for studying energy transitions. Motivated by this framework, we argue swift and expansive policy measures are needed to hasten global decarbonization and current policy-oriented studies tend to miss the mark on the importance of scale, complementarities, and feedbacks in energy systems [8–11].

The paper proceeds as follows. The "System-Level Approach" section introduces system-level analyses of energy transitions, primarily focusing on the multi-level perspective literature. The "Energy-Service System Model" section introduces the energy-service system framework using examples from the literature. We illustrate in the "Designing Policy for the Future" section how government policy can guide low-carbon technological change in an industrializing world. The "Energy-Economy Modeling of Energy Transitions" section provides a brief overview of energy-economy models and their benefits and limitations. The "Conclusion" section concludes.

The System-Level Approach

A variety of system-level perspectives have been developed to understand and frame the dynamic interrelationships between social, technological, and natural systems [12–15]. Arguably, the most commonly used framework in the historical energy transitions literature is the multi-level perspective (MLP). The MLP has been applied to analyze several technological transitions, e.g., the transition to steam ships, automobiles, and renewable energy technologies [12, 16–19].

The MLP organizes social and technological institutions into hierarchical constructs known as *niches*, *regimes*, and *landscapes*. Niches are the "protective spaces" that insulate entrant innovations from the competitive pressures of prevailing technological configurations [20–22]. Radical innovations occurring at the niche level are the sources of disruption that can potentially de-stabilize incumbent technologies. These protected niche markets permit innovations to develop to a point of cost-competitiveness with incumbent technologies, increasing the possibility of a transition [12].

Regimes represent the purposeful alignment of physical and institutional configurations to satisfy a particular societal function [12]. The mutual interdependency that results from alignment of these configurations tends to re-inforce prevailing technological trajectories via path-dependent processes, a key feature of the modern fossil-fuel-based energy system [23–25]. For niche market innovations to lead to a regime-level shift, innovative forces must be strong enough to push society to alternative pathways [26]. These regimes exert pressure on the lower, niche levels that lead to the development of radical innovations [27]. Importantly, technological transitions are characterized by shifts occurring at the regime level.

Landscapes are the macro-level, exogenous trends that exert pressures on prevailing regimes and niches [27]. A couple examples of landscape forces are demographic trends and environmental integrity. Changes at the landscape level can lead to pressure on regimes and niches falling under the landscape's umbrella of influence. Due to their size, landscapes take longer to transition than regimes or niches [12].

While the MLP is a flexible, comprehensive approach for studying energy transitions, some researchers have criticized the MLP for neglecting the role of consumer choice, government action, and entrepreneurship in technological transitions [14, 28]. Even though the MLP allows for the existence of markets as "rulemaking" institutions, which guide and re-inforce prevailing regimes, rational decision-making is underdeveloped in the MLP [27, 29, 30]. Thus, when market systems do not account for the environmental damages created by a fossil-fuel intensive energy regime, the MLP is a particularly silent source for understanding the appropriate pathways to achieve broader energy system transformations.

When it comes to managing the transition to the low-carbon economy, the failure of free-market institutions to provide adequate incentives for low-carbon technology adoption and consumption motivates the need for government intervention [31]. Consequently, unlike previous transitions, disruption of the technological trajectory of the entrenched fossil-fuel energy regime will require a beautifully orchestrated symphony of market reform mechanisms. Given the MLP is silent on the issue of market failures, an important question arises, what are the channels through which markets, policy institutions, and technology could drive the transition to a low-carbon energy system?

We address this shortcoming of the MLP approach by devising a framework that not only considers the technological configuration of an energy system, but its interaction with the prevailing market system. To differentiate this framework from the MLP, we introduce the concept of an *energy-service system*. An energy-service system represents the observed set of methods and designs that produce socially desirable forms of energy and the market systems that influence them [14, 32]. This interpretation is useful because the technological configuration of an energy system is independent of prevailing niches, regimes, or landscapes and provides a constant standard for comparison across time. Additionally, this framework aligns with recent evidence that suggests energy transitions have largely been catalyzed by novel combinations of energy sources and technologies to provide cheaper energy services to society [33].

The Energy-Service System Model

The technological configuration of an energy system is comprised of the primary energy sources and conversion technologies needed to produce a valued energy service, such as heat, power, or lighting [34]. Although seemingly more complex systems have emerged over time, this underlying structure has remained unchanged. By analyzing the technological configuration of an energy system together with the market systems in which transactions take place, i.e., an energy-service system, the framework we present below has the potential to inform on aspects of the low-carbon transition where the MLP approach is silent.

The core logic of the energy-service system model is that decisions are costly, and thus the source of change in this model is in the market system's ability to alter the relative cost and benefits of a low-carbon energy system versus maintaining the status quo. A market system (markets) is a complex network of buyers and sellers who trade goods and services with each other. Like other markets, in the market system for energy, interactions between the supply-side and the demand-side determine the pricing of goods and services and the allocation of scarce resources amongst agents. Ultimately, market prices provide the incentives that guide decision-making and give rise to the technological configurations found in society throughout time. However, prices do not capture the costs of environmental degradation and are lower than a welfare-maximizing market institution would dictate. Hence, without additional correction to these failures, only scarcity is priced by the markets, providing little incentive to de-carbonize the global energy system.

While most energy systems are comprised of multiple subsystems, the energy-service system framework presented in this paper focuses on the relationship between energy technologies and market systems. These relationships are summarized in Fig. 1. The technological configuration of an energy system is made up of energy sources, conversion technologies, and energy services. Energy sources are combined with conversion technologies to provide useful energy services to consumers. The market system is composed of a market for each component of a technological configuration. These markets interact directly with each other through social and technological institutions, as highlighted by the direct linkages between them. Most importantly, however, these markets interact indirectly with each other through the structure of the technological system, where markets within a configuration are complementary and markets across configurations are substitutes.

At the top level of the system, supply-side and demand-side pressures are exerted on the energy-service system. For example, on the supply-side, extraction costs and transportation costs exert pressures on existing markets by expanding the economic abundance of an energy source [35]. On the demand-side, preferences for higher quality fuels and environmentally friendly technologies introduce pressures for the development of new products and technologies. Given the interlinked structure of the technological system, information between markets flows either downstream from supply-side pressures or upstream from demand-side pressures, such that a change in any one component, under the right conditions, can alter the entire system state. In the next subsections, we introduce some examples of these pressures and frame them in the energy-service system framework.

Examples of Supply-Side Pressures

At the turn of the eighteenth century, coal mining in Britain relied on animal and human power to pump water from mines, where the latter was an expensive option given the high wage rates in Britain at the time [36, 37]. This likely incentivized coal producers to adopt the Newcomen and Watt engines in the eighteenth century. Referring to Fig. 1, the introduction of steam engines represented a supply-side shock that allowed producers to reach deeper reserves of coal ($E1$) at a lower cost [36]. This affected the coal market (M_{E1}) by reducing the relative cost of coal to alternative energy sources, such as wood ($E2$). The new information about the relative price of coal to biomass then translated to the market for conversion technologies, given the connections in Fig. 1. In the market for conversion technologies (M_{C1}), coal utilizing technologies ($C1$) gained an advantage over competing technologies ($C2$) leading to higher adoption rates. Ultimately, these feedback channels led to a larger market for a coal-based energy-service system after the supply-side shock induced a lower price for coal-based energy services ($S1$).

Similarly, the current shale gas revolution, driven by innovations in horizontal drilling and hydraulic fracturing techniques, has increased the natural gas supply in the USA to nearly 3 trillion cubic feet. Referencing Fig. 1, the shale gas revolution has essentially followed a similar process as the coal revolution in the UK. Innovation occurring in the

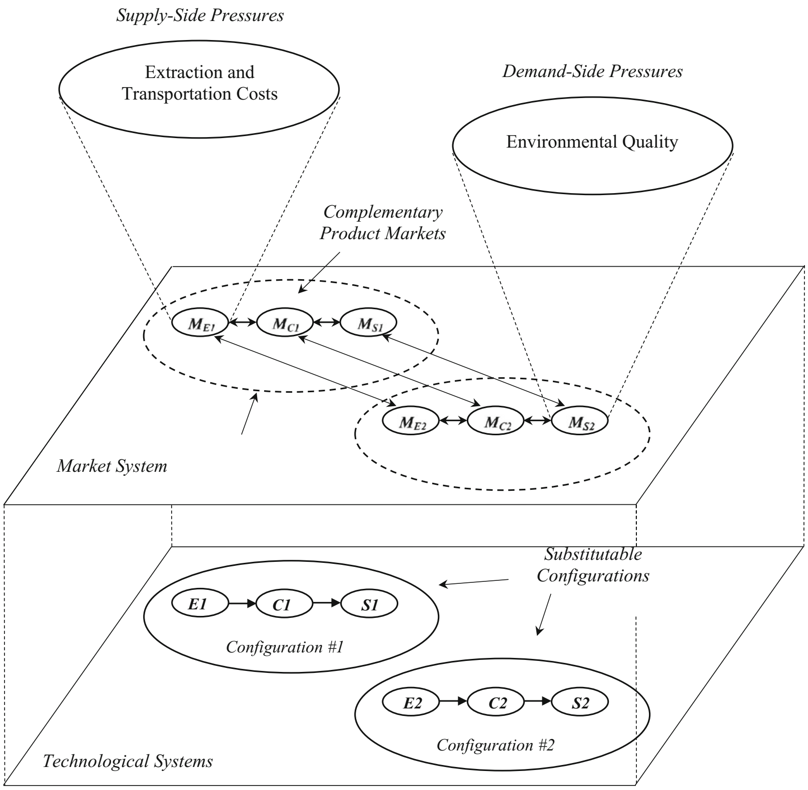

Fig. 1 The energy-service system. Figure is based on the multi-level perspective hierarchy [15]. The lowest level of the system represents the technological configuration of an energy system. In this level, alternative technological configurations combine primary energy sources, denoted as *E1* and *E2*, with conversion technologies, *C1* and *C2*, to produce an energy service *S1* and *S2*, respectively. The boundaries of each technology are represented by the circles. Each component of the configurations is linked with the respective markets in the top layer of the figure. Markets for the components are denoted by *M*. Markets that are present within the boundaries of a technological configuration are linked based on complementary relationships. However, the connections between markets can cross over these boundaries because of the substitutable nature of the two technological configurations. Finally, supply-side and demand-side pressures influence the outcomes of the markets for the technological components

supply-side of the market (M_{E1}) has lowered the relative price of natural gas, which in turn has reduced the price of generating electricity from natural gas sources (M_{C1}), leading to more widespread adoption of natural gas generation technologies [38].

Another supply-side pressure on the market system is variations in transportation costs. Traditionally, energy-service systems have relied on the natural resources readily available to humankind. Where large-scale transportation systems are either non-existent or transportation is too costly, the energy sources used in energy-service systems are constrained by the proximity of consumers to these sources [39]. In the early periods of human development, fire-making techniques relied on local floral growth to provide valuable services such as heating and lighting [40, 41]. In a modern context, impoverished households in rural China with limited access to energy infrastructure rely on local energy sources, such as wood, straw, and biogas, to satisfy a variety of household functions [42]. Hence, the cost of accessing energy sources weighs heavily on the choice of energy-service systems.

The role of transportation costs is also evident in the co-development of energy and industry infrastructure. In the USA, when hydroelectric plants were developed, local industries benefited from access to cheaper, higher quality electricity. As long-distance transmission lines and coal and natural gas plants spread throughout the USA, being near hydroelectric plants was no longer needed; in other words, industries were no longer tied to the location of power. This allowed industries to locate closer to other input sources, increasing industrial productivity [43]. Similarly, in the sixteenth century, when coal was introduced in England to replace wood, the location of economic activity moved north, closer to the coal sources. However, as canals and railroads spread through the UK, industries were no longer tied to the location of energy sources, and they began to locate in places that offered comparative advantage in other dimensions, e.g., access to markets [44].

As shown in these examples, pressures originate in the energy source market and propagate downstream to energy-service markets, lowering the energy service price. Because conversion technologies are tied to specific energy sources, the lower energy service price encourages adoption of the conversion technology, creating positive feedback between complementary markets. As the examples above suggest, for deep de-carbonization, supply-side innovations are necessary to make low-carbon technologies cost-competitive with fossil fuel alternatives [45].

Examples of Demand-Side Pressures

In the energy-service system, demand for energy services translates into a demand for energy sources due to the technological configuration of the system. Like the supply of energy sources discussed above, there are many factors that influence the demand for energy services. One demand-side pressure highlighted in the literature is the quality of an energy service. Historically, as global real income increased, both producers and consumers developed preferences for higher quality fuels, and these evolving preferences ultimately shaped the configuration of the energy-service systems in place in the modern world. Presently, the environmental quality of an energy service is most relevant for a low-carbon transition. If a service is of higher environmental quality, in that it produces less environmental externalities, ceteris paribus there will be a larger market for that good when consumers have a higher willingness to pay for environmental quality.

Energy sources differ in their chemical composition and, subsequently, in their energy and carbon densities. Historically, these differences have influenced the adoption of energy sources in different ways. Starting with bread and beer making, the use of coal soon spread to glass-making and eventually iron and steel. In the eighteenth and nineteenth century iron and steel industries, coal's displacement of biomass energy sources was, in part, driven by coal's advantages in production, storage, and transportation due to its higher volumetric energy content [46, 47]. However, broad diffusion of coal in iron and steel production was limited until the introduction of quality control techniques in the middle-to-late eighteenth century.

The story is similar for urban coal consumption during London's population boom in the early-to-middle sixteenth century. Rapid population growth in the city strained the local supply of wood fuel and necessitated transportation of wood from greater distances, thus leading to a doubling of the price of wood per unit of energy [48, 49]. Coupled with the relative advantages offered by coal's energy content, which translated into lower transportation costs, the relative price of coal was much cheaper than that of wood fuel in the late sixteenth century. However, widespread diffusion was limited until significant innovation in housing design, mainly after the introduction of chimneys and grates, took hold in early the seventeenth century [36, 37]. Showing the long lasting effects of seemingly minor modifications in society, inexpensive coal at the time encouraged expansion of inefficient building designs based on coal, which still persist today [50].

Coal's relative chemical advantage helped fuel the transition from biomass to coal in the iron and steel industries during Britain's energy transition, but with fossil fuels, higher chemical energy density is associated with a higher carbon density. In the case of coal, high-carbon content acted as a limiting factor in its expansion and diffusion in some sectors. For example, as coal gained prominence over wood fuel in London for residential heating services, the city experienced a drastic decline in local air quality, which likely increased mortality rates in the city [37, 51, 52]. During this time, the market system provided little incentives to switch to higher quality fuel sources, since cleaner energy sources, such as anthracite coal, commanded a higher price in the market. It was not until anthracite coal became cost effective that energy-service systems were designed to utilize this fuel source. The urgency of the future energy transition toward a decarbonized system requires swift, coordinated action to incorporate environmental considerations in the daily choices of individuals in society.

By discussing the literature through the lens of the technological configuration of the energy system in congruence with the respective market system, an energy-service framework emerges. Through this framework, overcoming market failures and de-carbonizing energy-service systems requires assertive pressures to be applied to the market system. When pressures are applied in one market, the technological configuration of the system re-directs the flow to affect the whole system. Thus, by using the energy-service system as shown in Fig. 1, policymakers can identify where to apply pressure and, more accurately, determine how much pressure is required to create positive feedbacks throughout the system.

Designing Policy for the Future

Broadly, the future low-carbon energy transition will require two distinct regime shifts: (i) a shift of post-industrialized, stable regimes in developed countries and (ii) a shift of emerging, possibly more flexible, regimes in developing countries. These two broad categories of regimes have historically differed in both the availability and supply of energy, the necessary supporting infrastructure to exploit energy sources, and their demand for energy services [53]. The barriers that must be overcome to establish a stable, deep-decarbonized energy system depend on the state of the existing regime and exemplify the need for diverse policy measures and international coordination.

Post-industrialized Economies

Mature regimes in post-industrialized countries are based on the use of fossil fuels and represent a legacy of large-scale investments in complementary energy infrastructure and technology. Scale economies, knowledge spillovers, and network externalities have contributed to mutually reinforcing economic, political, and technological barriers that "lock-in" fossil-fuel systems [23, 24, 54, 55]. Further, incumbent fossil-fuel technologies may benefit from new ideas introduced by entrant low-carbon technologies and push to remain competitive by developing new business strategies to maintain market share [56, 57]. Hence, the combined forces of lock-in and push-back necessitate a diverse array of policies to destabilize the existing fossil-fuel regime [26].

In post-industrialized economies, if innovators are profit motivated, then innovation activities are directed toward the larger, incumbent fossil-fuel energy-service system, causing further lock-in the fossil-fuel regime in the long run [58]. Additionally, if innovation is the locus of change in the energy-service system model, then destabilizing locked-in, existing fossil fuel regimes will require support for the development of novel, substitute low-carbon technologies. From this perspective, when markets provide little incentives for private research and development (R&D) in low-carbon technologies, governmental institutions can increase investment through policy initiatives that support development of low-carbon technologies.

Considering technical change as an endogenous factor in models used to analyze optimal policy intervention has the potential to greatly change the results of models that treat technical change as an entirely exogenous factor [59]. While economists have begun to analyze optimal policy intervention in a transition to clean technology in the presence of path dependency and directed technical change, this nascent and critically important literature has room to grow [58–61••]. So far, this research has found that a combination of research and development and carbon taxes are critical factors of optimal policy design to overcome lock-in in developed countries and tip the scales in favor of adoption of low-carbon technologies in developing countries. With the correct policy mixture, existing regimes can be destabilized and a new, low-carbon regime can reach a point of positive feedback and stability.

Climate change policy can include many different instruments that are designed to reduce environmental damage. These policies come in two flavors: command-and-control regulations or market-based instruments. Command-and-control regulations mandate producers to meet specific performance targets or invest in particular low-carbon technologies; in contrast, market-based policies, such as cap-and-trade, carbon taxes, or R&D subsidies, establish a specific market price for activities that either contribute to or avoid damaging the environment [31]. Naturally, market-based instruments raise the price of high-carbon sources relative to low-carbon counterparts, which leads to an increase in carbon intensive energy prices. A variety of studies that examine the relationship between climate policy, prices, and innovation find more stringent environmental policy and higher energy prices are followed by a non-trivial increase in low-carbon innovation activities [62–65]. Additionally, when the outcomes of R&D are highly uncertain, which is especially true during the early stages of a technology's lifecycle, government sponsored research programs can facilitate the transfer of niche products from basic research to the commercialization phase [66].

If new competition from low-carbon niche technologies forces incumbent fossil fuel technologies to invest in strategies to remain competitive, and the consumer adoption decision is determined by the relative prices of two competing technologies, then diffusion of low-carbon technologies is likely to be a gradual and slow process. Without additional policy support for uptake of low-carbon technologies, fossil fuel technologies may continue to enjoy their relative price advantage as producers seek new ways to improve performance considering the new competition from low-carbon alternatives. Hence, taxes and subsidies can be used to adjust these prices to favor low-carbon technologies and accelerate uptake in the market.

Emerging Economies

World energy consumption is forecasted to rise by around 50% in the next 25 years, as large countries like China, India, and Russia continue to industrialize and develop [67]. Largely void of large scale, fossil fuel infrastructure, developing countries are not necessarily subject to the same lock-in and push-back forces experienced by countries with mature fossil-fuel markets, infrastructures, and technologies. In contrast, industrializing and developing countries can take advantage of their development status and learn from the successes and failures of early adopters of low-carbon technology and policy to effectively "leap-frog" fossil fuel-based energy systems [68, 69•, 71]. However, additional impediments in developing countries, such as weak, or fledgling financial institutions or political corruption, may introduce new frictions for financing of large-scale low-carbon development projects and thus impede progress toward developing a low-carbon energy system [72].

The transfer of low-carbon, environmentally friendly technologies from developed to developing economies is an important feature of international environmental agreements, such as the Kyoto Protocol, but a fiercely debated topic in the recent Paris Climate Agreement [73]. While technology transfer is a somewhat ambiguous terminology, the concept encompasses the transfer of a range of knowledge and physical capital transfers between developed and less developed countries. A few studies have examined the international diffusion of environmental technologies. These studies suggest that international transfer of best-practice environmental regulations is a pre-requisite for successful adoption of environmental technologies from the world frontier [62, 74, 75].

For a global, low-carbon energy transition to take hold, energy policy in the developing world must be designed to take advantage of the early stages of development and bypass the entrenchment stage of large-scale, fossil-fuel dependent energy systems [25]. As nations advance in material welfare, market and political institutions also tend to become more inclusive and participatory in their structure; but, in theory, by introducing protectionist, anti-competitive, niche *imitation* strategies in the early stages of growth, developing nations can exploit frontier technologies to establish new technological regimes and experience more rapid growth rates in early development periods [76, 77]. This is commonly referred to as the “advantage of backwardness” [78]. However, for this strategy to be viable, developing countries must rely on international low-carbon technology transfer as a critical pathway for transitioning emerging regimes to a primarily low-carbon composition.

Energy-Economy Modeling of Energy Transitions

Due to a dearth of data for historical energy transition analysis, policymakers turn to a variety of quantitative approaches to forecast the impacts of alternative energy policy scenarios on energy resource consumption and technology choice. These approaches fall under a collective classification of models known as *energy-economy* models. Energy-economy models explicitly model the interactions between energy technologies and market systems and are generally divided into three categories of models according to the detail by which the interactions within the energy-service system are structured. The general classifications are typically divided into (i) bottom-up, (ii) top-down, and (iii) hybrid approaches. Overall, these classifications are special cases of the energy-service system framework.

While energy-economy models have increased in detail and sophistication over time, the oldest class of models is known as *bottom-up* approaches. The bottom-up approach is a *partial* equilibrium representation of an energy-service system and features a wide-range of technologies to capture the technological richness of the energy supply-side and demand-side components. Technology and fuel choice is cast as a cost-minimizing optimization programs, such as in the ETA, MARKAL, and MESSAGE models [79]. However, despite the technological richness of these modeling approaches, conventional bottom-up modeling generally neglects finer details regarding consumer behavior and broader market transformation [80–82]. Hence, application of these models has limited utility in determining the set of optimal policy instruments that would be required for a system-wide push to de-carbonization since, by design, they favor technology-based standards.

In contrast to conventional bottom-up approaches, *top-down* approaches represent energy market systems in a *general* equilibrium framework but lack explicit characterization of technological configurations of an energy system found in conventional bottom-up approaches. Top-down approaches tend to approach the energy-service system from an economy-wide perspective, and thus feature a highly aggregated level of analysis at the technological level. In most models, energy technology characteristics and technology adoption decisions are governed by aggregate parameters that proxy substitution between technologies and their characteristics. Governed by the choice of these parameters, aggregate system-wide technological changes do not afford much detail in terms of the microeconomic processes that dictate consumer and firm-level technology choice [59]. Consequently, the top-down approach’s focus on aggregate system changes comes at the expense of exploring the impact of alternative policies on substitution between alternative technological configurations of an energy system. Even more, the orientation of top-down models to aggregate market-driven processes limits policy analysis to market-based instruments [6].

In recent years, many analysts have recognized the limitations of conventional bottom-up and top-down approaches and have developed an alternative approach to bring energy-economy modeling closer to a fully integrated energy-service system framework [83, 84]. This class of modeling known as the *hybrid* approach combines the technological richness of bottom-up models with the market-oriented perspective of top-down approaches. The result of this combination is a richer characterization of feedback channels between technological and market systems that permits analysis of a broader array of policy instruments, i.e., combinations of technology-push and demand-pull policies. However, due to the intensive data requirements of the hybrid approach, most studies tend to narrowly focus on single sector analysis, e.g., the electricity sector, and neglect heterogeneity across other sector’s technology choices [85, 86].

The hybrid energy-economy approach is arguably the most comprehensive quantitative approach for analyzing the role of policy in catalyzing energy transitions. However, most studies focus on single-policy scenarios or single sector impacts. The energy-service system framework exemplifies the need for a broader set of policy instruments to de-carbonize the global energy system. Given the complexity of existing, combined bottom-up and top-down approaches, the energy-service system framework simplifies the dynamics at work so that policymakers and practitioners can glimpse into the black box of hybrid energy-economy modeling [87].

Conclusion

The transition to a low-carbon energy system has already been set in motion [88]. Given the urgency of the task, the set of questions for researchers is how to optimally guide the transition, overcome any social and technological impediments, and influence the speed of the transition using policy intervention.

Unfortunately, policy analysis is usually narrowly focused on individual sectors or technologies. As economists and policymakers analyze the role of policy intervention in guiding a low-carbon energy system transition, it is important to consider the strong interdependencies established by the energy-service system framework.

For deep de-carbonization to occur, policy interventions need to be swift and expansive. While there is a role for incremental efforts, overcoming carbon lock-in and push-back requires a large shock to the system [24]. For these shocks to be most effective, they need to occur on both the supply-side, influencing the markets for energy sources (M_{E1}), and on the demand-side, influencing the market for energy services (M_{S1}) to be most effective. Subsidies for consumption are needed to pull for a cleaner energy system, but an effective policy portfolio should include taxes and standards for the supply-side so that energy producers begin to push for a decarbonized energy system [58, 60••]. Finally, subsidies for innovation need to be all encompassing, creating the incentives to invest in new technologies that would facilitate the transition to a low-carbon energy system.

Going forward, the energy transitions literature must first take stock of where we are in terms of active policies, the development and diffusion of existing low-carbon technologies, as well as continue to study the role that markets play, especially in situations where path dependency is present [89–93]. Research needs to further its understanding of deep de-carbonization within an energy-service systems framework to hasten the future transitions [68, 94, 95•]. In particular, we must identify which limitations are currently present or may arise along the path of transition, such as technological, infrastructure, or labor constraints [70•, 96, 97].

Compliance with Ethical Standards

Conflict of Interest The authors declare no that they have no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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