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The Energy Technology Innovation System

Kelly Sims Gallagher,[1] Arnulf Grübler,[2] Laura Kuhl,[1] Gregory Nemet,[3] and Charlie Wilson[4]

[1] The Fletcher School, Tufts University, Medford, Massachusetts 02155; email: kelly.gallagher@tufts.edu, laura.kuhl@tufts.edu

[2] International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria; email: grubler@iiasa.ac.at

[3] La Follette School of Public Affairs, University of Wisconsin, Madison, Wisconsin 53706; email: nemet@wisc.edu

[4] Tyndall Centre for Climate Change Research, University of East Anglia, Norwich NR4 7TJ, United Kingdom; email: charlie.wilson@uea.ac.uk

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Abstract

This article reviews the concept of an energy technology innovation system (ETIS). The ETIS is a systemic perspective on innovation comprising all aspects of energy transformations (supply and demand); all stages of the technology development cycle; and all the major innovation processes, feedbacks, actors, institutions, and networks. We use it as an analytical framework to describe key features and drivers of energy innovation. A global snapshot of the ETIS is provided using investments as the main indicator. Rationales for government policy in energy innovation are discussed, and policy design guidelines for an effectively functioning ETIS are presented. The proposed guidelines are based on a survey of the literature and empirical case studies; they diverge substantially from polices implied by partial perspectives on innovation. Key research, information, and data needs are also identified.

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1. INTRODUCTION

This article presents the current understanding of the energy technology innovation system (ETIS). It highlights developments in the field since a 2006 article was published in the *Annual Review of Environment and Resources* (1)

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and particularly emphasizes the systemic nature of energy innovation. This review draws on material prepared as part of the 2012 *Global Energy Assessment: Toward a Sustainable Future* (2) and *Energy Technology Innovation: Learning from Historical Successes and Failures* (3).

Innovation is essential for addressing most challenges related to the extraction, processing, and use of energy, including: energy security, energy poverty, air and water pollution, and global climate change. All these challenges call for improved technologies of energy use (better efficiency) and supply and conversion (less-polluting energy sources). Energy innovation results from research, development, demonstration, and deployment efforts driven by collective learning processes involving both suppliers and users of technologies. These dynamic processes operate within specific contexts and incentive structures. The ETIS is the application of a systemic perspective on innovation to energy technologies comprising all aspects of energy systems (supply and demand); all stages of the technology development cycle; and all innovation processes, feedbacks, actors, institutions, and networks. This review provides a systemic approach that offers new insights that complement and improve upon more narrowly focused, fragmented analytical approaches and technology policies published in the scholarly literature to date.

In this article, we begin in Section 2 by establishing the concept of an ETIS and how it relates to the scholarship on energy innovation more generally, and we explore the key features and functions of the ETIS. In Section 3, we quantify the global ETIS, using investments as an indicator, to provide a global snapshot of current energy innovation efforts. Next, in Section 4, we articulate the main rationales for government policy to support the ETIS, and then turn to policy design guidelines for an effective ETIS in Section 5. Section 6 provides a synthesis of key research, data, and information needs. An overall summary and conclusions are included in Section 7.

2. THE ENERGY TECHNOLOGY INNOVATION SYSTEM

2.1. Innovation and Technological Change

Joseph Schumpeter called technological change "new combinations of productive means" (4, p. 66). Technological and congruent institutional and social changes have been widely recognized as major drivers of long-run economic growth (5–9), as well as of broader societal development (10). Innovation in energy systems determines which energy services are available, how efficiently energy services can be provided, at what costs, and with which associated externalities. Scholars agree on the importance of innovation in energy technologies during the past 200 years and its impact on social and environmental outcomes (e.g., References 11–15). Innovation can result from both "push" and "pull" influences, where push can be thought of as resulting from investments in the inputs (e.g., human capital, funding) to the innovation process, and pull from the market or government-induced demand (see References 16 and 17 for discussions of the role of the market).

Three grand patterns of innovation in energy technologies have been observed. First, the transformative power of technology arises from combinations of technologies (clustering) and applications of technologies outside their initial sector/use (spillovers).

Second, continued improvements in technology performance and costs result from both innovation efforts and market deployment ("learning"). Improvements and knowledge about possibilities and applications accumulate, generating further learning economies as the application range grows (18). These processes create powerful self-reinforcing mechanisms that can lead to "technology lock in" (e.g., References 19–23). New technologies, even when economically viable, typically face higher short-term adoption costs compared to established technologies (23, 24). Only after an extended period of experimentation, learning, and improvements, and the establishment of an

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industrial base do new technologies become capable of competing with existing ones on a pure cost basis.

Third, relative to other sectors, rates of innovation in energy systems remain slow, with technological transitions spanning several decades up to a century (see Reference 25). Four factors explain the slow rates of change: capital intensiveness, longevity of capital stock, time needed for learning and experimentation, as well as clustering and spillovers (26–28). Pervasive technological transformations thus require a long-term view, implying a need for both prompt action and sustained effort.

2.2. Understanding the Energy Technology Innovation System

The ETIS applies a systemic perspective to energy innovation (10, 29–33). Models of innovation typically highlight the various stages of innovation, and the interactions and feedback loops between these phases. In **Figure 1**, the innovation process begins with research and proceeds to development, demonstration, market formation, and diffusion. A successful technology eventually diffuses throughout the economy, but all eventually are modified or die, hence the term life-cycle model of innovation. Of course, most technological innovation is actually the product of combining existing technologies in different ways, "combinatorial evolution" (34).

This interactive view, often referred to as the "chained-linked" model of innovation, is a significant improvement over traditional "linear" models of innovation that assume innovation stages follow each other seamlessly. The systemic approach emphasizes that innovation is a collective activity involving many actors and knowledge feedbacks and that innovation processes are influenced by their institutional settings and corresponding incentive structures, including the market as well as government

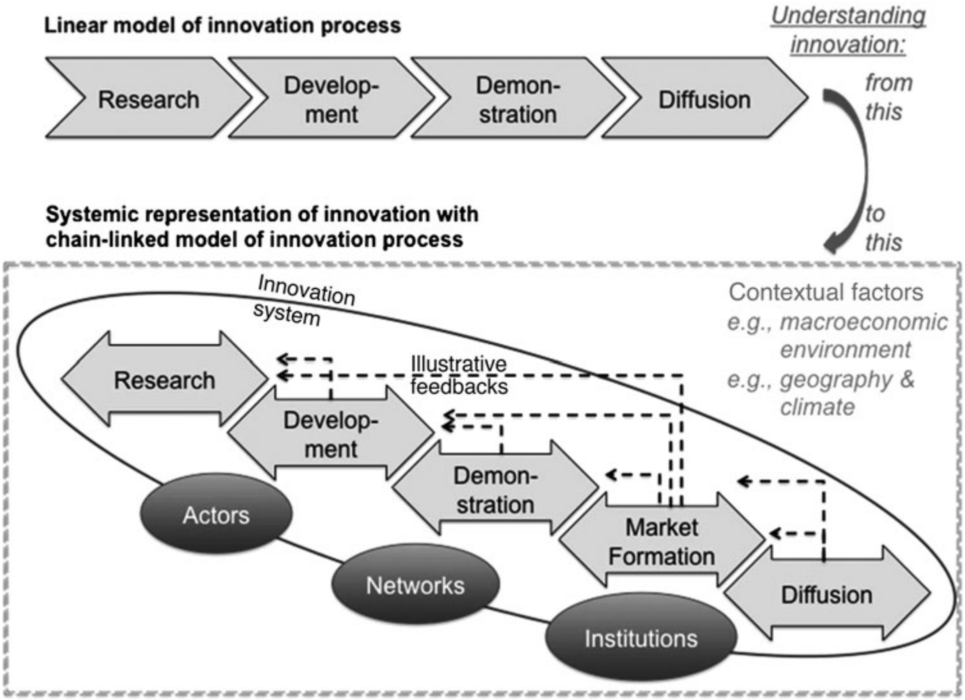

Figure 1

The evolution of thinking on innovation processes.

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policy (35–37). All of the actors and processes operate under conditions of uncertainty (38).

Analysis of the innovation system thus involves examination of data on the various stages of the innovation life cycle as well as study of the processes and mechanisms at work within the system, including the roles of actors, networks, and institutions. Different inputs into the innovation system, outputs of the system, and outcomes that result from the system can also be analyzed. Examples of inputs are human resources or financial investments; examples of outputs are patents or installed capacities; and examples of outcomes are changes in the carbon intensity (carbon emissions/gross domestic product) of an economy or productivity effects. For a detailed discussion of the inputs, outputs, outcomes analytical framework, please see References 1, 2, and 39.

The ETIS framework arises from empirical studies of energy technologies, including innovation histories and case studies of processes, such as learning, and the role of actors and institutions, such as public policies. Analysis of the global energy system requires data about, and understanding of, both the energy supply side and energy demand side, different energy technologies, and developed and developing countries.

The various components of the ETIS described in this review characterize what is understood about successful innovation, as well as what may be missing in cases of failed innovation. We use available evidence to abstract general guidance for policy makers rather than offering specific, universal prescriptions. Testing, critiquing, and improving the ETIS perspective is of critical importance and a key area ripe for further research.

2.3. Features of the Energy Technology Innovation System

Three key features of the ETIS are emphasized here: (*a*) knowledge and learning, (*b*) economies of scale, and (*c*) the roles of actors and institutions.

2.3.1. Knowledge and Learning. Creation of new knowledge is a powerful driver of innovation. Technological knowledge can be basic (know why) or applied (know how), as well as publicly available (e.g., through scientific or engineering journals) or tacit (e.g., accumulated experience of a production engineer). Knowledge is largely a public good. Once produced, it is difficult to control or restrict its use. The phenomenon of the non-appropriability of knowledge (40) can result in underinvestment in knowledge production on the part of the private sector (41), bolster the traditional argument for public-sector support for generation of new knowledge (42, 43), and support efforts to capture private research and development (R&D) returns through intellectual property right protection systems.

Next to traditional mechanisms of knowledge generation, such as R&D, knowledge transfer (spillovers) between different application fields, actors, and countries (30) are also essential. For energy technologies, the feedback processes from application experience to redesign and engineering have been particularly important (see, for example, Reference 44). Knowledge spillovers generally positively impact growth and productivity (45, 46), but with highly localized geographic effects (47).

Much knowledge remains tacit (or uncodified) in the form of personal or institutional knowledge and skills. In these cases, knowledge generation requires accumulation of experience (29), which must be achieved locally and cannot be entirely substituted by "imports." Generally, new knowledge tends to be less codified, making it more difficult to reproduce, memorize, recombine, and learn, which in turn makes it costly to transfer (48).

Empirical studies have shown the importance of knowledge spillovers in new energy technologies, particularly in the cases of photovoltaic solar energy (49, 50) and wind energy (50, 51). By stimulating public and private R&D in a broad base of industrial sectors and by simultaneously creating incentives for niche market deployment, the Japanese Sunshine

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Program for photovoltaic energy triggered positive feedback mechanisms, including R&D, knowledge spillovers, market growth, and price reductions (49). Denmark's success with wind energy involved not just R&D, but also the facilitation of feedback between users and producers of wind turbines (52). This positive feedback process, based on inter- and intrafirm knowledge spillovers, can potentially augment an industry's capability of knowledge production (43).

Processes of learning are also essential for the development and introduction of new technologies and their continuous improvements (53). Cost reductions are often illustrated by learning or experience curves, where changes in unit cost are presented as a function of cumulative production (54). This concept has been widely used to simulate the cost reductions that can be expected from programs that subsidize the demand for new technologies (55–57). Although useful, there are misconceptions about how to use and interpret learning curves (see References 58 and 59). For instance, a popular misinterpretation is that policies can simply "buy down" (e.g., Reference 60) technology costs through one-sided demand-pull policies without due regard to the equally needed supply-push innovation policies. Other pitfalls are the assumptions that learning can be anticipated (i.e., forecasted) and that learning invariably leads to cost reductions (see, e.g., References 59 and 61).

Indeed, it is important to recognize that technological knowledge can be accumulated (learned) but equally lost (unlearned). Knowledge depreciation particularly affects settings in which knowledge remains largely tacit and where the holders of knowledge (people) leave a firm or university setting, or are focused in different directions. A second type of depreciation occurs as old knowledge becomes obsolete. Knowledge can depreciate because of insufficient "recharge" (62) in cases where innovation proceeds rapidly, old technological knowledge is no longer relevant, and new learning cannot proceed quickly enough. The available literature suggests typical knowledge depreciation rates of 10%–40% per year in industries comparable to energy where innovation plays a significant role (49, 63–65). Given such high rates of knowledge depreciation, continuous knowledge recharge becomes extremely important. In the case of erratic stop-and-go policy support for knowledge generation, knowledge depreciation rates can outweigh knowledge recharge rates. This provides an important argument for prioritizing stability and the gradual expansion of inputs to the ETIS over crash programs that may not be sustained over significant time periods.

2.3.2. Economies of scale. Economies of scale describe reductions in unit costs as unit size or production expands. Larger devices or production facilities allow fixed costs to be spread over larger units or more units. Scaling up production improves payoffs to investments in standardization and automation. With larger volumes, the prices of some inputs through buying in bulk or making long-term purchasing contracts may be reduced as well. Large, centralized energy supply technologies, such as electric power (e.g., Reference 66) and petroleum refining (67), have historically achieved large cost reductions through economies of scale. Ultimately, diseconomies of scale can result in the case of complex technologies close to the unit scale frontier, such as nuclear reactors (68). Conversely, distributed smaller-scale energy conversion and end-use technologies are more likely to be characterized by manufacturing scale economies.

For energy technologies with perceived social benefits, consistent government policies that support market demand are needed to underwrite the scaling up of unit and/or manufacturing capacities. Conversely, stop-start market-based policies undermine manufacturers' confidence, increase the risk of investing in scaling up production, and ultimately can result in higher costs.

Alongside demand growth, technology standardization has proven important for manufacturing scale economies at the unit or plant levels. The more successful growth of nuclear

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power in France in comparison to the United States can be attributed in part to the standardization of reactor and plant design and to knowledge spillovers, both profiting from a well-tested reactor design (68).

Observed average cost reductions during the development and commercialization of an energy technology commonly conflate unit and manufacturing level scale economies as well as learning effects. Isolating the contribution of economies of scale at different levels, therefore, requires analyses that clearly disentangle the various influences on cost (59, 69, 70).

2.3.3. Actors and institutions. Actors and institutions strongly affect the ETIS (71, 72). The roles and importance of different actors and institutions vary among innovation systems, and they also change over the life cycle of an innovation (52). Typically, for example, as innovation systems increase in maturity, the importance of private actors increases (73).

Entrepreneurship is needed to bring new technologies, products, and practices to markets (74, 75). Entrepreneurial risk taking is essential to cope with the large uncertainties surrounding new combinations of technological knowledge, applications, and markets (76). The role of the entrepreneur is to turn the potential of new knowledge, networks, and markets into concrete actions that both generate and take advantage of business opportunities.

Innovation is always characterized by uncertainty. Shared or collective expectations are an important means of reducing uncertainty and catalyzing innovative activity in certain domains (31, 77, 78). Shared expectations help guide actors to select technological alternatives from the variety created by knowledge generation activities. Public policies can create collective expectations and/or shape changing societal preferences to reflect public policy objectives, such as energy efficiency or carbon mitigation.

Indeed, public policies can reinforce or shape broader institutional change within the innovation system regarding learning, collaboration, risk taking, and consumer preferences. Although some measure of policy stability is necessary, adaptive policy making in response to feedback is important for stimulating innovation under conditions of uncertainty (79). Policies to support market formation, for instance, have proven important in encouraging renewable energy technologies through their early commercialization. These policies have included subsidies, tax incentives, regulated feed-in tariffs, procurement policies, minimum production quotas, and exemptions from regulation, among others (38). But different institutional and systemic contexts usually require a unique mix of policies that need to be locally adapted.

New energy technologies often face resistance from actors with vested interests in incumbent systems. To build up innovation systems, actors, particularly from nongovernmental organizations and industry, can counteract this inertia through political lobbying and advocacy coalitions (80–82). Public institutions may also contribute (83), as in the case of planning agencies advising regional or national governments to develop supporting policies for emerging technologies.

2.3.4. Functions within the energy technology innovation system. Researchers have identified seven key functions in innovation systems. These seven functions are entrepreneurial activities, knowledge development, knowledge diffusion through networks, guidance of the search, market formation, resource mobilization, and creation of legitimacy/counteraction to resistance to change. Entrepreneurs and their investors take the risk of bringing new technologies, knowledge, and networks into the marketplace. Knowledge development relates primarily to learning through research, development, and demonstration (RD&D) as well as experimentation. Knowledge diffusion through networks is the exchange of information, including knowledge spillovers. "Guidance of the search" refers to the need for innovation actors (governments, firms, individuals) to make choices about where to focus innovation efforts because

RD&D: research, development, and demonstration

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resources are always limited. This is influenced by shared expectations. Market formation is the creation of protected space for new technologies. Resource mobilization includes both financial and human capital. Creation of legitimacy refers to the need for special efforts to help new technologies compete against incumbents because many proponents of the incumbents will resist the introduction of new technologies. These functions help explain why the innovation process is so dynamic. Also, these key functions interact strongly and can be supported by policy makers (76, 82, 84).

2.4. Properties of the Energy Technology Innovation System

The ETIS has certain key characteristics that emerge repeatedly in the literature: interdependence, uncertainty, complexity, and inertia. Interdependence means that different components of the ETIS influence one another, although the strength and direction of these influences may change. The outcomes of the innovation process are irreducibly uncertain, and it is not possible to ensure *ex ante* success for technology A if recipe B is followed. Complexity arises inevitably from the number and variety of innovation system components and their shifting interdependencies, which are further increased by context dependency and idiosyncrasies of specific technologies. Inertia also arises from interdependencies and the long-lived capital stock and infrastructures in the energy system, as discussed above.

From these characteristics follow certain key implications for efforts to intervene in the ETIS to support its effective functioning (in a qualitative sense) and to include coherence, alignment, consistency, stability, and integration. These are addressed in more detail below.

2.5. Strengths and Weaknesses of the Energy Technology Innovation System Perspective

Studying energy innovation from a systemic perspective is a relatively young endeavor, with an empirical bias toward national levels of analysis and supply-side energy technologies. Policy experiments and field experience are largely still ongoing, particularly in a Northern European context that, together with Japan, provides many of the innovation histories from which the ETIS framework has been derived (3).

The systemic perspective necessitates an integrative analysis from large-scale supply-side technologies to dispersed end-use technologies within the energy system and from early stage R&D through market formation to diffusion activities. Conventional data collection and analysis (as well as the formation of public and commercial institutions) usually focus on a single piece of this puzzle. In contrast, the ETIS analytical approach reveals certain patterns when examined at a systemic level, including a pronounced mismatch between public innovation investments (e.g., in large-scale energy supply) and diffusion needs (e.g., energy end-use technologies). This is elaborated further in Section 3.

Nevertheless, the understanding of mechanisms and linkages at work in an ETIS is incomplete. ETIS research is weak in certain areas, such as feedbacks among components of innovation systems. Data are partial, incommensurate, or otherwise limited, as discussed in Section 6. Studies in developing countries are particularly lacking. As a result, the ETIS should be seen as a general conceptual framework, not as a predictive model.

3. QUANTIFYING THE ENERGY TECHNOLOGY INNOVATION SYSTEM

It is common to think of innovation systems in the national context (85), and indeed assessments of the ETIS are warranted and useful at the nation-state level. But given the cross-border nature of many energy-related challenges, and the global markets for most energy-related technologies, it is also important to assess the ETIS at the global level. This article contains the first attempt to provide a snapshot of the global ETIS based on an

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Table 1 Summary of the investments in the current global public and private ETIS in US$(2005) billion by stage and type of technology application

Type of investment	Research, development, and demonstration	Type of research, development, and demonstration	Market formation	Diffusion	References
End use and efficiency	>>$8	Public $1.8 Private >>$6	$5[a]	$300–$3,500[b]	2, 86–90
Fossil-fuel supply	>$12	Public $2 Private >$10	>>$2[c]	$200–$550	2, 57, 86–88, 91–93
Nuclear	>$10	Public >$6.2 Private >$3.4	None[d]	$3–$8[e]	86–88, 94
Renewables (including renewable electricity)	>$12	Public $2 Private $7	~$20[f]	>$20[g]	2, 57, 86, 87, 89, 91–93
Electricity (generation and transport and distribution)	>>$1	Only public	~$100[h]	$450–$520	2, 57, 86, 87, 89, 91–93
Other[i] and unspecified	>>$4	Only public	<$15[j]	—	86, 87
Total	>$50[k]		<$150[l]	$1,000–<$5,000[m]	89

[a] Includes $2 billion asset finance (89, p.13), plus an estimated $2 billion from venture capital (VC) (based on $15 billion total VC in 2008 and assuming category proportion in cumulative VC investments over the 2002–2008 period).

[b] First-order estimate, rounded numbers for the lower bound: central estimate of energy-using components of end-use investments ($297 billion); upper bound, upper range of total end-use investments ($3,549 billion) as estimated in References 2 and 90.

[c] Estimated $2 billion from VC only (based on $15 billion total VC in 2008 and assuming category proportion in cumulative VC investments over the 2002–2008 period).

[d] Classified as mature technology and reported under diffusion investments.

[e] Estimate for 2–3 GW reactor completions per year at assumed costs $1,500–$2,500 kW.

[f] Biomass and biofuels total $24.8 billion minus $8 billion Brazilian ethanol (accounted for as diffusion investment) plus $2.4 billion estimated VC investments.

[g] Fuels only.

[h] ~$90 billion asset finance, including wind, solar, geothermal, marine, and small hydro) plus an estimated ~$8 billion from VC.

[i] Hydrogen, fuel cells, other power and storage technologies, and basic energy research.

[j] Unaccounted for technology categories.

[k] Lower bound estimate (rounded number).

[l] Rounded number, estimated market formation investments $140 billion derived from Reference 89.

[m] Rounded numbers.

analysis for the *Global Energy Assessment: Toward a Sustainable Future* (2). Financial investments in energy innovation are used as an indicator of ETIS activity. Investments are an input into the ETIS, and therefore they do not tell us anything about the quality of the subsequent innovation, or anything about the outputs and outcomes of the innovation process. Many more dimensions of ETIS inputs, outputs, and outcomes at both the national and global levels should be analyzed both quantitatively and qualitatively in future research (1). Available investment data are provided in **Table 1** and disaggregated into three main innovation stages: RD&D, (niche) market formation, and diffusion. We also distinguish investments by broad energy technology categories (e.g., supply versus end use).

3.1. Public-Sector Research, Development, and Demonstration Investments

RD&D expenditures are routinely collected by national and international statistical agencies (see Reference 95). However, energy-related

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IEA: International Energy Agency

PPP: purchasing power parity

OECD: Organisation for Economic Co-operation and Development

BRIMCS: the rapidly industrializing countries of Brazil, Russia, India, Mexico, China, and South Africa

or technology-specific RD&D data are not reported separately, creating formidable data challenges (96). Energy- and technology-specific RD&D data are available for public-sector expenditures in member countries of the International Energy Agency (IEA) (97), but information on non-IEA countries and private-sector energy RD&D is extremely fragmented and sparse (see Reference 39 for an initial estimate). Evidence suggests that the IEA public-sector energy RD&D statistics may cover only a quarter of all energy-related RD&D globally (2).

Energy RD&D investments are relatively small in magnitude (5% of total government RD&D), and the energy RD&D investments of most countries experience booms and busts along with oil price movements. There was a rapid expansion of energy RD&D in the wake of the oil crises of the 1970s, subsequent collapse (with corresponding knowledge depreciation) during the 1980s and 1990s, and only a gradual recovery after 2000. The public energy RD&D investment trends are in stark contrast to the continually expanding total public RD&D budget in IEA member countries. Total public-sector energy RD&D in IEA member countries in 2008 amounted to $12.7 billion purchasing power parity (PPP). Nuclear fission and fusion accounted for 39%[1] of total IEA member country investments in 2008, followed by energy efficiency at 13%, renewable energy at 12%, and fossil-fuel technology RD&D also at 12%, with the remainder spent on other energy issues (e.g., transport and distribution, hydrogen, storage). Here, a pronounced supply-side dominance can be observed.

Comprehensive energy RD&D statistics for non-IEA member countries are lacking. This results in the incorrect perception that energy RD&D and technology development is primarily performed in Organisation for Economic Development and Co-operation Development (OECD) countries. Public energy RD&D in the six major emerging economies—Brazil, Russia, India, Mexico, China, and South Africa (BRIMCS)—amounted to US$13.6 billion, about equal to the spending of all the IEA countries (39, 87, 97). The traditional distinction between public and private sectors is becoming increasingly blurred. Partially state-owned enterprises and subnational government investments constitute an important part of the energy sector in developing and emerging economies, and these are strongly influenced by national governmental policies. Combining public and semiprivate energy RD&D, BRIMCS countries had a total current energy RD&D budget in 2008 of approximately $18 billion (PPP). Even with this preliminary assessment, major data gaps still exist with respect to non-OECD countries (98).

3.2. Private-Sector Research, Development, and Demonstration Investments

The only available survey of private-sector RD&D specific to the energy sector is a study conducted by the World Energy Council (88) in seven OECD countries, covering the period 1985–2000. Total OECD private-sector energy RD&D from 1993–2000 amounted to an average of $12 billion annually. The technology-specific breakdown is too incomplete, and the data are too old, to warrant a detailed discussion. However, it is noteworthy that with the exception of Japan, private-sector RD&D on energy efficiency appears extremely small. The data also suggest that private-sector energy RD&D seems to follow the supply-side (fossil and nuclear) dominance apparent in public-sector energy RD&D.

There is evidence from the United States that private-sector energy RD&D follows comparable trends as public RD&D, and both are influenced by rising and falling oil prices. One persistent concern in the United States is whether public investments duplicate

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[1] In terms of cumulative public R&D expenditures, nuclear received some US$(2008)225 billion PPP, or 54% of the entire public-sector energy R&D budget of all IEA countries between 1974 and 2008. Nuclear fusion alone received US$41 billion more public R&D funding than all energy efficiency projects and technologies combined (US$38 billion).

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private-sector investments. Lack of data on private-sector expenditures makes it impossible to determine the extent of redundancy. Another concern is whether government investments substitute for or "crowd out" private-sector RD&D investments. Public investments are unlikely to completely substitute for private investments because the government funds basic research, and the private sector does so less and less. One study concludes that "[t]he signal of commitment that a large government initiative sends to private investors outweighs any crowding-out effects associated with competition over funding or retention of scientists and engineers" (99, p. 753). In other words, when the government through its energy-technology budgets and programs prioritizes certain types of innovation, firms then compete for much of the government funding. The public investments thus have a catalytic effect within firms, especially when firms cofund research. In sum, however, (the sparse) available empirical evidence available does not support the argument of crowding out effects (e.g., Reference 100).

On the basis of the limited data available, the order of magnitude estimate of global annual energy RD&D amounts to some $50 billion PPP, with $27 billion in public-sector RD&D and at least $23 billion by the private sector. At least half of all energy RD&D is spent on fossil fuels and nuclear, and less than 20% is spent on energy end-use and efficiency technologies according to this assessment (with the remainder invested primarily in renewable electricity in addition to energy infrastructure and general energy RD&D) (86, 101).

3.3. Market Formation Investments

Market formation investments include public and private investments in the early stages of technological diffusion and they include niche market investments. In the energy domain, these investments include government subsidies for certain technologies (e.g., feed-in tariffs or production tax credits) and public procurement. They also include private investments to take advantage of markets created by government policies, such as renewable portfolio standards or price instruments like carbon taxes. No systematic numerical estimate of public-sector market formation investments exists, but the numbers are likely to be small compared to private-sector market investments.

VC/PE: venture capital/private equity

Private-sector market formation investments can be measured by activity in three main asset classes: venture capital/private equity (VC/PE), both forms of risk-taking private investment, new listings on public markets, and asset finance. Although often used for large and more mature technologies, asset finance investments in new energy technologies are counted here because they are highly dependent on governmental subsidies and incentives, such as tax equity credits or feed-in tariffs. The technology sector that attracted the most investment for the 2004–2008 period (reviewed in Reference 2) was wind (89, 102). Conversely, market formation investments into energy efficiency are small for unknown reasons.

There has been a dramatic growth of investment by VC/PE investors into energy—and specifically into clean-energy technologies—since the mid- to late 2000s. Between 2002 and 2008, VC/PE invested at least US$41 billion into energy technology firms. In 2008, the total amount of energy (fossil and nonfossil) investments made by VC/PE investors worldwide was US$14.6 billion. The majority of investments made by VC/PE investors are in sustainable/renewable energy generation, particularly solar electricity generation and (to a lesser extent) energy end-use technologies (smart energy metering in buildings, demand response software systems, high-efficiency lighting, etc.) (89, 102).

Total global market formation investments in 2005 are estimated at some US$150 billion, with two-thirds going into renewable electricity, incentivized largely by public policy support particularly in the form of feed-in tariffs and portfolio standards. The remainder mostly went to biofuels (especially ethanol) and other generic energy technology options, with energy efficiency comprising only US$5 billion (or 3%) (2).

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3.4. Diffusion Investments

Diffusion investments constitute the bulk of investments into an ETIS and comprise both investments into the energy supply and the energy end-use components of the energy system. Total global diffusion-related ETIS investments are estimated to range between some US$1,000 and US$5,000 billion in 2005, with energy supply-side investments accounting for between US$700 and $1,000 billion, and energy end use between US$300 and $4,000 billion (2, 3, 86, 91–93). It is important to emphasize that all diffusion investments are strongly influenced by public policy as reflected in relative energy prices (e.g., by fossil-fuel subsidies) and other policy instruments, such as taxes and performance standards.

3.5. Energy Supply Investments

Data on energy supply investments are extremely limited, so the literature typically relies on model estimates or limited surveys. A common feature (and drawback) of all modeling studies is that energy sector investments are reported as cumulative totals for the projection horizon of typically 30 years (e.g., References 26, 57, and 86). The absence of published base year input data for energy sector investment projections not only reduces the credibility of the modeling studies, but also makes an assessment of current investment levels and structure difficult. Despite differences in estimated supply-side investments per category, the available data (see the review in Reference 2) suggest a likely order of magnitude of energy-supply-side investment of US$(2005)700 billion/year that could have extended to US$840 billion in 2007/2008, considering the higher ranges reported in the literature. Investments are dominated by electricity generation, transmission, and distribution, with some US$(2005)500 billion (range: US$450–$520 billion). Fossil-fuel supply, particularly the upstream component (i.e., exploration and production), accounts for US$250–$400 billion, mostly for oil and gas. When categorized as RD&D activity for future oil/gas reserves, as is the practice of some companies, oil and gas exploration with an estimated US$40 billion (which is not, strictly speaking an energy technology investment) would represent the single largest RD&D expenditure in the energy technology field.

3.6 Energy End-Use Investments

Firms and households make many purchases that strongly affect energy consumption, including furnaces, boilers, windows, and appliances. If the purchased products are relatively energy efficient, energy demand can be reduced, and vice versa. Consumers may also choose to switch among fuels and energy carriers, affecting the demand for individual fuels and carriers. The huge number of consumers decentralizes decision making. Energy end-use investments by private households and their corresponding classification as consumer expenditures (rather than innovation investments) and by firms whose energy-specific investments usually go unreported result in the absence of energy end-use investment numbers in the literature. This lack of data introduces a serious challenge in both energy modeling and policy. End-use energy efficiency, which is potentially the largest source of energy demand (and emissions) reduction, is either ignored or assumed to cost nothing. Energy-economic models that are used for evaluating energy and climate policy customarily assume away missing data, and instead introduce exogenous autonomous energy efficiency trends into the models that have no relationship with actual policies. Modelers also sometimes try to estimate the incremental costs of energy end-use investments that would be needed to improve energy efficiency and then introduce these estimates into the model. Both approaches are flawed because they are not based on sound empirical data nor are they commensurate with the modeling of energy supply technologies. To address this data gap, a first global, bottom-up estimate of total investment costs in energy end-use technologies was developed (2, 90).

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The investments in 2005 in end-use technologies are estimated to be on the order of US$1–3.5 trillion; the estimate in 2005 in the energy-using components of these end-use technologies is on the order of US$0.1–0.7 trillion. It should be emphasized that these end-use investment ranges are certainly underestimates, as many end-use technologies were omitted from the analysis owing to the lack of data. Taking into account the extent of end-use technologies for which data are unavailable, the range of demand-side investment costs is conservatively estimated to be US$0.3–4.0 trillion (2).

3.7. The Global Energy Technology Innovation System Snapshot Summarized

From the above analyses, the best available global estimate of energy innovation investments is compiled in **Table 1**. First, an increasing scale of resource mobilization across successive stages of an ETIS, from RD&D (∼$50 billion/year), to market formation (∼$150 billion/year), and finally to diffusion (>$1,000 billion/year), can be observed. Second, there are formidable data problems associated with the description of energy innovation, especially for the non-OECD countries and the private sector. This gap calls for a renewed effort in innovation data collection and sharing, without which public policy risks navigating either blind or one-eyed. Third, the structure of current investments is highly asymmetrical due to the dominance of diffusion investments in energy end-use technologies and their underrepresentation in the earlier stages of an ETIS, particularly in public RD&D budgets. Fourth, private niche market investments that are largely triggered by public policies like feed-in tariffs or renewable portfolio standards focus almost exclusively on renewable electricity projects (mostly wind and solar photovoltaic) with insignificant investments in energy end use and efficiency, which suggests a need to rebalance both public R&D budgets as well as market support policies towards energy end-use technologies and efficiency. Fifth, it is now clear that six major emerging BRIMCS economies account for a significant fraction of global ETISs. Significant regional imbalances persist, however. The increasing globalization of ETISs suggests that new mechanisms for international technology cooperation and coordination may be required.

4. RATIONALES AND POLICIES FOR THE ENERGY TECHNOLOGY INNOVATION SYSTEM

4.1. Rationales for Public Policy

When considering the rationale for investments in energy innovation, there are two main questions to be answered: Why should anyone—the government or private companies—engage in energy innovation? And, what is the particular rationale for government policy and investments in energy innovation?

A private firm endeavors to innovate to meet a perceived need in the marketplace. The global energy marketplace is very large, standing at around US$1 trillion per year in energy supply alone. It is projected to become much larger in the next few decades (104). Companies tend to invest in RD&D projects that are likely to bear fruit in the near term and are less interested in longer term, more fundamental RD&D (105). This is especially true during times of economic turmoil or recession and energy price volatility. Such volatility leads to a lumpy pattern of investment, where big investments are followed by precipitous declines. Innovation requires sustained and steady inputs to focus over the longer term on improving or developing energy technologies (1).

One of the primary rationales for government involvement is to support, complement, and leverage the private sector's efforts because a vibrant energy sector contributes to economic growth and prosperity. Second, many energy services contribute to meeting fundamental human needs, and improvement of those services can better the human condition. If innovation

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reduces the costs of energy access, consumer welfare and human well-being are improved. In developing countries, where millions still lack access to electricity, which enables services such as lighting and refrigeration, the government has an especially important role to play in designing systems to improve energy access. Government investment in energy innovation is also justified to make energy supply more reliable and secure, to reduce pollution (including greenhouse gases), and to reduce the negative impacts of energy production and use on water and land resources.

The final rationale for government policy is to overcome or remove outdated market barriers. Incumbent energy technologies or systems have institutions, infrastructure, and policies that support them, providing barriers to entry for new technologies (sometimes called lock in or path dependence) (23). There is also a so-called valley of death between the invention phase and the deployment phase (18, 106–108). There are often difficulties moving from R&D to demonstration and taking a proven technology to the marketplace during the early deployment phase. Governments can erect bridges across these valleys to reduce the barriers and speed the passage of these technologies from the laboratory to the market.

4.2. Instruments of Policy

Policies supporting the supply of innovation or the development of technologies include investments in R&D, intellectual property protection, laboratory and testing infrastructure, training and skills development, university-industry collaborations, formal and informal mechanisms of knowledge exchange, technology road maps to guide the direction of innovation, and financial incentives (such as tax credits for private investments).

Policies supporting the demand for innovations include demonstration projects, public procurement, market niche creation, and the creation of appropriate market incentives. Market incentives may be created via changes in relative prices (e.g., environmental taxes or feed-in tariffs), standards, and regulations. These technology-push and demand-pull policies are complements rather than substitutes.

Policy is influential at each stage of the innovation process and at the system level. The role of government is clearest at the earliest stage of basic science and research. However, governments are also engines of applied energy R&D and play an important role leveraging private-sector investment by supporting demonstration activities (to reduce risks) and market formation. First-of-a-kind technologies are often more expensive, and governments can create demand in niche markets through procurement and other policies (e.g., feed-in tariffs or technology portfolio standards). For new, cleaner energy technologies to be competitive in the broader market, government policies are also needed to correct for market externalities and define the rules of the game (e.g., through a carbon tax) while assuring an equal playing field across technologies (e.g., by removal of fossil-fuel subsidies).

More general policies for education, taxes and subsidies, and market regulation can also exert an important influence on energy innovation supply and demand. This reinforces the need for consistency, not just between direct innovation policies but also between the broader regulatory and institutional environments for innovation. Although government policy affects all stages of innovation, rarely do we see comprehensive government strategies to further the functioning of the ETIS. Instead, government policies persistently aim at isolated components of the system and all too often on an irregular basis.

4.3. International Dimension to Energy Innovation and Policy

International policy also creates incentive frameworks for the wider diffusion of energy technologies. This includes treaties (e.g., Kyoto Protocol); norms (e.g., technical standards); and institutions regulating trade, finance, investment, environment, development, security, and health issues (e.g., the IEA,

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World Trade Organization, World Bank, and United Nations Development Programme).

Energy technology is mostly diffused through private means; it routinely flows through foreign investment, licensing agreements, and international trade. Each implies different modes of knowledge transfer, whose effectiveness depends critically on firm strategies and on local assimilation capacities (109). Many of these knowledge flows are intrafirm flows within multinationals (110). Although the existence of more advanced and cleaner energy technologies has led some to believe that latecomer countries will leapfrog to such technologies quickly (111), this is by no means an automatic process (112).

International knowledge spillovers through government-sponsored collaboration efforts seem insufficient compared to what is needed to foster a significant global energy transition (113, 114). Participation of emerging and developing economies in the IEA's Implementing Agreements for energy technology collaboration is low. The IEA provides support for numerous international cooperation and collaboration agreements in energy technology R&D, deployment, and information dissemination (115). However, many are not really R&D collaboration projects but simply institutional arrangements for information exchange or standardization.

5. A PERSPECTIVE ON POLICY DESIGN GUIDELINES FOR AN EFFECTIVE ENERGY TECHNOLOGY INNOVATION SYSTEM

The systemic perspective on ETISs described in this review, as well as lessons from technology policy case studies, lead, in the view of the authors, to some guidelines for policy design. An important outcome of utilizing a systems perspective on energy innovation is that, as described below, these guidelines differ from those implied by a less systemic perspective. Given the generality of the ETIS, these guidelines are necessarily strategic and are in no way policy instrument prescriptive. The merits of particular policy instruments depend on technological specificities as well as national and local circumstances. We thus depart from our review in this section to provide policy guidelines that the authors deem useful on the basis of the available evidence and state of knowledge about energy innovation.

5.1. Address Innovation in a Systemic Way

A systemic approach to innovation policy requires a systemic approach to policy as well. Just as there are no technology silver bullets, there are no single policy bullets either. Policy packages must be broad in their coverage, supporting the successful functioning of the whole innovation system. Overall, the policy package needs to support knowledge development, feedback processes, and learning for the entire innovation system, as discussed below. A narrow technology focus runs counter to the systemic view of ETISs developed throughout this article.

Although social institutions play an important part in the success or failure of innovation processes, innovation policies tend to focus on technologies. The broader dynamic between technological change and social change is either sidelined or framed as a simple push-pull relationship with technologies driving responses in social institutions. As a result, social innovation, referring explicitly to changes in the adoption, use, and adaptation of technologies in a social and institutional context, is marginalized as a target for innovation policy. Myriad forms of social innovations include participatory planning processes, community-based initiatives, social learning, normative messaging on utility bills, information provision (to change attitudes), educative initiatives (to change values), supply chain alliances and pressures, new business models, and reporting and disclosure requirements. The package of instruments developed to support innovation systems should include policies targeting social innovation as well.

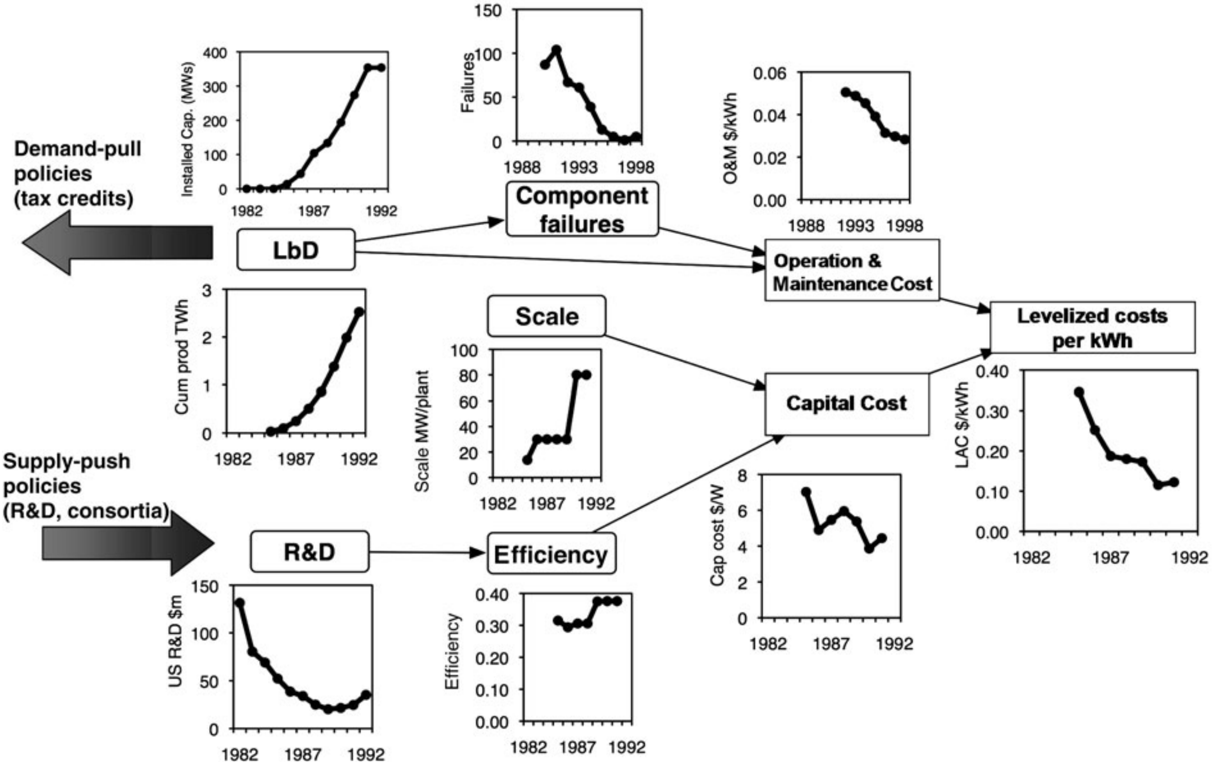

Figure 2

History of the US Solar Thermal Electric Program 1982–1992 (116). Abbreviations: LbD, learning by doing; R&D, research and development.

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5.2. Align Incentive Structures

To maximize the effectiveness of an ETIS, it is essential to align incentive structures and employ consistent policy signals. The US solar thermal electricity program is a good example of successful policy alignment, as shown in **Figure 2** (116). Here, demand-pull policies enabled expanding market applications, which in turn enabled scaling up of the technology and learning by doing, reducing component failures. Technology-push policies including R&D investments (even with declining budgets) led to technology improvements (efficiency). Combined, both capital costs and operation costs declined. Unfortunately, this virtuous innovation development cycle came to a halt in the late-1980s with the discontinuation of both technology-push and demand-pull public policy support, and production was eventually abandoned, which illustrates the pitfalls of policy instability (see the discussion below).

There are two types of alignment that must be considered: (*a*) alignment within a given innovation system, and (*b*) alignment across innovation systems to encourage spillovers. Aligned policies include the development of an explicit strategy for supporting technologies that are invented through demonstration and testing, and policies that facilitate the transition of technologies across both valleys of death (from R&D to demonstration, and demonstration to early deployment). Government often must also establish policies that create incentives for technologies to be pulled into the marketplace and to achieve large-scale diffusion. Throughout the growth phase of a technology (or set of technologies), government can devise mechanisms to gather from and share information

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among actors. When government fails to align the incentive structures for achieving desired outcomes, contradictions emerge, and perverse outcomes flourish. A common misalignment is government imposing performance requirements or making RD&D investments in energy efficiency while simultaneously subsidizing the price of retail fuels (see, for example, Reference 116). Another example of misalignment is the government encouraging RD&D investments in wind energy when local planning and zoning laws prohibit the installation of wind turbines.

5.3. Assure Policy Stability

Uncertainty in expectations about future policies increases the private risk of investing in innovation. Because externalities are pervasive in the clean-energy sector, owing to both knowledge spillovers and environmental externalities, these distant payoffs rely heavily on policy instruments. However, if expectations about the level or existence of these policy instruments in the future are uncertain, firms will discount the value of future policies and underinvest in innovation. Because technology development is in itself a risky endeavor, private companies only respond to policies that are credible, long-lasting, and have a reasonable degree of stability (118, 119). Moreover, volatility can accelerate knowledge depreciation and loss (120). A recent policy innovation has been the shift to policies that ensure stability by including time horizons. An important cautionary note is that long-term commitments can often include clauses that allow loopholes for governments to avoid meeting those commitments should compliance become more difficult than expected. Although the flexibility to change targets may have social benefits, it is important to understand the price paid in terms of reduced incentives for investment by private actors.

5.4. Experiment and Tolerate Failure

Historically, considerable experience has been gained with smaller-scale units before significant jumps in unit scale were successfully attempted (e.g., coal power, jet aircraft, and wind turbines). The consistency of this pattern points to the importance of experimentation with many small units as a precursor both to widespread diffusion and to upscaling (i.e., pushing technologies toward the unit scale frontier). The hallmark of this approach to innovation is granularity: individual eggs in many small baskets. This favors smaller-scale innovation investments over larger lumpy gigawatt (GW)-scale projects because the consequences of innovation failure are dramatically reduced.

Experimentation to generate knowledge on a technology's performance, efficiency, reliability, and other service attributes enhances the required capacity for capturing unit-scale economies (121). Governments can support experimentation in numerous ways. They can underwrite small-scale demonstration projects for innovations with less immediate or higher risk private returns; they can support variety in the early deployment phase by creating and protecting differentiated niches; and they can manage the natural commercial tendency to rapidly confirm a dominant design that confers market advantages and potential cost benefits through scale economies.

Energy innovation portfolios should not be judged negatively if they lead to some economic failures so long as they also produce a few relatively big successes (114, 122, 123). Failure is an inherent feature of a multifarious and granular portfolio of innovation experiments. Venture capitalists build energy technology portfolios with an expected 90% failure rate, knowing that the 10% that breakthrough will support returns for the portfolio as a whole. Accountability for taxpayer dollars and the associated political risks of funding failures (among other things) makes public innovation policies less tolerant. Building diverse granular portfolios of modular or smaller-scale technologies helps spread this risk of failure. Concentrating public resources on the rapid scaling up of a particular technology (e.g., fusion power or carbon capture and storage) magnifies the consequence of failure.

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5.5. Focus on Technology Portfolios

In designing innovation portfolios, a number of basic criteria need to be taken into account. First, portfolios need to reflect a blend of options spanning the entire energy system and spread investments across many technologies and projects. Portfolios should encompass all salient elements of the technology development cycle and different channels of technology knowledge creation, such as R&D, demonstration, niche market deployment incentives, and market creation measures. Portfolio design ideally includes a blend of the respective values of technologies from both demand-pull and technology-push perspectives (124).

Second, given inevitable resource constraints, the design of diversified portfolios is more feasible when focusing on granular, less capital-intensive technologies, such as end-use innovations and smaller-scale supply options. Conversely, large-scale, capital-intensive, high-risk innovations can be meaningfully considered only in global innovation portfolios and collaborations.

Third, in portfolio design, the inherent tension between the desirable goal of maintaining technological diversity and the equally desirable goal of improved economics through standardization, scale, and technology focus needs to be balanced. New information technologies and methodological advances have become available for knowledge sharing on ETISs and for designing innovation portfolios under due consideration of uncertainty and multiple policy objectives (see References 2 and 125 for examples). On one side, innovation policies need to avoid preempting the outcome of decentralized market-based technology innovation, experimentation, and early market deployment decisions that are key in technology development. On the other side, public-sector innovation policy legitimately needs to counter private innovation biases against large-scale, investment-intensive technologies that might be crucial in addressing broader social and environmental goals. Although resource limitations inevitably require a focus on a few strategic technologies, there is a downside: Pressures to concentrate on capital-intensive innovation projects (potential innovation "lemons") result in the public sector disproportionally shouldering innovation risks. Still, government-led innovation requires an acceptance of risk to achieve long-run social benefits (114, 126).

5.6. Enable Learning and Spillovers at All Scales

Feedback processes are essential for sustained and successful energy innovation (37, 51). Government can support these feedbacks but can also hinder—or even block—information and knowledge flows (127, 128). For instance, governments can support knowledge feedback between demonstration projects and niche market applications back to R&D by providing facilities where new technology options are tested and the results are communicated back to developers/manufacturers [a good example is the use of test centers in Denmark (129)]. For many new energy technologies, early experience in production and use, including experience in operation and maintenance, has been essential for success because experience is fed back into R&D and design changes. Extended feedback loops could be achieved through international cooperation and experience sharing. However, such international knowledge exchange initiatives remain in their infancy.

Local policies are necessary complements of international learning and spillover incentives, as local absorptive capacity must be fostered to take advantage of technology and knowledge produced abroad. Protecting intellectual property rights is an important consideration for knowledge exchange and technology transfer, but not the most important factor. Naturally, the financial requirements for acquiring hardware, machinery, and equipment are also a central aspect of international technology diffusion, especially in capital-intensive, large, and embodied energy technologies. International financial schemes and institutions play roles in the current technological lock in to the extent that they tend to screen out investment allocations to cleaner energy sources, local R&D efforts, and knowledge infrastructures.

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5.7. In Sum

To be effective, innovation policy makers must be conscious of the interdependencies across time, space, and actors, and act coherently. Isolated policies aimed at only one realm of the innovation system do not yield strong outcomes if they are not accompanied by coordinated and aligned support that addresses energy technology innovation systemically. The changing nature of technology should also be reflected in policy design. Instruments and incentives have to be adapted to the particular problems, tensions, and bottlenecks that characterize each stage of a technology's innovation life cycle. The dynamics of technology over time require the attention of innovation policy to development times and feedback processes. Technology search and development is a time-consuming activity that requires patient funding and active networking. Policy design must therefore be sensitive to the timing of investments and returns. Because knowledge development on suitable solutions and technology improvement takes a long time—and knowledge rapidly depreciates under erratic policy signals—early and persistent policy actions are very important.

The deep uncertainty that characterizes early phases of innovation calls for flexible institutional mechanisms that are able to shape expectations and respond to new information. However, as the innovation life-cycle advances and uncertainty about technical features decreases, capital-intensive investments demand long-term policy stability. Institutional design aimed at accelerating innovation must be aware of this trade-off between maintaining experimentation and technological variety and the economic drive toward standardization and have the ability to switch policy priorities over time in a predictable, consistent manner.

6. RESEARCH, DATA, AND INFORMATION NEEDS

The assessment reported in Reference 2 identified ten important data and research needs to address the core questions of technology innovation: What are the most appropriate policy instruments for a particular purpose? What resources are required? And what are the likely innovation system responses?

6.1. Data Needs

Five areas stand out where the gap between data needs and availability is particularly large:

- data on innovative activities (R&D) pursued by private firms;
- data on public and private technology-specific investments, particularly in end-use technologies;
- data on knowledge spillovers across different innovation fields and at the international level including, in particular, technology-specific trade data and joint technology development collaborations;
- systematic and up-to-date data on performance and economic characteristics for energy technologies that are internationally comparable and widely available for technology studies and policy assessments; and
- data from non-OECD countries.

6.2. Information Needs

Information needs include the following areas:

- identification of a limited set of appropriate and manageable criteria and metrics for the assessment of innovation systems in terms of inputs, outputs, and outcomes that can be matched with data sets;
- operational measurement models that describe knowledge depreciation in R&D and learning processes; and
- criteria for the selection of technology-specific case studies, especially in a comparative context across countries and across technologies.

7. CONCLUSIONS ON THE ENERGY TECHNOLOGY INNOVATION SYSTEM

The analytical framework of the Energy Technology Innovation System (ETIS) applies a systemic perspective on innovation to energy technologies. It allows one to assess energy systems in a holistic manner, including supply, demand, the stages of the development cycle, feedbacks, processes, actors, institutions, and networks. This systemic approach facilitates new insights that complement and improve upon traditional views and fragmented policy approaches.

Clearly, substantial and accelerated innovation is essential to respond to the sustainability challenges of energy systems at all levels, including the local, national, regional, and global scales. Furthermore, a coordinated approach is needed that works within and between industrialized and developing nations. Such innovations will comprise a combination of both incremental, cumulative changes and radical, discontinuous changes that can only emerge if the various innovation dimensions are nurtured simultaneously. Innovation entails technological, social, and institutional, as well as economic factors that influence the development, testing, and ultimate selection and adoption of new innovations.

A core message of this review is that the drivers of innovation, as well as the policies that support it, depend on the proper functioning of the others. The drivers are not substitutable, but instead complement and enhance each other. Innovation and technology policies also can no longer remain fragmented, ad hoc, and concentrated on individual technological options. A more strategic and long-term approach is required to harness the potential of a well-functioning ETIS. To involve relevant stakeholders and take account of international developments, it is necessary to formulate the goals and objectives; weigh the different (sometimes conflicting) objectives, strategies, and implementation plans to be followed; and evaluate the criteria for continued reassessment. Strategies and polices need built-in mechanisms to assure flexibility and the ability to adjust courses of actions and reflect new developments to react to and correct for unanticipated outcomes and surprises. There is an inherent tension between the desired criteria of flexibility on one hand and the equally desirable criteria of alignment, consistency, and patience on the other. Reconciling them requires an institutional and policy architecture that can mobilize collective learning processes and widely shared strategic goals. Determining the overarching goals for energy access, human health, energy security, and climate protection is the appropriate starting point to formulate implementing policies and strategies that can guide global ETIS frameworks and efforts.

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SUMMARY POINTS

1. Energy technology innovation requires a systemic approach that addresses all stages of the technology development process as well as all aspects of energy use (supply as well as demand) and innovation processes, feedbacks, actors, institutions, and networks.
2. There are a multitude of attributes and drivers of innovation, including new knowledge, knowledge depreciation, economies of scale, linkages and spillovers to other sectors, and the phenomena of increasing returns.
3. Emerging economies play an important role in the ETIS and are making significant investments in RD&D, contrary to traditional conceptions that the development of an ETIS primarily occurs in OECD countries.
4. Recently available data on RD&D expenditures suggest that energy end-use technologies are of critical importance in the ETIS and need to be better reflected in future RD&D, market deployment incentives, and business models.

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5. Alignment and consistency of policies are important for fostering an ETIS.
6. Policies, measures, and incentives to support the ETIS are complementary rather than substitutable, and neither technology push (e.g., accelerated, stepped up RD&D programs) nor demand pull (e.g., cost buy down in new technologies) are sufficient.
7. Historically, successful innovations are characterized by the prevalence of a multitude of diverse, small (locally adapted) solutions to problems, as opposed to singular, large-scale, planetary solutions. Granular, small-scale innovations offer the potential for multiple and repeated experimentation, learning, and adaptation to diverse adoption environments.

FUTURE ISSUES

The assessment identified a number of issues for future research.

1. The development of conceptual models that answer the question of how measurable inputs and outputs of innovation systems relate to each other is urgently needed.
2. The development of a metatheory of energy innovation that enables the establishment of appropriate conditions would allow analysts to compare and assess the dynamics of change and of policy effectiveness across different technologies and development/adoption environments.
3. Comparative assessments of the effectiveness of alternative policy instruments aimed at influencing individual components, or the entirety, of an ETIS would provide information useful to governments.

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