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# Policies for the Energy Technology Innovation System (ETIS)


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# Contents

## Dedication

We dedicate this work to our families for their understanding and support for our long, collaborative journey that led to this chapter and which included both sad and joyful moments.

In loving memory to Maria, Georg, and Gerth, who departed us while we were working on this chapter.

With a warm welcome to Heidi Marie, Estelle, Henry Ian, Inés, and Alfred Victor who joined us in our collective travel towards a sustainable future.

# Executive Summary

Innovation and technological change are integral to the energy system transformations described in the Global Energy Assessment (GEA) pathways. Energy technology innovations range from incremental improvements to radical breakthroughs and from technologies and infrastructure to social institutions and individual behaviors. This Executive Summary synthesizes the main policy-relevant findings of Chapter 24. Specific positive policy examples or key take-home messages are highlighted in italics.

The innovation process involves many stages – from research through to incubation, demonstration, (niche) market creation, and ultimately, widespread diffusion. Feedbacks between these stages influence progress and likely success, yet innovation outcomes are unavoidably uncertain. Innovations do not happen in isolation; interdependence and complexity are the rule under an increasingly globalized innovation system. Any emphasis on particular technologies or parts of the energy system, or technology policy that emphasizes only particular innovation stages or processes (e.g., an exclusive focus on energy supply from renewables, or an exclusive focus on Research and Development [R&D], or feed-in tariffs) is inadequate given the magnitude and multitude of challenges represented by the GEA objectives.

A first, even if incomplete, assessment of the entire global resource mobilization (investments) in both energy supply and demand-side technologies and across different innovation stages suggests current annual Research, Development & Demonstration (RD&D) investments of some US$50 billion, market formation investments (which rely on directed public policy support) of some US$150 billion, and an estimated US$1 trillion to US$5 trillion investments in mature energy supply and end-use technologies (technology diffusion). *Major developing economies like Brazil, India and above all China, have become significant players in global energy technology RD&D, with public- and private-sector investments approaching US$20 billion, or almost half of global innovation investments, which is significantly above the Organisation for Economic Co-operation and Development (OECD) countries' public-sector energy RD&D investments (US$13 billion). Important data and information gaps exist for all stages of the energy technology innovation investments outside public sector R&D funding in OECD countries, particularly in the areas of recent technology-specific private sector and non-OECD R&D expenditures, and energy end-use diffusion investments.*

*Analysis of investment flows into different stages of the innovation process reveals an apparent mismatch of resource allocation and resource needs.*

Early in the innovation process, public expenditure on R&D is heavily weighted toward large-scale supply-side technologies. Of an estimated US$50 billion in annual investment globally, less than US$10 billion are allocated to energy end-use technologies and energy efficiency.

Later in the innovation process, annual market (diffusion) investment in supply-side plant and infrastructure total roughly $US_{2005}$$0.8 trillion, compared with a conservative estimate of some US$1–4 trillion spent on demand-side technologies. These relative proportions are, however, insufficiently reflected in market deployment investment incentives of technologies, which almost exclusively focus on supply-side options, to the detriment of energy end use in general and energy efficiency in particular foregoing also important employment and economic growth stimuli effects from end-use investments that are critical in improving energy efficiency. *The need for investment to support the widespread diffusion of efficient end-use technologies is also clearly shown in the GEA pathway analyses. The demand side generally tends to contribute more than the supply-side options to realizing the GEA goals. This apparent mismatch suggests the necessity of rebalancing public innovation expenditure and policy incentives to include smaller-scale demand-side technologies within innovation portfolios*.

Given persistent barriers to the adoption of energy-efficient technologies even when they are cost competitive on a life cycle basis, technology policies need to move toward a more integrated approach, simultaneously stimulating the *development* as well as the *adoption* of energy efficiency technologies and measures. *R&D initiatives that fail to incentivize consumers to adopt the outcomes of innovation efforts (e.g., promoting energy-efficient building designs without strengthened building codes, or Carbon Capture and Storage [CCS] development without a price on carbon) risk* *not only being ineffective but also precluding the market feedback and learning that are critical for continued improvements in technologies.*

Little systematic data are available for private-sector innovation inputs (including investments), particularly in developing countries. Information is patchy on innovation spillovers or transfers between technologies, between sectors, and between countries. It is also not clearly understood how fast knowledge generated by innovation investments may depreciate, although policy and investment volatility are recognized as critical factors. Technical performance and economic characteristics for technologies in the lab, in testing, and in the field are not routinely available. Innovation successes are more widely documented than innovation failures. Although some of the data constraints reflect legitimate concerns to protect intellectual property, most do not. Standardized mechanisms to collect, compile, and make data on energy technology innovation publicly available are urgently needed. The benefits of coupling these information needs to public policy support have been clearly demonstrated. *A positive policy example is provided by the early US Solar Thermal Electricity Program, which required formal, non-proprietary documentation of cost improvements resulting from public R&D support for the technology.*

The energy technology innovation system is founded on knowledge generation and flows. These are increasingly global, but this global knowledge needs to be adapted, modified, and applied to local conditions. The generation of knowledge requires independent and stable institutions to balance the competing needs and interests of the market, policy makers, and the R&D community. *The technology roadmaps and the policy regime that characterize innovation in end-use technologies in the Japanese Top Runner program are a good example of the actor coordination and knowledge exchange needed to stimulate technological innovation.*

Generated knowledge needs to spread through the innovation system. Knowledge flows and feedbacks create and strengthen links between different actors. This can take place formally or informally. Policies that are overly focused on the development of technological "hardware" should be rebalanced to support interactions and learning between actors. *The provision of test facilities in the early years of the Danish wind industry is a good example of how policy can support knowledge flows and the strengthening of collaborative links within networks of actors in an innovation system (energy companies, turbine manufacturers, local owners).*

Long-term, consistent, and credible institutions underpin investments in knowledge generation, particularly from the private sector, and consistency does not preclude learning. Knowledge institutions must be responsive to experience and adaptive to changing conditions. Although knowledge flows through international cooperation and experience sharing cannot presently be analyzed in detail, the scale of the innovation challenge emphasizes their importance alongside efforts to develop the capacity to absorb and adapt knowledge to local needs and conditions. *The current global cooperation in energy technology innovation is well illustrated by the International Energy Agency (IEA) technology cooperation programs reviewed in Section 4.4; all invariably show a sparse involvement from developing countries.*

Clear, stable, and consistent expectations about the direction and shape of the innovation system are necessary for innovation actors to commit time, money, and effort with only the uncertain promise of distant returns. To date, policy support for the innovation system has been characterized by volatility, changes in emphasis, and a lack of clarity. *The debilitating consequences on innovation outcomes of stop-go policies are well illustrated by the wind and solar water heater programs in the United States through the 1980s, as well as the large-scale (but fickle) US efforts to develop alternative liquid fuels (Synfuels). The legacy of such innovation policy failures can be long lasting. The creation of a viable and successful Brazilian ethanol industry through consistent policy support over several decades, including agricultural R&D, guaranteed ethanol purchase prices, and fuel distribution infrastructures, as well as vehicle manufacturing (flex fuel cars), is a good example of a stable, aligned, and systemic technology policy framework. It is worth noting that even in this highly successful policy example, it has taken some three decades for domestic renewable ethanol to become directly cost competitive with imported gasoline.*

Policies need also to be *aligned*. Innovation support through early research and development is undermined by an absence of support for their demonstration to potential investors and their subsequent deployment in potential markets. Policies to support innovations in low-carbon technologies are undermined by subsidies to support carbon-intensive technologies. *Fuel efficiency standards that set minimum (static) efficiency floors fail to stimulate continuous technological advances, meaning innovations in efficiency stagnate once standards are reached. As a further example of misalignment, the lack of effective policies to limit the demand for mobility mean efficiency improvements can be swamped by rising activity levels.*

Policies should support a wide range of technologies. However seductive they seem, "silver bullets" do not exist without the benefit of hindsight. Innovation policies should use a portfolio approach under a risk-hedging and "insurance policy" decision-making paradigm. Portfolios need to recognize also that innovation is inherently risky. Failures vastly outnumber successes. *Experimentation, often for prolonged periods (decades rather than years), is critical to generate the applied knowledge necessary to support the scaling up of innovations to the mass market.*

The whole energy system should be represented in innovation portfolios, not only particular groups or types of technologies; the entire suite of innovation processes should be included, not just particular stages or individual mechanisms. Less capital-intensive, smaller-scale (i.e., *granular*) technologies or projects are less of a drain on scarce resources, and failure has less serious consequences. *Granular projects and technologies with smaller scales (MW rather than GW) therefore should figure prominently in any innovation portfolio.*

Finally, public technology policy should not be beholden to incumbent interests that favor support for particular technologies that either perpetuate the lock-in of currently dominant technologies or transfer all high innovation risks of novel concepts to the public sector.

## 24.1 Introduction

### 24.1.1 Welcome to Chapter 24

Unlike resources found in nature, technological and social innovations are human-made resources that can be generated and expanded as a matter of social choice but come with costs and with uncertain outcomes. Energy-technology innovations not only encompass new inventions and improvements in the performance or attributes of technologies like coal gasification, solar thermal electricity, batteries, or energy-efficient windows or light bulbs, but also in how firms develop and markets and users relate to and utilize such technologies. Social innovations that result in changes in behavior of technology suppliers as well as users can therefore be just as important as improvements in technological efficiency or emissions performances of individual technological artifacts.

Innovations do not fall like manna from heaven; they need to be created through a multistage process. The stages include research, development, demonstration, market formation, and finally, the culminating pervasive diffusion of successful innovations. In the most general definition, energy technology change is the capital-embodied result of institutionalized R&D and collective learning processes[1] between developers/suppliers and users of technologies, operating within specific innovation and adoption environments that are strongly shaped by policies. This chapter therefore adopts a systemic view of an Energy Technology Innovation System (ETIS) and focuses on the particular role of policy in the energy innovation process and the functioning of ETIS.

Chapter 24 is both theoretical and deeply empirical: it provides the first ever quantitative estimate of global investments in energy-technology innovation (Appendix I), as well as a rich set of new case studies (summarized in Appendix II). These case studies trace the evolution of individual energy technologies, describe often neglected aspects of energy technology innovation, and assess the role of policies in influencing energy technology innovation. Throughout, this chapter emphasizes the importance of understanding the energy-technology innovation system in its entirety, including its many feedbacks. Because the energy-technology innovation system is complex and remains incompletely understood, readers are advised to use caution when seeking precise mathematical formulations for models or simple policy recipes. Nonetheless, despite its limitations, a systems perspective on energy technology innovation – particularly one that integrates supply and demand aspects – offers new insights that complement and improve upon traditional views and resulting fragmented technology policy approaches.

Chapter 24 provides guidance to policy makers about how to positively influence energy innovation, as well as how policy can be harmful and counterproductive. Common myths are explicitly examined. Refraining from being overly prescriptive about particular individual policy instruments, Chapter 24 instead offers broad guidelines drawn from the case studies for improved innovation policies that recognize both the inevitable uncertainty in the innovation process and its systemic nature. The chapter concludes with research and information/data needs and summary findings. Space limitations preclude a full presentation of the 20 case studies drawn upon in Chapter 24. They are presented in one-page summaries as an appendix to this text and are available upon request.[2]

### 24.1.2 Roadmap of Chapter 24

Figure 24.1 shows a roadmap of Chapter 24. After the introduction (Section 24.1), Chapter 24 moves to the assessment of ETIS, which consists of three main parts.

Section 24.2 characterizes ETIS. The review is necessarily selective, but identifies key components and themes. Features of ETIS are organized around knowledge and learning (Section 24.2.2); attributes of energy technologies and their industries and drivers of changing technology characteristics, such as economies of scale and scope (Section 24.2.3); and the functions of actors and associated institutions (Section 24.2.4). These are the distinct mechanisms of innovation described in the engineering, economics, management, and sociological literature and include knowledge accumulation (and depreciation), economies of scale and scope, and various learning processes. This part concludes with an integrative representation of ETIS and its components according to the "functions of innovation systems" literature. This emphasizes the dynamic, evolving nature of an ETIS over time (Section 24.2.5).

Section 24.3 identifies ways of assessing ETIS. The breadth of assessment metrics are reviewed in detail in the *Assessment Metric* case study

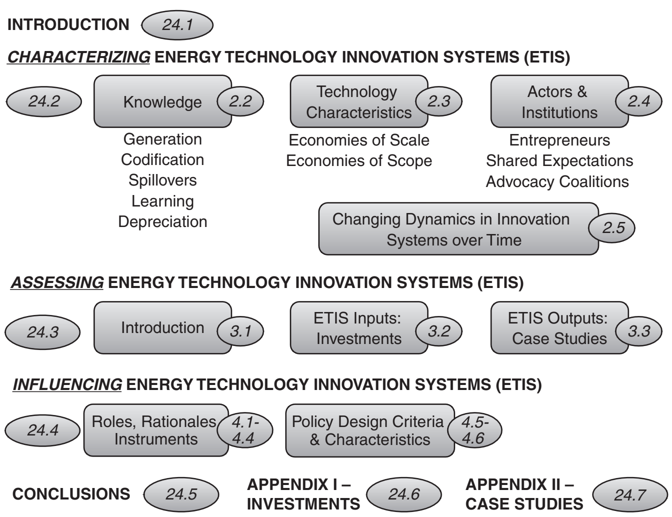


**Figure 24.1** | Roadmap of Chapter 24

1 Excellent historical studies on oil-refining (Enos, 1962) and gas turbines (Watson, 2004) illustrate these processes.

2 Available at www.globalenergyassessment.org.

(see summary in Appendix II). The discussion then proceeds to a quantitative commensurate assessment of current investment inputs into ETIS, as summarized in Section 24.3.2. In order to assess ETIS in terms of outcomes (Section 24.3.3), Chapter 24 draws upon 20 case studies, which are summarized in Appendix II. Section 24.3.3 provides an overview of the case studies, their rationale, and selected illustrative examples of ETIS outputs across a variety of energy technologies.

Section 24.4 then examines the question of how to influence the direction and effective functioning of the ETIS. The policy community is a key constituency for the findings in Chapter 24. The ETIS framework presented is an integrative conceptual framework that neither can nor should be used to generate policy prescriptions. Therefore, after an overview of actors and rationales for technology policy (Sections 24.4.1 and 24.4.2), policy models and instruments (Section 24.4.3) and their increasingly international dimension (Section 24.4.4) are outlined. Chapter 24 abstracts generalizable *policy design* guidelines and criteria that should support innovation success and mitigate against innovation failure (Section 24.4.6).

Chapter 24 culminates in a discussion of the research, data, and information needs identified in this assessment (Section 24.5.1), as well as overall conclusions (Section 24.5.2).

As noted, this chapter is written to provide a practical guide for policy makers concerned with supporting the effective functioning of the ETIS in the context of the GEA objectives on climate, access, security, and health. To develop policy guidance, Chapter 24 also reviews some key characteristics and metrics of ETIS. These sections (24.2.2 to 24.2.5) are written with greater technical depth and language, and are aimed also at those in the research and business communities interested in understanding the fundamentals and mechanisms of innovation in an energy context. Readers more interested in policy aspects can move on to Section 24.3, revisiting the more technical material of Section 24.2 at a later stage. Given the range of potential audiences, considerable effort has been made to define key terms (see Table 24.1 and also the GEA Glossary), use consistent terminology, and support conceptual arguments with empirical details from the case studies.

### 24.1.3 Technological Change in Energy Systems

Technological and congruent institutional and social changes have been widely recognized as main drivers for long-run economic growth ever since Solow (1957), and for broader societal development as well (Freeman and Perez, 1988). In terms of causality, caution is advised as technology and institutional/social setting co-evolve, mutually depending on and cross-enhancing each other. Technological change in energy systems to a large degree determines how efficiently energy services can be provided, at what costs, and with which associated externalities. Scholars agree on the importance of technological change in past and future energy transitions (e.g., Smil, 1994; Grubler, 1998; Nakicenovic et al., 2000; Grubler, 2008; and the literature review in Halsnæs et al., 2007).

The *Grand Designs* case study (summarized in Appendix II, see also Wilson and Grubler, 2011) provides a synthesis of major patterns driving historical energy transitions and contrasts this historical perspective by examining also the scenario literature on the importance and patterns of technological change in alternative futures. The transformative power of technology arises from: (1) combinations of interrelated individual technologies (clustering) and applications of technologies outside their

**Table 24.1** | List of key terms

| Key Term | Definition as Used in Chapter 24 |
|---|---|
| ETIS | Energy Technology Innovation System: the innovation systems approach applied to the energy system. In this approach, innovation is understood as an interactive process involving a network of firms and other economic agents that, together with the institutions and policies that influence their innovative behavior and performance, bring new products, processes, and forms of organization into economic use |
| Invention | origination of an idea as a technological solution to a perceived problem or need (usually codified via a patent) |
| Innovation | putting ideas into practice through an (iterative) process of design, testing, and improvement, including small-scale demonstration or commercial pilot projects, and culminating in the establishment of an industrial capability to manufacture a given technological innovation |
| Diffusion | widespread uptake of a technological innovation throughout the market of potential adopters |
| R&D (Research and Development) | knowledge generation by directed activities (e.g., evaluation, screening, research) aimed at developing new or improving on existing technological knowledge |
| Demonstration | construction of technology prototypes or pilots demonstrating technological feasibility |
| RD&D (Research, Development and Demonstration) | integration of the required upfront stages in a technology life cycle (invention-innovation)<br>related terms: RDD&D (i.e., RD&D + deployment) |
| Market Formation | application of a technology in a specific limited market setting (or niche) by harnessing either a specific comparative advantage (e.g., PV electricity in remote areas without grid connections) or via public early deployment incentives (e.g., feed-in tariffs)<br>related terms: market creation, niche markets, deployment, early commercialization |
| Learning | improved (technological) knowledge derived from production experience (learning-by-doing) and/or user experience (learning-by-using) that leads to performance improvements, including cost reductions |
| Knowledge Spillovers | knowledge transfer between different innovation actors and technology application fields through mechanisms such as imitation, trade, licensing, foreign direct investment, and/or movement of people |

initial sector/use (spillovers); (2) the continued improvements of technology performance and costs as a result of innovation efforts and market growth (learning and economies of scale effects, among others); (3) energy end-use and technology users/consumers are particularly critical; and (4) generally, rates of capital turnover and technological change in the energy systems remain slow. These four "grand" patterns of energy technological change are addressed in more detail below.

(1) No individual technology, as important it may be, is able to transform whole energy systems that are large and complex. The importance of technology arises in particular through *clustering* (combinations of interrelated individual technologies) and *spillover* (applications outside the initial sector/use for which a technology was initially devised) effects. The concept of general purpose technologies (GPT) (e.g., Lipsey et al., 2006) captures this notion that some technologies, like steam power or electricity, find multiple applications across many sectors, industries, and energy end-uses. Technologies operate more effectively as families or as "gangs" rather than as individuals. Strong interrelatedness conditions major innovations in the energy sector to a multitude of complementary changes, including also new business and financing models, as demonstrated in the history of electric light and power (Hughes, 1983) or the emergence of oil-based individual motorized mobility with automobiles (Freeman and Perez, 1988). Once a technology is adopted, a number of related technologies, derived products, and business models become established. Improvements and knowledge about possibilities and applications accumulate, generating further learning economies as the application range grows (Watson, 2004). Combined, these processes create powerful self-reinforcing mechanisms that make it very difficult to dislodge a dominant technological regime, a fact referred to in the technology literature as "path dependency" or "technology lock-in" (e.g., Frankel, 1955; Arthur, 1988a; 1988b; 1989; Unruh, 2000). As a result, new technologies, even when economically feasible, face higher short-term adoption costs compared to established technologies (Cowan and Hulten, 1996; Unruh, 2000).

(2) Generally, when new technologies are introduced, they are initially crude, imperfect, and very expensive (Rosenberg, 1994). Incumbent technologies are generally more advanced in their respective technology life cycle and thus enjoy an associated learning and deployment advantage (Cowan, 1990). Therefore, performance (the ability to perform a particular task or deliver a novel energy service) of a new energy technology initially dominates economics as a driver of technological change and diffusion. Only after an extended period of experimentation, learning, and improvements, and the establishment of a corresponding industrial base (in many cases, profiting from standardization, mass production, and scale economies of a growing industry) do new technologies become capable of competing with existing ones on a pure cost basis. In other words, *attractive beats cheap*, at least initially. Policy intervention can short-cut this evolutionary pattern and are justified when "attractiveness" is defined by lower externalities (e.g., emissions, energy security, etc.). However, such policy interventions come at a price: either costly direct public subsidies or changed economic incentives (via levies, fees, taxes imposed on incumbent, undesirable technologies – and paid for by consumers). There is also a risk of policy-induced premature "lock-in" in technologies that ultimately turn out to be either socially undesirable, too expensive, or risky for unregulated markets (cf. the *French Nuclear* case study in Appendix II), or pose unanticipated social/environmental challenges, e.g., land competition with food production or greenhouse gas emissions associated with fertilizer use and land-use changes in the case of first generation biofuels (Plevin et al., 2010).

(3) The history of past energy transitions highlights the critical importance of end-use services (i.e., consumers, energy *demand*). Historically, energy supply has *followed* energy demand in technology applications, and energy end-use markets have been the most important market outlets for new energy technologies (as quantified in the *Grand Designs* case study. See also Appendix I for a quantification of current energy end-use versus energy supply investments). In other words, new energy technologies generally need to find consumers (users), preferably many. This holds important implications for both modeling future energy transition scenarios and technology innovation and diffusion policies alike, where energy end-use technologies are often underrepresented.

(4) The process of technological change (from innovation to widespread diffusion) takes considerable time, usually many decades. In addition, rates of change become slower the larger the energy system or its components, and when consequences of those changes are more disruptive. A novel approach that quantifies the historical scaling dynamics of energy technologies and illustrates this conclusion is reported in the *Scaling Dynamics* case study. The historically slow rates of change of energy technologies and systems, which span from several decades up to a century (for a review, see Grubler et al., 1999), arise from four phenomena:

- Capital intensiveness: investments in energy technologies are among the most capital-intensive across industries, characterized by high up-front costs, a high degree of specificity of infrastructure, long payback periods, and strong exposure to financial risk (IEA, 2003). Capital intensiveness, therefore, ceteris paribus slows technology diffusion.

- Longevity of capital stock: the lifetime of the capital stock of energy systems in many end-use applications (buildings), conversion technologies (refineries, power plants), and above all, infrastructures (railway networks, electricity grids), is generally long compared to other industrial equipment or consumer products (Smekens et al., 2003; Worrell and Biermans, 2005). Longevity of capital stock tends to slow capital turnover and thus the diffusion speed of new technologies.

- Learning/experimentation time: extended time is required for experimentation, learning, and technology development from invention to innovation, to initial specialized niche market applications, and finally, in case of success, to pervasive adoption across many sectors, markets, and countries.

- Lastly, considerable time is also required for technology clustering and spillover effects to emerge.

Only in exceptional cases does the diffusion of new technologies proceed via a premature retiring of existing capital stock, as is the case in current cell phone markets or with information and communication technologies (ICT) in general. In view of the generally slow rates of change in large technology systems like energy, pervasive technological transformations require a long-term view, and it is better for transition initiatives to start sooner rather than later.

The above characteristics of technological change in energy systems are important for policy, as they suggest that approaches must be systemic, long-term, and cognizant of inevitable innovation uncertainties. Short-term, piecemeal efforts to stimulate innovation and speed technology diffusion are unlikely to result in the kind of major technological transformations needed to achieve more sustainable energy systems as called for throughout the GEA.

## 24.2 Characterizing Energy Technology Innovation Systems

### 24.2.1 Introduction to the Energy Technology Innovation System

#### 24.2.1.1 From Linear Models to Innovation Systems

The evolution of technology is often conceptualized through a life cycle model that proceeds sequentially from birth (invention, innovation), to adolescence (growth), maturity (saturation), and ultimately senescence (decline due to competition by more recent innovations). Models of innovation describe the drivers and mechanisms behind this technology life cycle. These have evolved substantially and continue to evolve further. The intellectual history of innovation concepts reaches back into the nineteenth century (e.g., Marxist economic theories and their conceptualization of technological innovation). Still influential today are the theories of Joseph A. Schumpeter (1942), who emphasized the importance of radical or disruptive technological and organizational changes, the role of entrepreneurship, and competition. In contrast to Schumpeter's emphasis on radical "breakthrough" innovations, the importance of the compounded effects of numerous, smaller (incremental) innovations is also now widely recognized. Concepts formulated by Vannevar Bush in his 1945 report to the US president, *Science the Endless Frontier*, were influential on early models of innovation (Bush, 1945). These are often referred to as "linear" models. These models emphasize the role of basic,[3] largely publicly funded science in a linear innovation process from basic research to applied development, demonstration, and concluding with the diffusion process (see the upper part of Figure 24.2).

3 The term "basic research" refers to study and research in pure science that aims to increase the scientific knowledge base. This type of research is often purely theoretical and has the intent of increasing the basic understanding of certain phenomena or behaviors; it does not seek to identify concrete applications of phenomena studied or to solve particular applied problems.

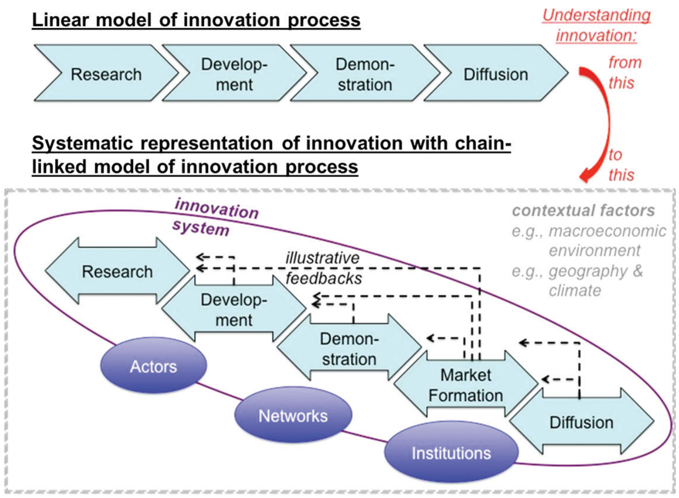


**Figure 24.2** | The Evolution of Thinking on Innovation Processes.

In truth, it is well understood that the innovation process is neither linear nor unidirectional (Mowery and Rosenberg, 1979; Landau and Rosenberg, 1986; Freeman, 1994). Rather, the stages of the innovation process are linked, with feedbacks between each stage, giving rise to the term "chain-linked" model (Kline and Rosenberg, 1986; Brooks, 1995). This is illustrated in the lower part of Figure 24.2. The linear knowledge flow direction from basic science to applied technology as implied by the old "linear" model is now recognized to be more complex because it can also go in the opposite direction, with applied technologies enabling breakthroughs in basic science.[4] Likewise, research has identified the importance of knowledge spillovers and networks in collective learning processes, as there is no quasi-automatic "trickle down" from basic scientific knowledge to industrial applications of that knowledge.

Figure 24.2 represents the main modifications and additions to this "chain-linked" model of the innovation process. In this improved model there are multiple feedbacks among the different stages and their interaction, combining elements of "supply push" (forces affecting the *generation* of new knowledge) and "demand pull" (forces affecting the *demand* for innovations) (see the review in Halsnæs et al., 2007). Indeed, the stages often overlap with one another and the more interaction among the various stages, the more efficient the innovation process as offering more possibilities for learning, and knowledge and technology spillovers. And, of course, some technologies are successful without proceeding through each step in the innovation process (Grubler, 1998).

The distinction between supply-push and demand-pull has traditionally been important, especially as they imply different technology policy instruments – e.g., public R&D expenditures or incentives for private R&D as classical technology "supply" instruments versus government purchase programs, mandated quantitative portfolio standards, regulated feed-in tariffs, or subsidies as classical technology "demand"

4 For example, satellite measurements leading to the discovery and subsequent explanation of previously unrecognized environmental problems such as stratospheric ozone depletion.

policy instruments. As argued here, from the perspective of a systemic innovation model characterized by multiple feedbacks, this technology supply-demand dichotomy is artificial to a degree. Transformative technological change generally requires the simultaneous leveraging of all innovation stages, processes, and feedbacks, and thus a combination of both supply- and demand-side technology policy instruments.

In an additional improvement over previous models, a market formation stage[5] has been added in explicit recognition of the so-called "valley of death"[6] observed in this innovation process between technology demonstration and diffusion. Many technologies fail at this or a similar hurdle between development and demonstration if they are too expensive, otherwise uncompetitive, too difficult to scale up, or lack perceived market demand. Market formation activities support new technologies that can struggle to compete with incumbent technologies that enjoy economies of scale and the learning advantages resulting from their more mature technology life cycle. In some cases, natural market niches exist that value the relative advantages of the new technology and offer a price premium. In other cases, it is important to create new niches (Kemp et al., 1998).[7]

The importance of the institutional context in which innovation occurs is also increasingly emphasized (Nelson, 1993; Geels, 2004). This points to the need for a more systemic approach to innovation, extending beyond the technology-focused "hardware" innovation process to also include analysis of actors, networks, and institutions.

Finally, the broader context of the innovation system matters. Technological, national or geographical factors affect the relative importance, roles, and relationships between components of the innovation system or the specific incentives structures in place. The concept of "national systems of innovation" (Nelson, 1993; Lundvall, 2009) describes this specificity. As a result, innovation systems for specific energy technologies vary substantively in their details, involving different sets of actors (e.g., incumbents or new entrants), interacting in different ways (e.g., research or market development), focusing on different problems (e.g., problem solving or learning by doing), and acting at different spatial scales (e.g., national or global) (Jacobsson and Lauber, 2006; Hekkert et al., 2007).

#### 24.2.1.2 The Innovation Systems Approach

Taken together, the different elements described in the preceding section comprise the innovation systems approach used as the conceptual framework for this chapter. This is represented in the lower part of Figure 24.2. The different traditions of innovation and energy technology research outlined above (from linear to systemic) are drawn upon to support this chapter's integrative perspective. The innovation systems approach centers on the set of factors that drive and direct innovation *processes.* From a systemic perspective, innovation is understood as an interactive process involving a network of firms and other economic agents (most notably users) who, together with the institutions and policies that influence their innovation and adoption behavior and performance, bring new products, processes, and forms of organization into economic use (Nelson and Winter, 1982; Freeman and Perez, 1988; Lundvall, 1992).

The innovation systems approach emphasizes that the life cycle of a particular technology must develop in tandem with its corresponding innovation system (Jacobsson and Johnson, 2000). For new technologies that are incremental improvements to existing ones, innovation systems are already in place. For example, the development of a more efficient gas turbine occurs within a mature innovation system comprised of large firms with high R&D spending, strong networks between suppliers and users of the technology, established markets and well-aligned institutional infrastructures. In contrast, innovation systems need to be built up for radically new or disruptive innovations that strongly deviate from existing technologies and practices (van De Ven, 1993). Current examples of radical innovations in the energy domain are solar photovoltaic (PV) and electric vehicles. Innovation systems emerging around such technologies may be characterized by poorly developed markets, misaligned institutional settings, poorly structured knowledge networks, and small firms with limited resources to develop and market the new technology (Alkemade et al., 2007).

It takes time to build up an innovation system, particularly for radical innovations whose initial development typically takes place over decades (see the *Scaling Dynamics* case study). Weak or immature innovation systems may delay the progress of an innovation, or decrease the likelihood of its success (van De Ven, 1993). In the initial stages of the innovation process, only a few actors are involved in developing a new technology. Over time, other actors enter, the knowledge base starts to grow, often the legitimacy of the new technology increases, and more financial resources become available (although sometimes creating exuberant expectations that can lead to investment bubbles). Through this "formative phase," the innovation system around a new technology is built up (Jacobsson and Lauber, 2006). At a certain point, the innovation

5 Traditionally, market formation policies have been used in the defense (e.g., jet engines) and space sectors (e.g., photovoltaic [PV] technology) to kick-start a minimum level of technology demand for a nascent industry or technology.

6 The "valley of death" describes a situation where a successful R&D project either cannot attract funding for further development, or, once developed, cannot attract funding for large-scale demonstration of the new technology. It can also occur when the capital intensiveness of a project exceeds the financial resources of an otherwise willing investor (e.g., venture capital) or when promised public support does not materialize. For instance, the US FutureGen "clean coal" (advanced coal gasification, combined cycle, electricity generation plant combined with CCS) demonstration project was discontinued mid-stream after the US Department of Energy stopped funding due to substantial cost overruns (Rapier, 2008).

7 Examples of "natural" market niches include the first applications of PV in instruments (calculators) and toys in the Japanese electronics industry that did not need any public policy support and incentives, see the *Solar PV* case study in Appendix II. For an example of "created" niche markets, consider the case of Switzerland, where regulation requires electricity back-up systems for all public and technological infrastructures. This has created niche markets for microturbines and fuel cell applications for onsite electricity generation in hospitals, supermarkets, or cell phone towers.

system becomes large and developed enough for technology diffusion to take place during a "growth phase" (Jacobsson and Lauber, 2006).

#### 24.2.1.3 The Energy Technology Innovation System (ETIS): What is it? Why is it needed?

ETIS is the application of this systemic perspective on innovation to energy technologies. In terms of the innovation system, this means the synthesis and analysis of data on the various stages of the innovation process; on different inputs, outputs and outcomes; on actors and institutions; and on the key innovation processes. In terms of the energy system, this means the synthesis and analysis of data on both the energy supply side and the energy demand side; on different energy technologies; and on both developed and developing countries. ETIS is thus an integrative approach that aims to comprehensively cover all the components of energy technology innovation systems, in terms of innovations, mechanisms of change and supporting policies, and energy technologies (supply and end-use), as well as in terms of geographical and actor network coverage.

Why is such a systemic approach needed? The GEA sets out clearly the magnitude of the challenge facing the global energy system. The GEA transition pathways – described in Chapter 17 – illustrate that a substantive and pervasive technological transformation in energy systems towards vastly improved efficiency and decarbonization is needed. This holds regardless of the ongoing debate over whether it is possible to improve existing technologies incrementally, with the primary challenge one of diffusion (Pacala and Socolow, 2004), or whether breakthroughs with radically new technologies are needed with the main challenge being basic and applied research (Hoffert et al., 2002; Hoffert, 2010).

It is the magnitude of the challenge that most clearly points to the need for a systemic perspective rather than a piecemeal approach focused on particular technologies (e.g., PV or CCS) or particular drivers (R&D or feed-in tariffs). This is fully supported by the accumulating body of knowledge on innovation processes and innovation histories, both successful and failed. New research carried out for this chapter adds to these findings. All point to the interrelationships and dependencies within effectively functioning innovation systems. This too necessitates a systemic approach.

ETIS has certain key characteristics which emerge repeatedly through the literature and are worth emphasizing. These include interdependence, uncertainty, complexity, and inertia. Interdependence means that different components of ETIS influence one another; moreover, 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. This is further exacerbated by context-dependence in the application of the ETIS framework to specific energy technologies. Inertia also arises from interdependencies, and is exacerbated by 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 ETIS to support its effective functioning. Again, these emerge repeatedly in the literature and include coherence, alignment, consistency, stability, and integration. "Effective functioning" is used here in a qualitative sense. ETIS that demonstrate the full complement of drivers, mechanisms, actors, and institutions described in this chapter are more likely to be successful than ETIS that are lacking in one or more areas. Failure and success are not defined in absolute terms. Innovation system success could be interpreted most simply as widespread diffusion of new technologies and practices and when innovation benefits outweigh costs (in a large societal context). This is the ultimate outcome of interest for innovation processes in the context of energy system transformation required by the GEA objectives. Conversely, innovation system failure can be dramatic, as in a technology which fails in the "valley of death," or relative, as in a technology which diffuses slowly, to a low extent, or in a stop-start manner.

#### 24.2.1.4 Strengths and Weaknesses of the ETIS Perspective

A systemic approach to innovation in an energy context is largely novel and challenges some established wisdoms. This is a recurring theme throughout Chapter 24 and is explicitly noted in the final policy guidance section, which directly questions certain policy myths, and in the quantitative assessment of financial inputs into ETIS presented in Appendix I. 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) has tended to focus on one piece of this puzzle. This chapter's comparative assessment makes (within the limitations of available data) commensurate what have to date largely been apples, oranges, pears, and peaches. Certain patterns emerge from this commensuration that have direct implications for the ETIS and its effective functioning. An example is an apparent mismatch between the target of innovation investments and the need for diffusion investments. This is explained and discussed at length below. Here, it suffices to note that the implications of the systemic perspective offer a challenge to prevailing practice and thinking. One example is the question of whether the technological, market, and institutional differences between the supply side and demand side of the energy system mean an integrative comparison is worthwhile or even meaningful. The ETIS perspective contends that it is, as the resulting insights are both important and potentially transformative.

Despite the strengths of the systemic perspective, its weaknesses and limitations should also be acknowledged. Though rich and detailed in certain areas, ETIS research is weaker in others, such as feedbacks between components of innovation systems. Studying innovation from a systemic perspective in the energy domain is a relatively young endeavor, with an empirical bias toward national, sustainable, 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 inductively derived. Studies in developing countries are particularly lacking, although this assessment begins to fill the gap with specific case studies on R&D expenditures in emerging economies, energy technology innovation in China, and lessons from solar PV market deployment in rural Kenya. Data are partial, incommensurate, or otherwise limited, as discussed below in the context of assessing ETIS (see Section 24.5.1 on data and information needs identified in this assessment). The understanding of mechanisms and linkages is incomplete. As a result, the ETIS perspective should not be interpreted as a full systemic dynamics model that can support quantitative modeling, simulation, or optimization. Rather, ETIS as developed in this chapter is a conceptual framework with the necessary generality to apply across the entire energy domain.

#### 24.2.1.5 Empirical Basis of the ETIS Perspective

ETIS integrates current understanding of innovation processes within the energy system, their interlinkages, and the roles and influence of different actors and institutions including public policy. This systemic perspective is founded upon empirical work on technology histories such as wind power, processes such as learning, actor networks such as advocacy coalitions, social institutions such as expectations, and so on. This empirical work is covered in extensive literatures, which are referenced throughout the text. In addition, this chapter contributes a series of new empirical studies that are summarized in Appendix II, published in full in a companion volume, and referenced throughout the text. These are also summarized in Tables 24.2, 24.3, and 24.4 below and discussed further in the *Assessment Metrics* case study, summarized in Appendix II.

It is important to emphasize this empirical basis for the ETIS perspective. The various components of the ETIS described here characterize what is understood about successful innovation, as well as what may be missing

**Table 24.2** | Chapter 24 case studies (innovation histories): demand-side technologies.

| Short Name | Summary Description | Example of Relevance for ETIS | Chapter Section |
|---|---|---|---|
| Hybrid Cars | Development of hybrid electric vehicles in Japan, United States, and China, emphasizing the role of public policy. | Importance of policy alignment and consistency. Role of market demand and end-user preferences. | 24.7.9 |
| Solar Water Heaters | Early success and later failure of the solar water heater industry, particularly in the United States. | Lasting legacies of industry failure, including knowledge depreciation. Alignment of innovation system actors. | 24.7.10 |
| Heat Pumps | Different stages of heat pump diffusion in Sweden and Switzerland, emphasizing the role of public policy. | Interactions between supply of, and demand for, innovation. Importance of policy stability and consistency. | 24.7.11 |
| US Vehicle Efficiency | The "CAFE" standard for vehicle efficiency in the United States, and its influence on technological change. | Interaction between policy standards and changing market characteristics, including prices. | 24.7.12 |
| Japanese Efficiency | The "Top Runner" program to improve end-use efficiencies in Japan, and the role of dynamic incentives. | Flexible policies creating dynamic incentives within a clear overall strategic direction. | 24.7.13 |

**Table 24.3** | Case studies (innovation histories): supply-side technologies.

| Short Name | Summary Description | Example of Relevance for ETIS | Chapter Section |
|---|---|---|---|
| Wind Power | Evolution of innovation stages and strategies in different wind power markets worldwide. | Need to integrate RD&D support with market formation. Interaction and feedback between innovation actors. | 24.7.14 |
| Solar PV | Development of solar PV in different markets worldwide, focusing on drivers of cost reduction. | Long-term R&D support complemented by market formation activities to stimulate commercial learning. | 24.7.15 |
| Kenyan PV | Market dynamics in the solar PV market in Kenya, emphasizing product quality issues. | Local institutions to set and enforce standards for quality control and assurance. | 24.7.16 |
| Solar Thermal | Early experience of solar thermal electricity in the US, and spillovers to later stage production. | Codification of knowledge. Interaction between R&D and learning to support cost reductions. | 24.7.17 |
| US Synfuels | History of US government investment in synthetic fuel production as oil substitute, and ultimate innovation system "failure." | Over-exuberant expectations in the context of changing market conditions. Public/private roles in innovation system. | 24.7.18 |
| French Nuclear | Review of pressurized water reactor (PWR) program in France, including cost escalation. | Interaction between learning effects and institutions, including standards and regulatory stability. Limitations of learning paradigm in technology cost reductions. | 24.7.19 |
| Brazilian Ethanol | History of ethanol production and developments in automotive technologies in Brazil, focusing on supporting role of policy. | Coalitions and shared expectations among innovation system actors, and interactions between related technologies. | 24.7.20 |

**Table 24.4** | Case studies (innovation processes and metrics).

| Short Name | Summary Description | Example of Relevance for ETIS | Chapter Section |
|---|---|---|---|
| Grand Designs | Review of patterns, drivers, and dynamics of energy systems, both historically and in future scenarios. | Knowledge spillovers and inter-dependence between innovations creating inertia and path dependence. | 24.7.1 |
| Scaling Dynamics | Comparison of rates and extents of growth in 8 energy technologies historically. | Experimentation with small-scale units takes place during extended early formative phase. | 24.7.2 |
| Technology Portfolios | Tools to guide the selection of innovation portfolios under conditions of uncertainty. | Formal tools to support portfolio selection and diversification. Historical under-representation of end use technologies. | 24.7.3 |
| Knowledge Depreciation | Loss or obsolescence of knowledge, with examples in the context of energy innovation. | Importance of stable, sustained inputs to knowledge generation. High potential rates of knowledge depreciation. | 24.7.4 |
| Assessment Metrics | Quantitative metrics and qualitative approaches for assessing innovation. | Assessment of inputs, outputs, or outcomes, but not typically innovation systems as a whole. Data limitations. | 24.7.5 |
| Chinese R&D | Overview of R&D investments in China, with relevant institutions and mechanisms. | Substantive and growing R&D, dominated by industry but with strong government role. Supply-side technology emphasis. | 24.7.6 |
| Emerging Economies R&D | Review of RD&D investments in 6 major emerging economies, by technology type and source. | Increasing importance of emerging economies in global energy technology innovation system. Supply-side technology emphasis. | 24.7.7 |
| Venture Capital | Trends and targets of venture capital investments in energy technology innovation. | Rapidly growing venture capital investments in energy innovation. Non-fossil supply-side emphasis. | 24.7.8 |

in cases of failed innovation. In this way, it should be treated as descriptive, induced, and interpreted *ex post* from available evidence; it should not be treated as normative. Partly for this reason, we use the ETIS perspective in the concluding section to abstract some general guidance for policy makers rather than offering more specific, universal prescriptions. As noted, the ETIS perspective is not sufficiently developed nor detailed to support a quantified system dynamics model. Nor is it necessarily appropriate to generate formalized, testable hypotheses which are replicable in both form and method across different technologies and contexts. Clearly, further work is needed in this direction. Testing, critiquing, and improving the ETIS perspective is of critical importance, given the magnitude of transformation needed in the energy system as captured by the GEA.

## 24.2.2 Characteristics of ETIS (I): Knowledge

### 24.2.2.1 Sources and Generation of Knowledge

"The most fundamental resource in the modern economy is knowledge and, accordingly, the most important process is learning" (Lundvall, 1998). Knowledge is a ubiquitous and powerful driver of technological change. Technological knowledge can be basic ("know-why") or applied ("know-how"), as well as publicly available (e.g., through scientific or engineering journals) or entirely tacit (e.g., resting with accumulated experience of a production engineer in manufacturing). Understanding the process of generation, reproduction, and diffusion of knowledge and the constraints to knowledge flows is therefore critical for innovation policy.

Knowledge is generally largely a public good. Once produced and disclosed, it is difficult to control or restrict its use. For activities organized around reward systems based on reputation and primacy of discovery, like science, this poses less of a problem (Dasgupta and David, 1994). As more basic knowledge becomes integrated into technological solutions and into the realm of private production, the public aspect of knowledge which makes it expensive to generate, but cheap to reproduce, is generally classified as a source of market failure. This results in underinvestment in knowledge production (Arrow, 1962a). This is the traditional argument for encouraging public sector support for the generation of basic knowledge and allowing knowledge appropriability of private R&D through systems of property right protection.

Knowledge is generated at several different levels of innovation systems, through several distinct processes of knowledge exchange and transformation within and between agents and institutions. It is, therefore, a powerful source of feedback, correction, and advance in innovation systems. Basic science is, of course, a strong component of innovation in energy systems (Ausubel and Marchetti, 1997) and the disciplines that support it are numerous. However, technical change in energy systems tends to be based dominantly in engineering practices and disciplines, and the origins of major innovations have often come from outside basic energy science proper. (The best historical example is the development and application of steam engines much before the discovery of the Laws of Thermodynamics.) These specialized sources of knowledge outside classical basic science are crucial for energy technology innovation. Technology knowledge is also spawned during productive experience and a result of producer-user collaborations in technology development and of producer-producer collaborations in technology production at the manufacturing stages (von Hippel, 1988; Lundvall, 1992; see also Fridlund, 2000 for a case study on user-producer learning in the electric power sector in Sweden). Experience in production and use, as well as knowledge exchange between different types of producers and users, are important sources of specific knowledge that cannot be generated by scientific research (i.e., cannot be predicted from general principles or comparable technologies). This feedback process from application experience to redesign and engineering has been particularly important in energy technologies (see the *Wind Power*, *Solar PV*, and *Kenyan PV* case studies summarized in Appendix II) and highlights the importance of market applications as main knowledge and learning feedbacks enhancing R&D efforts that require appropriate incentives beyond R&D.

Applied energy research and development on the supply side has been oriented and guided by four main sets of goals, or "focusing devices" (Rosenberg, 1982):

- harnessing new energy sources and carriers with special qualities like energy density, abundance, transportability, but also flexibility, convertibility, and modularity;
- increasing efficiency, both in thermodynamic as well as in economic terms (cost reductions);
- improving control, security, and stability of energy conversion and delivery infrastructures; and
- improving adverse social and environmental impacts of energy systems.

Whereas the first three goals can be considered endogenous for the energy system, the goal of improved social and environmental performance has historically been triggered by regulation. R&D intensity (R&D expenditures per unit of value added) in the energy sector is strongly differentiated between energy supply (e.g., electric utilities) and energy demand (e.g., manufacturing of electricity using equipment such as TVs or computers) industries. At least in developed countries, energy supply industries have lower R&D intensity levels than the manufacturing average, similarly low as in the textile industry (see Figure 24.3). Conversely, electrical machinery, transport equipment and motor vehicles exhibit higher than average R&D intensities, although no information is available to differentiate their R&D into energy- and non-energy-related components (e.g., more fuel efficient engines versus safety improvements in motor vehicles).

#### 24.2.2.2 Characteristics of Knowledge: Codification and Spillovers

Knowledge possesses a number of unique characteristics. It is *nonrival* (the use of knowledge by someone does not preclude its uses by someone else); *nonexhaustible* (can be used/reproduced without paying for an additional copy); *combinatorial* (knowledge is combined from different specific knowledge bases); and *cumulative* (builds on pre-existing knowledge). These features of knowledge can generate very high social rates of return and call for minimizing or even eliminating access costs to knowledge if social welfare is to be maximized (Foray, 2004). Indeed, much knowledge relevant in an industry is routinely shared and used by private actors through nonmarket mechanisms, a phenomenon referred to as knowledge "spillover."

Knowledge spillovers across sectors and across countries have been considered key engines of technological development and economic growth. The most salient sources of knowledge spillovers explored (e.g., Falvey et al., 2004) are universities and R&D centers; personnel training; scientific publications and patents; personnel movements, interfirm turnover; formal and informal networks of scientists, engineers, and technicians; licensing and technology transfer agreements; foreign direct investment; international research collaboration and research; reverse engineering, and international trade in final, intermediate, and capital goods.

The literature is vast and not free of controversies. In general, it has been shown that knowledge spillovers positively impact growth and productivity (Coe and Helpman, 1995; Coe et al., 2009), with highly localized

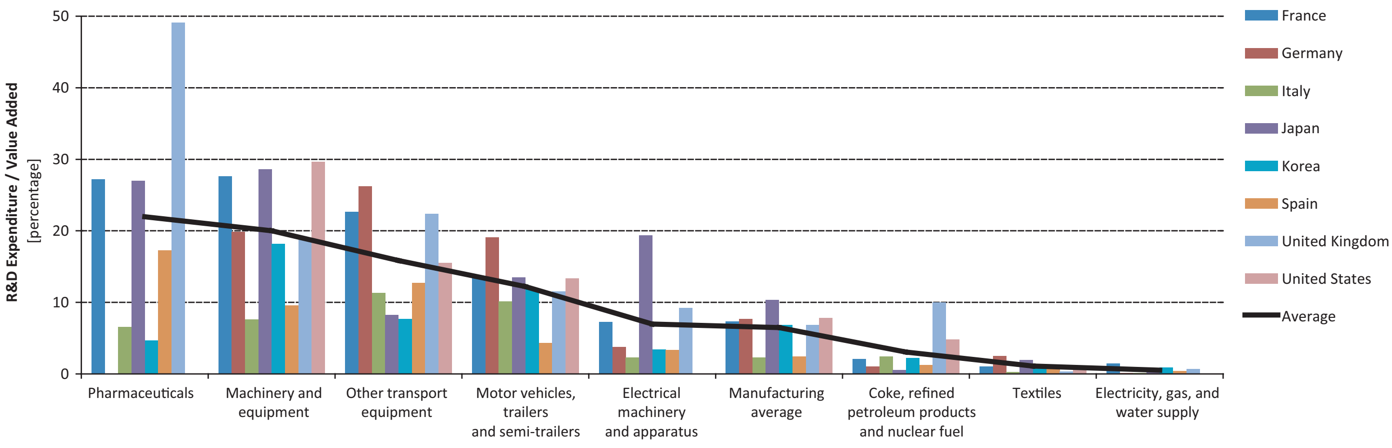


**Figure 24.3** | R&D intensity (expenditures per value added, in percent) for selected sectors and OECD countries in 2002. Source: The OECD Research and Development Expenditure in Industry database and STAN Database.

geographical effects (Jaffe and Trajtenberg, 1999). It has also been shown that the extent of international knowledge spillovers depends on national R&D efforts (Mancusi, 2008; Unel, 2008). Thus, knowledge spillovers depend critically on the assimilative capacity of the recipient country. There are very few studies focusing specifically on knowledge spillovers in the energy sector (an exception being Bosetti et al., 2008). Measuring knowledge spillovers poses many challenges, for knowledge is highly heterogeneous, unobservable, and difficult to define in quantitative terms (Mohnen, 1997; van Pottelsberghe de la Potterie, 1997).

However, there are other important barriers to learning and knowledge advancement through spillovers, which are more relevant for innovation policy design. Knowledge implies more than simply information such as data and formulas; it also implies the cognitive capability to interpret, process, and articulate information. Similarly, in order to understand a problem and make sense of knowledge produced elsewhere, firms require a minimum threshold of accumulated knowledge or absorptive capacity, derived from their direct involvement in R&D, production experience, or training (Cohen and Levinthal, 1990). In many cases, it has been shown that firms engage in R&D not only to produce new knowledge, but to be able to learn knowledge produced elsewhere (Cohen and Levinthal, 1989). In other words, enforcing knowledge appropriability (i.e., knowledge access) is insufficient for knowledge generation and learning (Foray, 2004). Policies are therefore also needed to further absorptive (assimilative) capacity to facilitate learning in firms, but also in the public sector and society at large. For energy technology innovation policy, this implies that an exclusive focus on technology transfer (knowledge appropriability) is entirely insufficient to guarantee technology diffusion, as the latter critically depends on sufficient local knowledge or assimilative capacity. Local knowledge is needed to first decide which globally available technologies offer local diffusion potentials, which requires capacity building for technology assessment both in the public and private sectors. Local knowledge is also needed to import/manufacture, adapt, install, and above all *use* a new energy technology effectively (see e.g., the *French Nuclear* case study, which illustrates the importance of local technological capability in the successful scaling up of imported reactor designs, or the *Kenyan PV* case study as an illustration of the problems arising if local capacity for testing and evaluating technical characteristics [and defects] of imported PV cells are unavailable).

It also important to note that not all technological knowledge is embodied in artifacts or codified in blueprints, manuals, and sets of instructions; much knowledge remains tacit (uncodified) in the form of personal or institutional knowledge and skills. In this case, knowledge generation implies practicing and accumulation of experience (Nelson and Winter, 1982), which needs to be achieved locally and cannot be substituted by "imports." Generally, new knowledge tends to be less codified and articulated, which makes it more difficult to reproduce, memorize, recombine, and learn, which in turn makes it costly to transfer in a usable form (von Hippel, 1994). For new energy technologies, this implies above all a need to develop a local industrial base (either in manufacturing or in using/marketing a new technology) and to promote partnerships that can further the transfer of tacit knowledge. For example, the *Wind Power* case study illustrates the importance of public testing facilities for new wind turbine designs that furthered localized learning and tacit knowledge transfer among firms.

Knowledge is also highly dependent on local conditions and environments and on market structures, and therefore tends to be dispersed by the division of labor and specialization, which raises difficult coordination and communication problems (Machlup, 1984; Smith, 2002). The public sector therefore has an important role to play in furthering formal or informal coordination mechanisms, e.g., technology development "roadmaps,"[8] and setting dynamic technology performance standards (see the Top Runner program described in the *Japanese Efficiency* case study).

Lastly, knowledge can depreciate rapidly if it is not continuously replenished. This depreciation occurs through personnel turnover and retirement, technological obsolescence, and institutional inertia (see Section 24.2.2.4).

For all these reasons, knowledge cannot simply be assumed to generate automatic "spillover" effects. A (local) enabling learning environment is as important, as is the generation of knowledge (elsewhere) in the first place.

The nature of spillovers also depends on the type of knowledge, on the type of industry, and, finally, on the life cycle stage of a technology. In the early phases of the technology life cycle, disembodied knowledge tends to be predominant. As learning experience accumulates,[9] underlying phenomena are better understood and measured, practices and procedures become increasingly codified, and hardware is adapted and developed. The more codified and embodied (in artifacts) technological knowledge is, the easier it is to capture spillovers.

Empirical studies have shown evidence on the importance of knowledge spillovers in new energy technologies, particularly in the cases of PV (Watanabe et al., 2002) and wind energy (Kamp et al., 2004; Lako, 2004).

In Watanabe et al. (2002), a virtuous cycle between R&D, knowledge spillovers, market growth, and price reduction is thoroughly illustrated for the case of the Japanese PV industry. By stimulating public and private R&D on a broad base of industrial sectors and by simultaneously creating incentives for niche market deployment,

8 Successful examples of technology roadmaps can be found especially in the semiconductor industry.

9 The concept of learning via knowledge spillovers is sometimes referred to as "learning-by-interacting" (Lundvall, 1992).

the Japanese Sunshine Program triggered a range of mutually enhancing positive feedback mechanisms. The technology knowledge stock increased rapidly both from proprietary R&D and knowledge spillover effects among Japanese PV R&D and manufacturing firms (even after accounting for knowledge depreciation). Next to innovation, learning contributed to important cost reductions in PV cells, which further induced increases in demand and production; market growth in turn further increased R&D expenditures, closing a positive feedback loop between knowledge generation and market development. As shown in the *Solar PV* case study, PVs also benefited importantly from inter-industry learning spillovers and scale economies, among other factors. The *Wind Power* case study confirms this conclusion: knowledge spillovers have been important sources of innovation and design improvements, including knowledge spillovers between industries (materials, aerodynamic simulations, and designs) and between manufacturers nationally (facilitated by testing stations), as well as internationally. Denmark's success involved not just R&D, but also the facilitation of feedback between users and producers of wind turbines (Garud and Karnoe, 2003). This positive feedback process, based upon inter- and intra-firm knowledge spillovers in which learning and absorptive capacity production are mutually reinforced, can potentially augment an industry's capability of knowledge production (Foray, 2004). The *Solar Thermal* case study shows how interactions between researchers and firms commercializing technologies create feedbacks so that real world problems can stimulate improvements in design. This "learning-by-doing" can be more important for technology development than R&D, and is discussed further below. The *Kenyan PV* case study shows how interactions between firms and users are important to communicate how users adapt technologies into their daily practices, thereby revealing potential quality and technology problems that in turn form the basis for further design improvements.

#### 24.2.2.3 Knowledge Creation through Learning-by-Doing and Learning-by-Using

Processes of learning are essential for the development and introduction of new technologies and comprise a complex set of actors (*who*) and processes (*what* and *how*). Learning results in improved and standardized production processes and products, which in turn can often result in cost reductions. In order to highlight that learning processes require dedicated efforts rather than just the passage of time, resulting cost reductions are often illustrated by so-called "learning curves," i.e., curves that describe the cost development as a function of cumulative production (as a proxy for learning).[10] In reality however, it is not the act of production per se that provides a source of learning but rather a complex set of interrelated processes that include learning at the individual and organizational scale, classical economies of scale in manufacturing, knowledge spillovers, market conditions and structure (e.g., raw material prices, degree of competition), etc. Common to all is that they exercise their impact on costs and cost reductions via accumulated production/market deployment and/or growing industry size.

The learning curve originates from observations that workers in manufacturing plants became more efficient as they produced more units (Wright, 1936; Alchian, 1963; Rapping, 1965). The roots of these microlevel observations can be traced back to early economic theories about the importance of the relationship between specialization and trade, which were based in part on individuals developing expertise over time (Smith, 1776). Drawing on the concept of learning in psychological theory, Arrow (1962b) formalized a model explaining technical change as a function of learning derived from the accumulation of experiences in production: Arrow's "learning by doing" (LbD) model. Accumulating experience in the early stages of an innovation's life cycle can be a powerful strategy both for maximizing the profitability of firms (BCG, 1972) and for the societal benefits of technology-related public policy.

In its original conception, the learning curve referred to the changes in the productivity of labor that were enabled by the experience of cumulative production within a manufacturing plant. It has since been refined. For example, Bahk and Gort (1993) make the distinction between "labor learning," "capital learning," and "organizational learning." Subsequently, the Arrow model was complemented by an analogous concept, that of "learning by using" (LbU), referring to learning effects from the perspective of technology users (e.g., plant and equipment operators or consumers as opposed to technology producers).

Often, the term "experience curve" is used in the literature to provide a more general formulation of the learning concept, including not just labor but all manufacturing costs (Conley, 1970) and aggregating entire industries rather than single plants (Dutton and Thomas, 1984) or entire technological "trajectories" rather than individual technology generations. Though somewhat different in scope, each of these concepts is based on Arrow's explanation that "learning-by-doing" provides

10 In the functional form of: $C_t = C_0 * X^{-\varepsilon}$ where the costs at ***t*** are a function of the costs at ***0*** multiplied by the cumulative production volume X to the exponent of the so-called learning rate $\varepsilon$. Thus a learning rate $\varepsilon$=0.2 indicates a cost reduction by 20% per doubling of cumulative production. A related concept used in the literature is the so-called progress ratio $PR = [P_0 * (2X)^{-\varepsilon}]/[P_0 * X^{-\varepsilon}] = 2 - \varepsilon$. Hence a progress ratio of 0.8 (1-$\varepsilon$) indicates that costs are at 0.8 of their original value after a doubling of cumulative production. A specific characteristic of learning curves is that costs are reduced by a constant percentage with each doubling of output. As the doubling of cumulative production is more rapid in the early phases of an industry compared to mature ones, cost reductions invariably are steeper in early industries and tend to decline with increasing maturity as the doubling of cumulative production volume requires ever longer time. The observed cost reduction for different technologies analyzed in the literature covers a range up to 40% cost reductions for each doubling of the total number of units produced (e.g., Argote and Epple, 1990). There are also well-documented cases in the aircraft and nuclear reactor industries that exhibit "negative" learning, i.e., costs increase rather than decrease with accumulated production volumes. (See the *French Nuclear* case study in Appendix II.)

opportunities for cost reductions and quality improvements and the following discussion will therefore refer to this phenomenon simply as "learning"[11] or "learning curve."

There have been a number of misconceptions about how to use and interpret learning curves (see Neij, 2004; Nemet, 2006) that have resulted in certain pitfalls in communicating with policy makers. For instance, a popular misinterpretation of learning (or experience) curves is that policies can simply "buy down" (e.g., Brennand, 2001) technology costs through, for example, one-sided demand-pull policies without due regard to the equally needed supply-side technology innovation policy aspects. A second pitfall of cost "buy down" policy approaches is the assumption that the extent of possible "learning" can be *ex ante* anticipated (i.e., "forecasted"), which evidently is not possible. Evidence from the descriptive case studies performed within Chapter 24 is used to inform the general insights for policy design covered in Section 24.4.

Learning phenomena and curves are frequently evoked in cost trend analysis of nonstandardized products produced globally or nationally. The resulting uncertainties and variation in estimates/projections need, however, to be assessed critically (van der Zwaan and Seebregts, 2004). Variations in calculated learning (or experience) curve parameters as a function of different levels of spatial aggregation, observational period, or the use of price data as a proxy for cost information are examples of important uncertainties. Future prices may not only be reduced as a function of "learning," but may also increase as a result of escalating input prices, quality improvements of the product, or lack of competition in quasi monopoly markets, especially under rapid demand growth. The example of wind turbines illustrates this point nicely. Whereas prices fell in line with the "learning curve concept" until the late 1990s, prices have risen since the early 2000s. A recent study reviewed cost estimates in offshore wind projects in the United Kingdom and found a real-term cost escalation of a factor of two since 2000 to some £3000/kW, or US$5000/kW (UKERC, 2010). Similar trends have been observed in the VS as well (Bolinger and Wiser, 2012). The reasons for such cost escalation are varied and include rising material prices, much larger wind turbines, and component supply bottlenecks, among others. It also appears that policy (favorable feed-in tariffs) stimulated rapidly increasing demand growth for wind turbines and enabled opportunistic pricing strategies of wind turbine manufacturers. The rapidly growing demand led to significant supply bottlenecks, further reducing competition in this oligopolistic industry.

11 Often the literature refers to "experience curves" to describe cost reductions in aggregate costs over entire industries and across a whole series of technological generations and thus includes the effects of product design changes and improvements as well as manufacturing economies of scale in cost reductions, which were initially excluded in "learning curve" analyses (for a discussion of these two concepts see Nemet, 2009b). However, this terminological distinction has not become standardized and aggregate cost reductions over entire industries continue to be referred as "learning curves" as well. To add to the confusion, the ensuing cost reductions of learning processes are also defined differently in the literature, either as percent cost reductions per doubling of cumulative output (or manufactured units), or as the percent original costs remaining after a doubling of cumulative output (cf. the discussion in footnote 10).

Secondly, the driving forces of the cost reductions remain unexplained by such aggregate analyses. In order to develop scenarios of possible future technology cost trends as a guide for policy, the sources of cost reduction must be identified and analyzed separately – be they characteristics of innovations (radical or incremental), knowledge generation and spillovers, the importance of economies of scale effects, or other factors. Such detailed analyses are increasingly becoming available (see, e.g., Krawiec et al., 1980; Hall and Howell, 1985; Nemet, 2006; van den Wall Bake et al., 2009; see also the *Solar PV* and the *Brazilian Ethanol* case studies).

R&D investments or other sources of knowledge generation are now increasingly recognized as not being simple substitutes for the accumulation of actual production experience (see the discussion in Halsnæs et al., 2007). These two sources of technological learning are therefore more usefully conceptualized as complementary to each other.

#### 24.2.2.4 Knowledge Depreciation

It is important to recognize that technological knowledge – like all knowledge – can be accumulated (learned) but equally lost (unlearned). Knowledge depreciation particularly affects settings in which knowledge remains largely tacit, residing in individuals or organizational entities (e.g., managers) and needs to be acquired again in case of staff turnover or stop-and-go production schedules. A second type of depreciation occurs as old knowledge becomes obsolete. Knowledge can depreciate because of an insufficient "recharge" (Evenson, 2002) of knowledge in cases where innovation proceeds rapidly such that old technological knowledge is no longer relevant for updated processes/techniques, but new learning cannot proceed quickly enough because of financial constraints. It is the latter type of unlearning that is of particular concern in energy technology innovation systems – when rapid rates of innovations coincide with erratic funding and policy support, for which history provides ample examples.

Both knowledge gained from experience through market deployment and knowledge gained from R&D depreciate. The *Knowledge Depreciation* case study (Appendix II) discusses the case of R&D knowledge depreciation of nuclear power (and energy efficiency) R&D in the member countries of the International Energy Agency (IEA), but there is also evidence of nuclear knowledge depreciation beyond R&D, such as in the ability to construct nuclear power plants illustrated in the recent disappointing experiences (substantial costs and construction time overruns) at the two construction sites of the European Pressurized Water Reactor (EPR). (See also the *French Nuclear* case study.)

The particular vulnerability of tacit knowledge to depreciation implies that learning by doing is prone to especially high rates of knowledge depreciation, since experience in production is less likely to be codified than research and development activities and may thus be "unlearned" rather quickly.

As an example of the first source of knowledge depreciation, it has long been recognized in the management literature that in service industries (e.g., pizza franchises) organizational and production knowledge can be lost quickly, especially under high rates of staff turnover (that may be up to 300%/year). Argote et al. (1990) and Darr et al. (1995) report knowledge depreciation rates of between 25–50% month in service industries. Such high rates of knowledge depreciation basically imply that after a year only between 0–5% of the original knowledge of an organization remains. Kim and Seo (2009) arrive at similarly high depreciation rates of some 26%/month in their analysis of Liberty ships manufacture during World War II, even if earlier studies on the same case (e.g., Thompson, 2007) estimate much lower rates of 4–6%/month.

A classic technological un-learning case discussed in the literature is that of the Lockheed L1011 Tri-Star aircraft (Argote and Epple, 1990). The experience in aircraft industries suggests a significant reduction in manufacturing costs as more production experience (output volumes) is accumulated (learning by doing). The only exception seems to be the Lockheed Tri-Star aircraft. When production resumed after an extended production halt, manufacturing costs were much higher and also did not decline, reflecting lost experience or unlearning. The reason for this knowledge depreciation was basically the same as for pizza franchises. During the production halt, the entire staff of the manufacturing plant was fired, including managers who, according to Michina (1992; 1999), are the main locus of organizational learning and knowledge accumulation in aircraft manufacturing. Benkard (2000) reports corresponding knowledge depreciation rates of typically 40%/year in aircraft manufacturing.

In innovation-intensive industries, estimates of knowledge depreciation are extremely limited. Hall (2007) provides one of the few comprehensive efforts to estimate knowledge depreciation across various industry sectors, relating the market value of firms to patent data to estimate the R&D knowledge depreciation in six US industry sectors. Hall finds knowledge depreciation to vary significantly over time and across industries, with median R&D knowledge depreciation rates of between 15%/year (drugs and instruments) to 36%/year (electrical). Watanabe et al. (2002) provide one of the few estimates for energy technologies. By constructing a knowledge stock model for the Japanese PV industry that includes both R&D by firms and knowledge spillovers from other firms (measured via patent citations), he estimates a mean PV knowledge depreciation rate of some 30%/year (Watanabe et al., 2002). This implies that without continuous recharge (R&D), an existing technology knowledge stock is reduced to some 25% of the original value after five years and to less than 5% after 10 years. Nemet (2009a) provides an illustration for the US wind turbine industry by analyzing a set of "highly cited" wind energy patents. He finds that 40% of all (cumulative) citations occur during the first five years, after which citations decline to basically zero after 25 years. This declining trend in patent citations after year five reflects their decreasing significance and can be used as a proxy for R&D knowledge depreciation, which corresponds to a rate of approximately 10%/year after the fifth year.

The available literature thus suggests typical knowledge depreciation rates of 10–40%/year in industries comparable to energy (i.e., where innovation and R&D play a significant role). Given such high rates of obsolescence of technological innovation knowledge, continuous knowledge recharge becomes extremely important. In case of erratic stop-and-go policy support for knowledge generation, e.g., through R&D, knowledge depreciation rates can outweigh knowledge recharge rates, as discussed in the *Knowledge Depreciation* case study for nuclear. The nature of knowledge generation support (stable versus erratic) is thus as important as the absolute levels of resources made available, which provides an important argument for stability and gradual expansion of inputs to ETIS over "crash" programs that may not be sustained over any significant time periods.

In their study of knowledge depreciation of professional services, Boone et al. (2008) conclude that the extremely low rates of knowledge depreciation found in engineering design firms are explained by comprehensive knowledge documentation (earlier designs are documented and kept for subsequent use), as well as much lower staff turnover rates (3%), particularly among senior engineers. As such, the study provides valuable lessons for improved knowledge management in ETIS, highlighting the importance of documentation, codification, and preservation of knowledge, as well as the need for a minimum degree of continuity in senior staff that are the living memory of organizations.[12]

### 24.2.3 Characteristics of ETIS (II): Economies of Scale and Scope

A discussion of the sources of technological advance is not complete without reference to the rich body of literature on sources for cost improvements beyond product and process innovation and new knowledge application discussed above, including in particular economies of scale and economies of scope. While economies of scale are recognized as particularly powerful drivers in the historical evolution of energy industries such as electric power (e.g., Lee and Loftness, 1987) or petroleum refining (Enos, 1962), economies of scope merit discussion here for their potential impact on future energy systems.

#### 24.2.3.1 Economies of Scale

**What are Economies of Scale?**
Economies of scale describe reductions in average unit costs as output or production increase over the long run, assuming all factors of

12 It is significant that private firms practicing comprehensive reassignment (job-rotation) policies frequently lack any institutional memory of earlier corporate strategies and corresponding innovation successes and failures. For instance, a group of managers at a major oil company attended a workshop with one of this chapter's authors. At the workshop, these managers contemplated possible investment strategies into renewables, entirely unaware that the company had invested previously in solar PV and biofuels and had already sold these activities.

production are variable. They are often conflated with technical returns to scale, which describe a more than proportional increase in output for a given increase in inputs. For examples, see Table 24.5. For further discussion and theory, see Chapter 4 of Rosegger (1996).

Economies of scale can act at different levels (see Table 24.5). Cost reductions associated with scaling at the unit level of a technology (e.g., size of wind turbines) or at the level of manufacturing plants (size/output of a manufacturing plant producing wind turbines) are all important drivers of change in energy technologies.

### Unit and Manufacturing Level Economies of Scale

Figure 24.4 illustrates the increasing unit scales of energy technologies over the twentieth century (for other graphical examples, see Smil, 1994; 2008). The graph on the top shows average unit capacities; the one on the bottom shows unit scale frontiers (maximum size of units produced/installed) with characteristically concentrated periods of scaling up (note the log-scale y-axis on both graphs). Increases in unit scales have been a pervasive phenomenon for energy technologies throughout the twentieth century.

Observed increases in unit capacities of energy technologies are strongly linked to falling costs driven by economies of scale, particularly for large capacity energy supply and conversion technologies. For example, over a 50-year period, beginning with World War II, the average cost/unit output of a performance optimized fluid catalytic cracking unit in a US oil refinery fell by around 4%/year on a compounded basis (close to an absolute cost reduction by a factor of seven). These continuous cost improvements were driven by capital and labor productivity gains associated with an order of magnitude increase in unit capacity from 15,000 to 140,000 barrels/day (Enos, 1962).

Additional examples of unit-level economies of scale are presented in the *Solar PV, Solar Thermal,* and *French Nuclear* case studies. Distributed energy conversion and end-use technologies are more likely to be characterized by manufacturing scale economies. The exemplar is the car, beginning with the Model T Ford produced from 1908–1927. Bywords of Fordist manufacturing include *specialization* of machine tools, *routinization* of labor tasks, *standardization* of output, and sequencing of manufacturing along *assembly lines* (Raff, 1991). These technical, process, and organizational innovations allowed a scaling of manufacturing output from a single plant at Highland Park near Detroit, with remarkable increases in labor productivity. In a 12-month period between 1913 and 1914, the labor requirements for assembly of a single Model T fell from 12.5 to 1.5 man-hours. This, in turn, contributed to the price of a Model T falling by two-thirds over its 20-year production run (Ruttan, 2001).

Further examples and discussion of manufacturing level economies of scale are presented in several of the case studies, including *Solar PV*, *Hybrid Cars*, *Heat Pumps*, and *Brazilian Ethanol*.

### Drivers of Economies and Diseconomies of Scale

Table 24.5 summarizes some common drivers of scale economies. The examples given above further emphasize the relationship between scale and technical efficiency (e.g., wind power), labor productivity (e.g., cars), and capital productivity (e.g., refineries). Demand growth and standardization are two other important factors.

**Table 24.5** | Economies of scale at different levels, using wind power as an example.

| Level of Scale Economy | Example of Scale Economy | Outcome of Scale Economy using Wind Power as an Example |
|---|---|---|
| unit level | increases in wind turbine blade length and tower height<br><br>cf. **technical returns to scale**: outputs increase proportionally more than inputs, e.g., inputs = f(area), outputs = f(volume)<br>fixed balance of system components spread | lower $/MW for<br>larger MW wind turbines<br>higher MWh/MW for larger MW wind turbines (no reference to costs)<br><br>lower $/MW for |
| plant level<br>(also facility or installation level) | over larger numbers of units operating | larger MW wind farms |
| manufacturing level<br>(also production level) | capital productivity improved by spreading fixed input costs over higher output volumes | lower $/turbine for larger turbine manufacturing facilities |
| organizational level<br>(also firm level) | labor productivity improved by specialization;<br>lower cost volume purchases of capital equipment* | lower $/MW or $/turbine for larger turbine manufacturers or wind farm developers |
| industry level | political economic influence (rent-seeking) securing, e.g., increased subsidy or price support* | lower cost or higher revenue as contribution of industry to GDP or job increases |
| inter-industry level<br>(also external or system level)** | development of enabling infrastructure (e.g., distribution networks) and institutions (e.g., forward contracts);<br>development of complementary industries (e.g., materials or equipment suppliers) | lower cost or higher revenue as share of total electricity production increases |

*Rosegger (1996) refers to these as "pecuniary" economies of scale, which are nontechnical and associated with input costs or output revenues.
** External economies of scale are one explanation for the potential benefits of both national industry clusters and transnational economic unions e.g., Henriksen et al., 2001a.

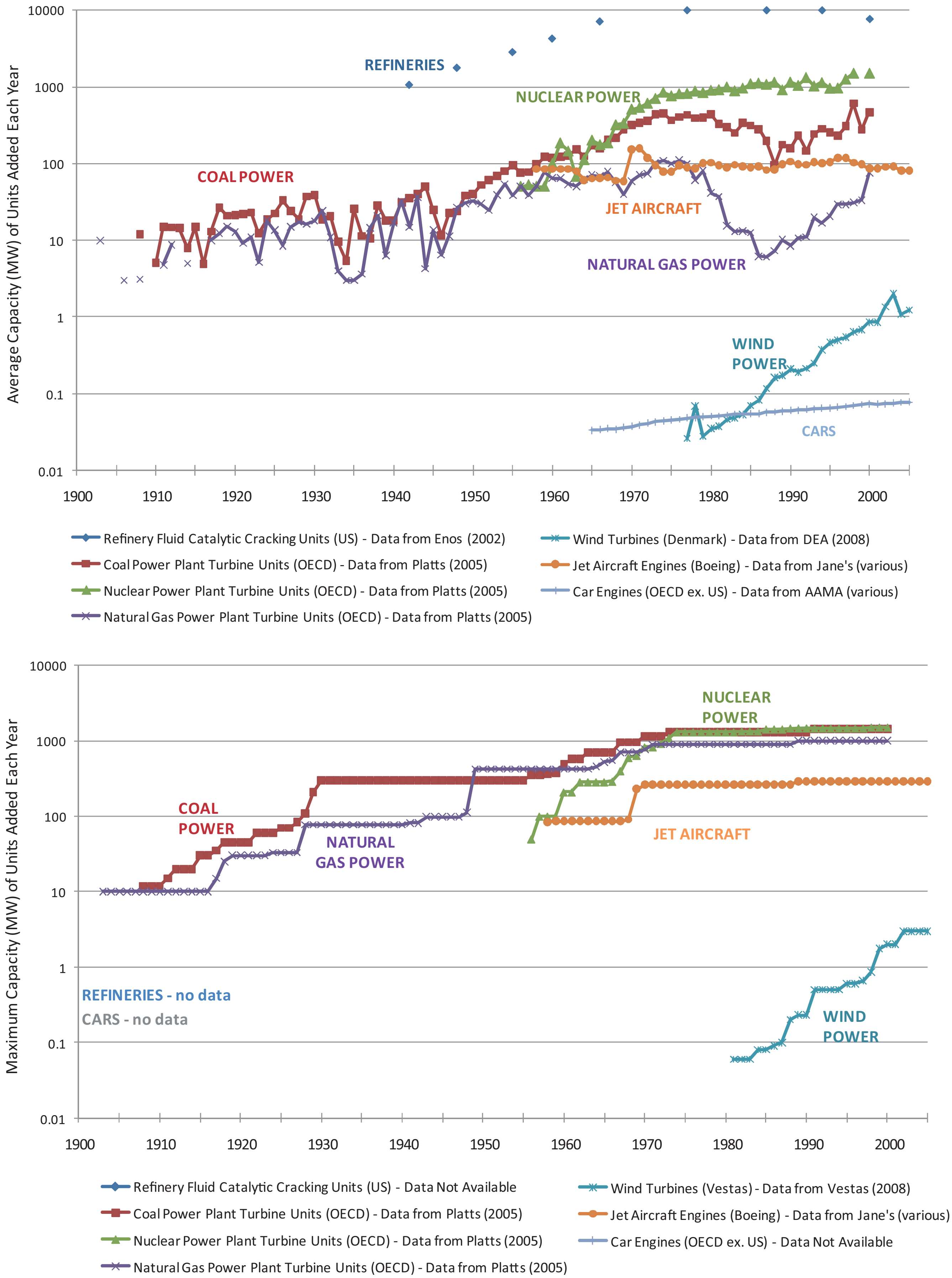


**Figure 24.4** | Increasing unit of scale of energy technologies, average (top) and scale frontier (bottom). Unit scales are expressed as MW capacities and plotted on log-scale y-axes. For details, see: Wilson, 2009.

For energy technologies with perceived social benefits, consistent government policies to 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 market collapse. This is clearly demonstrated in the *Solar Thermal* case study.

Alongside demand growth, technology standardization has proven important for manufacturing scale economies at the unit or plant levels. The more successful growth of nuclear 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 US Westinghouse reactor design. Later in the French nuclear program, scaling of unit capacities from the standardized 900 MW reactor to more bespoke or "Frenchified" 1300–1500 MW reactors led to marked cost increases (see the *French Nuclear* case study).

These cost increases also demonstrate the possibilities of diseconomies of scale – not lower, but higher \$/MW or \$/MWh – associated with an increase in the complexity of designing, building, and operating integrated technologies close to the unit scale frontier (Rosegger, 1996). For large-scale power plants in the late 1970s, complexity led to additional borrowing costs during the construction phase due to delays (Koomey and Hultman, 2007) and foregone revenues during the operating phase due to an increase in the frequency and duration of unforced outages (Ruttan, 2001; Lovins et al., 2002). Increasingly stringent health, safety, and environmental regulations also impacted larger scale plants more severely. The transition through the 1980s and 1990s from large-scale coal and nuclear power plants to smaller scale, more flexible and less capital-intensive natural gas-fired units (better suited for increasingly deregulated markets) illustrates well that the availability of economies of scale are contingent on both technical and market factors.

**Isolating Economies of Scale as a Source of Cost Reduction**

Simple engineering models relate cost to scale in the form:

$$\frac{\$_t}{\$_{t-\square}} = \left(\frac{scale_t}{scale_{t-\square}}\right)^{(scale\ factor)} \qquad (1)$$

with a scale factor less than one indicating economies of scale. A study of wind turbines in Germany during the 1990s found that a scale factor of 0.84 described the observed fall in wind turbine investment costs per MW installed capacity by 11% for a doubling of turbine size from 0.3 to 0.6 MW, and by a further 18% for a subsequent unit size increase from 0.6 to 1.5 MW (Grubler, 2010).

However, 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 models that disaggregate the various influences on cost.

Econometric approaches typically use a Cobb-Douglas functional form (linear in log-transformed variables) to explain unit cost as a function of scale. Models fitted to data on coal power plants built in the United States from 1960–1980 showed that a doubling of unit scale reduced the cost per unit capacity by 12–24%, controlling for learning effects, compliance with environmental regulation, and changes in productivity and input prices (Joskow and Rose, 1985; McCabe, 1996). It is worth noting that the data period to which these models were fitted describes the rapid growth phase of unit scale during which unit scale economies might be expected to be most evident (see Figure 24.4 above).

More sophisticated engineering models control for the effect of non-scale related drivers of cost reductions over time. A good example is presented in the *Solar PV* case study for the United States. Manufacturing scale economies were found to explain 43% of observed cost reductions in solar PV module cost ($\$/W_{peak}$) between 1980 and 2001 (Nemet, 2006). During this period, manufacturing plant output had scaled by two orders of magnitude, from 125 kW/year to 14 MW/year.

### 24.2.3.2 Economies of Scope

Whereas economies of scale describe the reduction in unit costs with increasing scale of production of a standardized good/commodity, economies of scope describe the reduction in unit costs that can be achieved by producing more products jointly as opposed to individually (see Panzar and Willig, 1975; Teece, 1980, for an exposition).

The traditional manufacturing economic literature draws the following contrast: whereas economies of scale describe production processes where the focus is on quantity and the emphasis is on reducing unit costs, the focus in economies of scope is on product variety. Economies of scope are realized through the effective sharing of knowledge, facilities, equipment, and other inputs such as marketing and design services. In addition, machinery and production processes were designed to facilitate and speed-up the process of change-over between products. Economies of scope can also be realized when there are cost savings arising from byproducts in the production process.

In the energy field, the literature on economies of scope is somewhat limited (examples include Mayo, 1984; Kwon and Yun, 2003; Farsi et al., 2008; Shum and Watanabe, 2008). A concept used to describe energy plants that reap economies of scope from the production of an array of multiple energy carriers is sometimes referred to as energy "combinates." The prime example of economies of scope in energy are, therefore, cogeneration systems, i.e., the joint production of electricity and heat in power plants (combined heat and power [CHP] plants), where the waste heat can be used for heating purposes, e.g., via district heating systems. More recently, such schemes also include district cooling systems, such as using steam generated in electricity plants to drive chillers and the distribution of chilled water for air conditioning purposes.

A necessary condition for the realization of economies of scope in cogeneration systems are either an appropriate co-location of industrial and end-use applications with energy conversion facilities or the possibility to interconnect these diverse users and energy uses through district heating/cooling pipeline systems. Given the usually large scale of electricity generating plants, such schemes are generally only economically viable if generation and demand are not too distantly located (e.g., cogeneration from power plants located within larger cities) or have a sufficiently high energy demand density to justify the high investment costs of heat pipeline systems. Conversely, the advent of decentralized distributed energy systems can increase cogeneration potentials. Examples of applications include natural gas microgeneration (with waste heat recovery for heating of commercial and larger residential buildings and sales of electricity back to the grid),[13] or biomass gasification coupled to gas engines for joint production of electricity and heat.

### 24.2.4 Characteristics of ETIS (III): Actors and Institutions

#### 24.2.4.1 Introduction

Innovation processes take place within an environment that consists of actors and institutions (Edquist, 2001). Collectively, this makes up the innovation system at the heart of the ETIS perspective. Models of innovation typically highlight the various stages of innovation, and the interactions and feedback loops between these phases (see Figure 24.2 above). The systemic approach emphasizes that innovation is also a collective activity involving many actors, and that innovation processes are influenced by their institutional settings and its corresponding incentive structures (Edquist and Johnson, 1997; Lundvall, 2007).

Institutions are not only organizations and formal structures like rules and regulations, but also established habits, practices, routines, and norms of the various actors within the system. In this sense, institutions can be seen as learned patterns of behavior and interaction, marked by the historical specificities of a particular system and moment in time. As such, their salience and strength may shift as conditions change. Learning and unlearning on the part of actors in the innovation system are thus essential to the evolution of a system in response to new challenges.

There are many different actors and institutions in ETIS. Many have been covered in preceding sections. An example in the section on knowledge feedbacks and spillovers are the networks of interacting and cooperating innovation system actors that enable and mediate this knowledge exchange (Carlsson and Stankiewicz, 1991). Three examples not covered previously are considered below in more detail. These are entrepreneurs and experimentation, shared expectations, and advocacy coalitions.

13 See for example, www.lichtblick.de/h/index.php.

Another key set of actors and institutions influencing the innovation system relate to public policy. Policies can reinforce or support broader institutional change within the innovation system with regard to learning, collaboration, risk taking, consumer preferences, and so on. While some measure of policy stability is necessary, adaptive policy making in response to feedback from policy dynamics (the interaction of policies and the traditional habits and practices of the actors) are important for stimulating innovation under conditions of uncertainty (Mytelka, 2000).

Policies to support market formation have proven important in encouraging renewable energy technologies through their early commercialization. Such policies might involve subsidies, tax incentives, regulated feed-in tariffs, procurement policies, minimum production quotas, and exemptions from regulation, among others (Raven, 2007). The *Wind Power* case study shows the importance of early market creation efforts by the Danish government for small-scale wind turbines. The *Solar Thermal* case study and the *Kenyan PV* case study illustrate the importance of niche markets for building the capacity to construct, operate, maintain, and assure quality control of a new technology.

The roles and importance of different actors and institutions varies between innovation systems, and also changes over the life cycle of an innovation. For example, a wide range of both public and private actors can be involved in mobilizing resources to support ETIS, and in developing their skills and competences as a result of this resource mobilization (Carlsson and Stankiewicz, 1991). Typically, as innovation systems increase in maturity, the importance of private actors increases (Suurs and Hekkert, 2009a). Various case studies profile the changing importance of public and private actors. In the *US Synfuels* case study, for example, a hybrid approach to public-private roles was ultimately undermined by how mobilized resources were used.

#### 24.2.4.2 ETIS Actors and Institutions (I): Entrepreneurs

There is no such thing as an innovation system without entrepreneurs (Carlsson and Stankiewicz, 1991). Entrepreneurial risk-taking is essential to cope with the large uncertainties surrounding new combinations of technological knowledge, applications, and markets (Meijer and Hekkert, 2007). Above all, entrepreneurship is needed for bringing new technologies, products, and practices to markets. Experimentation is integral to the process of knowledge generation and learning described earlier, allowing for the evaluation of the reactions to new applications on the part of consumers, governments, competitors, and suppliers. The role of the entrepreneur is therefore to turn the potential of new knowledge, networks, and markets into concrete actions that both generate and take advantage of new business opportunities. Entrepreneurs can either be new entrants who see new market opportunities (e.g., university spin-offs) or incumbents who diversify their business strategy to take advantage of new developments.

In most innovation processes, a period of variety creation driven by experimentation takes place before a dominant design emerges and is further developed. The *Wind Power* case study shows how entrepreneurial experimentation led to a large variety of wind turbine designs from which the three-blade vertical axis turbine eventually emerged as the dominant design. The *Hybrid Cars* case study shows the importance of entrepreneurial experimentation among Japanese car manufacturers for initiating the buildup of an innovation system. The *Scaling Dynamics* case study emphasizes the importance of experimentation during the formative phases of many different energy technologies, whereas the *French Nuclear* case study illustrates the consequences of "short-cutting" extended experimentation in the interest of rapid upscaling of a dominant technological design.

#### 24.2.4.3 ETIS Actors and Institutions (II): Shared Expectations

Innovation is always characterized by uncertainty. The expected merits of a new technology in terms of performance or costs cannot be known *ex ante* as being shaped by the agency at play in ETIS (R&D strategies and funding levels, niche market developments, extent of possible learning effects, etc.) as well as by exogenous factors (such as oil prices, as illustrated in the *US Synfuels* case study). Strategic decisions on the direction of the innovation process and the more promising technological avenues can be important to sustain innovation system development. Note, however, that trying to force technology development over short timeframes risks disappointing high initial expectations, as is demonstrated in the *US Synfuels* case study.

Shared or collective expectations are an important means of reducing uncertainty and stimulating entrepreneurial activity (van Lente and Rip, 1998; Borup et al., 2006). This is clearly demonstrated by the *Solar PV* case study. Shared expectations help guide the search of actors within the innovation system by selecting technological alternatives from the variety created by knowledge generation activities. As such this function is equivalent to the "visioning" step advanced in the technological transition literature (Smith and Stirling, 2010; see also Chapter 16 for a more detailed discussion).

Guidance functions can be provided by a variety of actors, including individual firms, actor networks, or governments, as has been the case in Japan (see *Japanese Efficiency* case study). Policies can shape changing societal preferences to reflect public policy objectives like greenhouse gas emission reduction. The *Hybrid Cars* case study clearly shows how zero-emission vehicle regulations and large-scale R&D programs affected the research direction of car manufacturers. The *Brazilian Ethanol* case study shows that strong political leadership can be another important means of guiding the search within an innovation system. Long-term technology roadmaps are another important means of establishing shared technological innovation expectations, as are credible long-term policy signals – for instance, in the form of pollution (e.g., carbon) taxes that rise over time at pre-announced, predictable rates.

#### 24.2.4.4 ETIS Actors and Institutions (III): Advocacy Coalitions

New energy technologies face resistance from actors with interests vested in incumbent systems. To build up an innovation system, actors – usually from nongovernmental organizations (NGOs) and industry – must counteract this inertia through, for example, political lobbying and building advocacy coalitions (Sabatier, 1987; Sabatier, 1988). Public institutions may also contribute (Fligstein, 1997), as in the case of planning agencies advising regional or national governments to develop supporting policies for emerging technologies. In all such cases, innovation system actors try to convince other actors to take particular actions that they cannot conduct themselves. Nonetheless, it should be emphasized that incumbent technology systems often have great lobbying power to resist changes.

### 24.2.5 Changing Dynamics Over Time in Effectively Functioning ETIS

Researchers in the "functions of innovation systems" tradition have identified seven key processes in emerging innovation systems that are needed for a successful maturation through the formative phase (Jacobsson and Lauber, 2006; Bergek et al., 2008). These key processes interact strongly and all can potentially be supported by policy makers. Although networks between actors in an energy innovation system tend to be international, national policies can strongly influence how the formative phase in specific countries occurs. Table 24.6 summarizes the seven key processes and references the earlier sections in which they were discussed.

Positive interactions and feedbacks between the key processes shown in Table 24.6 are integral for the successful build up of an innovation system (Jacobsson and Bergek, 2004; Hillman et al., 2008). These positive feedback loops are referred to as "motors of innovation" (Suurs and Hekkert, 2009b).

In the first phase of innovation system development, a "science and technology push motor" is characterized by knowledge development and the creation of positive expectations about the new technology by scientists and engineers to help guide the search and stimulate funding that supports further knowledge development in and beyond R&D.

The science and technology push motor can turn into an "entrepreneurial motor" if entrepreneurial experimentation leads to knowledge exchange between the entrepreneurs and the research community. Next, a "system building motor" involves a wide range of actors involved in the development and production of a technology lobbying for market formation and an alignment of institutional structures with the needs of the new technology. If successful, this collective activity can overcome the resistance to change of incumbent actors with vested interests.

**Table 24.6** | Seven key processes in innovation systems.

| # | Key Process | Summary Description | Relevant Sections in Chapter 24 |
|---|---|---|---|
| 1 | Entrepreneurial experimentation | Taking risks, creating variety, "field" testing, developing business opportunities. | Knowledge Generation; Learning; Actors (Entrepreneurs) |
| 2 | Knowledge development and exchange in networks | Generating and sharing knowledge to improve performance, learn from experience, etc. | Knowledge Generation; Knowledge Spillovers; Learning; Actors (Exchange) |
| 3 | Guidance of the search | Strategic directioning of the innovation process to reduce uncertainty. | Economies of Scale and Scope; Institutions (Expectations) |
| 4 | Market formation | Creating, protecting or supporting niches for innovations to enter the market. | Innovation Models;Niche Markets |
| 5 | Resource mobilization | Allocating financial, material and human capital to the innovation process. | Economies of Scale and Scope; Metrics and Assessment |
| 6 | Counteract resistance to change | Overcoming systemic inertia and vested interests. | Actors (Advocacy) |
| 7 | Materialization | Building up production or manufacturing capacity. | Innovation Models; Economies of Scale; Metrics and Assessment |

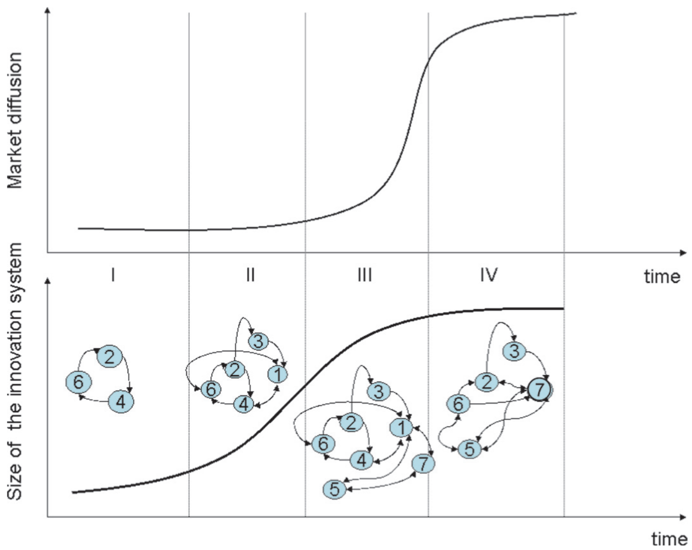


**Figure 24.5** | Stylized life cycle of a new technology over time (Phases I to IV, top) and corresponding build up of the technology's innovation system and the seven key processes involved (circles) and their interactions (arrows) (bottom). See Table 24.6 for a definition of the key processes.

Finally, a "market motor" may emerge once market formation has taken place and a technology has started to diffuse with a concomitant build up of production capacity. Overcoming resistance to change and guidance of the search now become less important. The succession of these four motors of innovation is represented stylistically in Figure 24.5 (bottom panel), alongside the S-shaped curve describing a technology's life cycle (top panel). The build up of the innovation system can be measured in terms of the number of actors involved, the extent and complexity of the networks between these actors, and the specific institutions aligned with the innovation. However, such indicators are specific to individual technologies and innovation system contexts and cannot be generalized. Figure 24.5 shows how the innovation processes (represented as circles) and the interactions between them (represented as arrows) increase through the formative phase prior to the technology's diffusion into the market (Phases I-II). As market diffusion accelerates (Phase III), the innovation system grows to its maximum (Phase IV).

## 24.3 Assessing Energy Technology Innovation Systems

### 24.3.1 Introduction

There is no uniform simple metric to describe ETIS in terms of commensurate measures of needed inputs and corresponding system outputs. Unlike in macroeconomics, it is not possible to develop a simple production function of ETIS. The *Assessment Metrics* case study reviews in detail the literature on innovation metrics from which Chapter 24 draws to structure this section.

In terms of assessing the inputs to ETIS, Section 24.3.2 (see also Appendix I) provides a comprehensive overview of ETIS in terms of current (as of 2005) investments into energy technologies across the entire life cycle phases of ETIS, from knowledge generation to market formation (niche market investments), to technology diffusion (in both energy supply and end-use technologies). The choice of this metric arises from three considerations:

- *Novelty*: Such an overview assessment has to date been absent in the literature, which invariably has focused only on pieces of the entire system, like public energy R&D expenditures, or investments into renewables.

- *Commensurability*: The metric needs to be comparable across all technologies, across all ETIS activities/processes, and across different sectors and markets (regions); hence the use of the US dollar as a core metric.

- *Centrality*: Investments are a central element of ETIS, constituting a core input to knowledge generation and any embodiment of technological change. They are a key process in ETIS (resource mobilization) and also constitute an important constraint for ETIS in their own right.

The adoption of a single metric to assess current inputs into ETIS does not suggest that readers should ignore the multidimensionality of metrics proposed in the literature on ETIS (see the *Assessment Metrics* case study) but rather to allow to put the relative weight of different stages of ETIS and currently revealed preferences (in terms of resource mobilization) into a quantitative perspective. As such, Section 24.3.2 also provides a baseline against which the needed redirection of ETIS investment flows as described by the GEA transition pathways scenarios (Chapter 17), for which these numbers served as important input, can be assessed (see in particular Section 17.3.5).

The assessment in terms of outputs of ETIS is necessarily more eclectic and illustrative as there is no single common metric for describing technological change (the "output" of ETIS) across all technologies, life cycle stages, and markets. Section 24.3.3 therefore provides salient illustrative examples drawn from Chapter 24's case studies. The focus is on two core dynamic metrics: technology diffusion and costs, which evolve over time to illustrate both their dynamic nature as well as their mutual interdependence. Falling costs drive expanding market applications which, in turn, provide yet further cost reductions, e.g., through economies of scale effects in manufacturing and learning (by doing and using) processes.

### 24.3.2 Quantitative Assessments of Inputs (Investments)

#### 24.3.2.1 Introduction and Overview

This section attempts a first ever quantitative overview of financial resources that constitute a fundamental input to energy technology innovation in terms of required resource mobilization. Evidently, money is not the only resource that needs to be mobilized: the development of knowledge, skills, supporting institutional settings, etc. is important too. Financial investment data, however, are more readily available than other ETIS input, output, or outcome metrics. In addition, they are a useful tool for policy makers, as budgets are a key policy tool in governments and industry alike. Finally, even if the information provided below is still relatively scarce, investments in innovation give a sense of the scale of the energy innovation enterprise.

The key messages of this section are as follows. First, there are formidable data problems associated with the need to describe energy technology innovation, which highlights important areas of future research and renewed initiatives to provide better technology-specific data for informed policy choices. In addition, consideration of institutions needed to collect and share these data at the national and international levels is badly needed.

Second, this section illustrates the increasing scale of resource mobilization across successive stages of ETIS, from research, development, and demonstration (~50 billion[14]), to market formation investments (~150 billion), and finally to the dominant diffusion investments (>1000 billion). If large-scale technological change is on the agenda, changes in the diffusion environment and associated incentives for technology adoption and diffusion – e.g., through changes in relative prices – are key in addition to developing improved technologies in the upstream stages of ETIS.

Third, this analysis reveals that the structure of current investments in ETIS is highly asymmetrical between the dominance of diffusion investments in energy end-use technologies, and their under-representation in the investments in the earlier stages of ETIS. In other words, this overview helps elucidate the relatively large support for supply-side technologies such as fossil fuels and nuclear energy in RD&D. This is difficult to reconcile with the energy innovation needed to respond to the multitude of challenges of current energy systems, ranging from energy access to energy security and climate change mitigation, all of which call for vastly improved energy end-use efficiency.

Fourth, six major emerging economies – Brazil, the Russian Federation, India, Mexico, China, and South Africa, known collectively as BRIMCS countries – now account for a significant fraction of global ETIS. However, significant regional imbalances, particularly in the support for energy RD&D, persist. The increasing globalization of ETIS in general and of energy technology RD&D in particular suggests that new mechanisms for international technology cooperation and coordination might be called for, which again raises the question of the need of an appropriate institutional (re)design, as existing institutions such as the IEA are limited in scope and membership (mostly oil-importing OECD countries).

Innovation inputs are quantified in this chapter by the associated financial resource mobilization per broad technology class and by stage of the technology life cycle. The definition of the innovation stage is straightforward, as characterized by RD&D expenditures, which are a well-defined expenditure category in macroeconomic and corporate accounts. The subsequent phase of market creation investments is defined by either relying on special funding mechanisms such as venture capital or special (government-induced) market incentives such as feed-in tariffs, production tax credits, and the like, but the definitional boundaries are necessarily more blurred. Finally, diffusion investments are those that represent commercialization of mature technologies and that need no special policy incentives to mobilize the required investment in markets. Evidently, all investments across the entire technology life cycle will always be influenced by the overall incentive environment, as characterized by relative prices, taxes, etc., i.e., by numerous nontechnology-specific policies. What differentiates market creation from diffusion investments is the degree to which investments rely on dedicated technology policy support for their early

14 R&D expenditures represent aggregates of national statistics, which are mostly available only in International $ (i.e., in PPP terms). When expressed in US$ (i.e. at market exchange rates, MER), R&D expenditures would be lower by some $10 billion. As private sector R&D is significantly underreported, a global order of magnitude estimate of $50 billion energy R&D can be considered commensurate with the subsequent niche market and diffusion investment numbers that are expressed in US$ (i.e., MER-based).

**Table 24.7** | Summary of current global public and private ETIS investments (in billion $US_{2005}$\$) by stage and type of technology application (first order estimates and ranges from the literature).

| | Innovation (RD&D) | | market formation | | diffusion | |
|---|---|---|---|---|---|---|
| End-use & efficiency | >>8 | 1) | 5 | 8) | 300–3500 | 15) |
| Fossil fuel supply | >12 | 2) | >>2 | 9) | 200–550 | 16) |
| Nuclear | >10 | 3) | 0 | 10) | 3–8 | 17) |
| Renewables | >12 | 4) | ~20 | 11) | >20 | 18) |
| Electricity (Gen+T&D) | >>1 | 5) | ~100 | 12) | 450–520 | 16) |
| Other* and unspecified | >>4 | 6) | <15 | 13) | n.a. | |
| **Total** | >50 | 7) | <150 | 14) | 1000–<5000 | 19) |

Notes: * hydrogen, fuel cells, other power & storage technologies, basic energy research

1) Public RD&D 1.8 billion (IEA, 2009a; BRIMCS case study); private RD&D >>6 billion (WEC, 2001; BRIMCS case study).
2) Public RD&D 2 billion (IEA, 2009a; BRIMCS case study); private RD&D: >10 billion (WEC, 2001; BRIMCS case study).
3) Public RD&D >6.2 billion (IEA, 2009a; BRIMCS case study); private RD&D >3.4 billion (WEC, 2001; BRIMCS case study).
4) Numbers also include renewable electricity. Public RD&D (excl. electricity): 2 billion (IEA, 2009a; BRIMCS case study); private RD&D (includes electricity): 7 billion.
5) Only public RD&D (IEA, 2009a; BRIMCS case study).
6) Only public RD&D (IEA, 2009a; BRIMCS case study).
7) Lower bound estimate (rounded number)
8) NEF/SEFI, 2009 includes 2 billion asset finance p.13, plus estimated 2 billion from venture capital (based on 15 billion total VC in 2008 and assuming category proportion in cumulative VC investments over the 2002–2008 period).
9) Estimated 2 billion from venture capital only (based on 15 billion total VC in 2008 and assuming category proportion in cumulative VC investments over the 2002–2008 period).
10) Classified as mature technology and reported under diffusion investments.
11) Biomass and biofuels total of 24.8 billion (NEF/SEFI, 2009, p.13) minus 8 billion Brazilian ethanol (accounted for as diffusion investment) plus 2.4 billion estimated VC investments.
12) ~90 billion asset finance (NEF/SEFI, 2009, p.13, including wind, solar, geothermal, marine and small hydro plus estimated ~8 billion from VC).
13) Unaccounted for technology categories.
14) Rounded number, estimated market formation investments ~140 billion derived from NEF/SEFI, 2009.
15) Chapter 24 first order estimate, rounded numbers, cf. Appendix I; lower bound: central estimate of energy-using components of end-use investments (297 billion), upper bound: upper range of total end-use investments (3549 billion).
16) Source: Table 24.5 in Appendix I.
17) Estimate for 2–3 GW reactor completions per year (IAEA-PRIS, 2010) at assumed costs between 1500–2500 $/kW.
18) Source: Table 24.5 Appendix I, fuels only.
19) Rounded numbers.

market deployment. A tentative, albeit incomplete, attempt at a global overview is provided in Table 24.7. Further details are provided at Appendix I.

### 24.3.3 Case Study Assessments of Innovation Outputs

As part of this assessment, Chapter 24 conducted 20 case studies. This section discusses the rationale for conducting these case studies, as well as the rationale for selecting this particular set of cases. All 20 assess the innovation system and are intended to complement the quantitative overview described above. The implications for understanding energy innovation and for public policy are described in Sections 24.4.5 and 24.4.6 below. Some illustrative results from the assessment of innovation processes that emerge from the case studies are included here as well (see Section 24.3.3.3). Space limitations precluded the full presentation of all case studies in this chapter; they are summarized in Appendix II. The full case studies will be published separately quot are also reported on the GEA Chapter 24 website.[15]

#### 24.3.3.1 Rationale and Logic of Case Studies

The rationale for conducting case studies arises from the need to complement quantitative evaluations with richer descriptive characterizations of innovation systems. This assessment uses evidence from descriptive case studies to further illustrate the general insights for policy design covered in Section 24.4. The complexities of the dynamics of the innovation process are often ignored in quantitative models. While a growing body of work on quantitative evaluation improves understanding, their explanatory power has so far proven limited.

15 For more information, see www.globalenergyassessment.org.

Attempts to econometrically identify the effects of demand-pull and technology-push – e.g., Kouvaritakis et al. (2000); Watanabe et al. (2000); Miketa and Schrattenholzer (2004); Klaassen et al. (2005) – have provided limited claims in the available studies because of their sensitivity to assumptions about the depreciation of R&D knowledge stock and about the lags between policy signals and decisions to innovate. Both of these parameters have proven difficult to estimate empirically. Using the observation that most technologies tend to decline in cost over time, the notion of the "learning (or experience) curve" has been widely used to simulate the cost reductions that can be expected from programs that subsidize demand (Duke and Kammen, 1999; Wene, 2000; IEA, 2008b). However, observed discontinuities in learning rates, perhaps resulting from omitted variable bias, limit their reliability. Moreover, large dispersion in observed learning rates, even including negative rates, complicates choices of which point estimates to apply (Nemet, 2009b).

The relationship between R&D investments and technical change is even more difficult to model, in part due to the inherent stochasticity of the R&D process. One notable approach has been to measure the value of the commercialized projects that emerged from federal R&D programs (NRC, 2001). This cost-benefit valuation approach has been used to evaluate the US Department of Energy's wind and PV R&D investments. Key shortcomings in this approach center on the assumptions needed to construct a counterfactual case in which one must characterize outcomes in the event that the R&D investment was not made. Prospectively, another approach common to R&D management has been employed in which decision analytic techniques are often used to obtain the necessarily subjective judgment of experts who are most familiar with the specific technologies (Peerenboom et al., 1989; Sharpe and Keelin, 1998; Clemen and Kwit, 2001). A report by the National Research Council (NRC, 2007) recommends that the US Department of Energy adopt a process including expert elicitations. They provided prototype elicitations for carbon storage, a vehicle technologies program, and four other programs. Examples of such assessments include studies of PVs and carbon capture (Baker et al., 2009).

More generally, quantitative assessments of innovation systems may be biased toward the selection of cases for which detailed data are available. This may explain the lack of empirical work on energy end-use technologies relative to supply technologies. Also, it may limit comparisons across countries, as there may be insufficient variables for comparing the results of heterogeneous studies across countries. Finally, the reduction of the complex process of innovation to a few factors may omit important aspects of the system and contribute little in mechanistically explaining causality.

The qualitative descriptions in case studies provide an avenue for incorporating explicit considerations of the innovation system's complexities and feedbacks, which would otherwise be ignored. It is important to note that generalizing from case studies is limited by the specifics of context and technical characteristics, which are described. Selection bias is also discussed. Policy conclusions take these limitations into account.

#### 24.3.3.2 Summary of Case Studies

The selection of case studies was based on the following criteria. First, in many cases the focus was on individual technologies. For these technology-focused studies, technologies were selected that had a dynamic aspect – for example, technically, economically, or in terms of deployment. Second, many of the cases included a situation in which public policies played an important role in affecting the process of innovation and diffusion. The case studies were particularly interested in describing the activities of governments. Third, to the extent that data availability allowed, an effort was made to include international diversity and include cross-country comparisons. Fourth, care was taken to also include from the available case studies illustrations of innovation failures or imperfections (e.g., *US Synfuels*, *Solar Thermal*, or *French Nuclear*). Finally, some case studies were conducted because they illustrate specific attributes of the innovation system, as described above. In selecting studies under this criterion, a special effort was made to evaluate ETIS characteristics that are poorly explained in the literature (e.g., *Knowledge Depreciation* or *Scaling Dynamics*).

This chapter's assessment includes 20 case studies, which can be categorized in several ways (Table 24.8). Six of the case studies explicitly address innovation in developing countries. Fifteen include some assessment of government actions affecting the innovation system. At least 12 include a discussion of knowledge feedbacks in the innovation system – or in some cases, the lack of feedbacks. The case studies can also be categorized by whether they were conducted in order to illustrate a particular aspect of the innovation process described above, or whether they were focused on evaluating the innovation system for a particular technology. The latter category was divided into cases that examined end-use technologies and those that examined supply-side technologies. Emphasis was placed on achieving a rough balance between these two technologies to address the exceptionally weak empirical basis for understanding innovation in end-use technologies. Table 24.8 categorizes the 20 case studies as (1) illustrations of specific characteristics of innovation systems; (2) energy end-use technologies; and (3) energy supply technologies.

#### 24.3.3.3 Illustrative Examples of Innovation Outputs from Case Studies

Six examples illustrate the types of work that can be used to evaluate the outcomes of the innovations process, particularly in response

**Table 24.8** | Innovation case studies conducted for Chapter 24.

| Short Name | Summary Section | | Developing Country | Public Policy |
|---|---|---|---|---|
| | | **1. Illustrations of Specific Characteristics of Innovation Systems** | | |
| Grand Designs | 24.7.1 | Grand Designs: Historical Patterns and Future Scenarios of Energy Technological Change | √ | |
| Scaling Dynamics | 24.7.2 | Historical Scaling Dynamics of Energy Technologies | √ | |
| Technology Portfolios | 24.7.3 | Technology Portfolios | | √ |
| Knowledge Depreciation | 24.7.4 | Knowledge Depreciation | | √ |
| Assessment Metrics | 24.7.5 | Metrics for Assessing Energy Technology Innovation | √ | √ |
| Chinese R&D | 24.7.6 | China Energy Technology Innovation Landscape | √ | √ |
| Emerging Economies R&D | 24.7.7 | Energy R&D in Emerging Economies (BRIMCS) | √ | √ |
| Venture Capital | 24.7.8 | Venture Capital Investments in the Energy Industry | √ | |
| | | **2. Energy End-use Technologies** | | |
| Hybrid Cars | 24.7.9 | Hybrid Cars | √ | √ |
| Solar Water Heaters | 24.7.10 | Solar Water Heaters | √ | √ |
| Heat Pumps | 24.7.11 | Heat Pumps | | √ |
| US Vehicle Efficiency | 24.7.12 | Role of Standards – Example: CAFE | | √ |
| Japanese Efficiency | 24.7.13 | Role of Standards – Example: Japanese Top Runner Program | | √ |
| | | **3. Energy Supply Technologies** | | |
| Wind Power | 24.7.14 | Comparative Assessment of Wind Turbine Innovation and Diffusion Policies | | √ |
| Solar PV | 24.7.15 | Comparative Assessment of PV (European Union, Japan, United States) | | √ |
| Kenyan PV | 24.7.16 | Solar Innovation and Market Feedbacks: Solar Photovoltaics in Rural Kenya | √ | |
| Solar Thermal | 24.7.17 | Solar Thermal Electricity | | √ |
| US Synfuels | 24.7.18 | The US Synthetic Fuels Program | | √ |
| French Nuclear | 24.7.19 | French Pressurized Water Reactor Program | | √ |
| Brazilian Ethanol | 24.7.20 | Ethanol in Brazil | √ | √ |

to public policy. Common to all is the adoption of the perspective of technology diffusion, as well as costs. In terms of ETIS outputs, the dynamics of widening market applications, as well as costs and their interdependence, serve as core metrics in these six illustrative examples.

Figure 24.6 illustrates one possible outcome of ETIS in terms of accelerated diffusion of new energy technologies in later adopting regions via spillover and learning effects (*Scaling Dynamics* case study).

Figure 24.7 illustrates the response to policy, in this case the introduction of the Corporate Average Fuel Economy (CAFE) standard in the United States, in terms of diffusion of the induced technological innovations in the automotive sector (*US Vehicle Efficiency* case study).

Figure 24.8 illustrates the components in cost reductions of sugarcane production in the Brazilian ethanol industry as a twin example of an analytical opening up the "black box" of technology cost improvements and an example of technology responsiveness to an exemplary decades-long sustained public policy effort (*Brazilian Ethanol* case study).

Figure 24.9 shows cost reductions and technical improvements in early solar thermal electricity generation in the United States, from 1982–1992. A virtuous cycle (i.e., a positive, self-reinforcing feedback loop) of unfolding of ETIS came abruptly to an end with the discontinuation of policy support, illustrating the pitfalls of erratic policies and the key importance of continuous policy support (*Solar Thermal* case study).

Figure 24.10 shows the declining cost of PV associated with the Japanese subsidy program from 1994–2004 and provides the positive example of the responsiveness of ETIS outputs to a sustained and predictable policy environment (*Solar PV* case study).

Finally, Figure 24.11 summarizes the cost trends of non-fossil energy technologies analyzed in the Chapter 24 case studies. These data have been updated with most recent cost trends (2010) available in the literature for PV Si Modules (IPCC SRREN, 2011) and US onshore wind turbines (Wiser and Bolinger, 2011). Note that the summary illustrates comparative cost trends only and is not suitable for direct economic comparison of different energy technologies due to important differences between the economics of technology components (e.g., PV modules or heat pumps [only]) versus total systems installed, cost versus

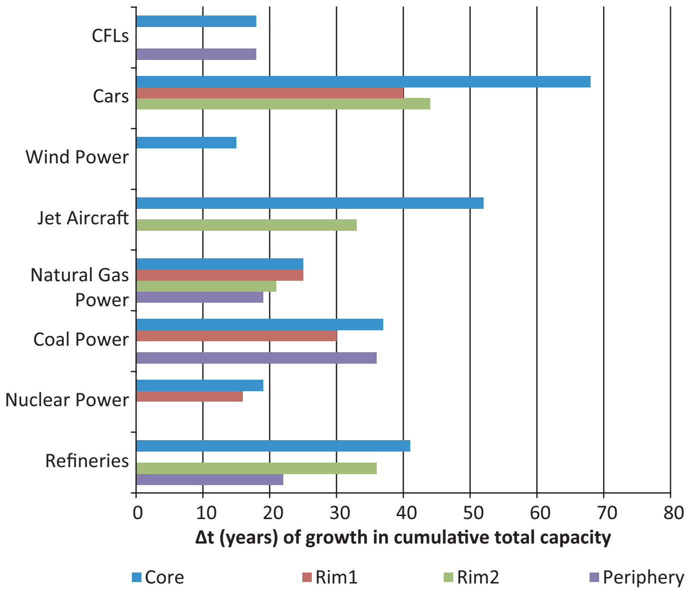


**Figure 24.6** | Diffusion rate or $\Delta t$ – time to grow from 10–90% of installed cumulative capacity – between innovating *Core* regions and later adopting rim (graduated between *Rim1* and *Rim2*) and *Periphery* regions for a range of energy technologies (CFLs denoting compact fluorescent light bulbs). Note that the geographical diffusion categorization is based on technology adoption rates rather than country aggregates. Source: Wilson, 2009.

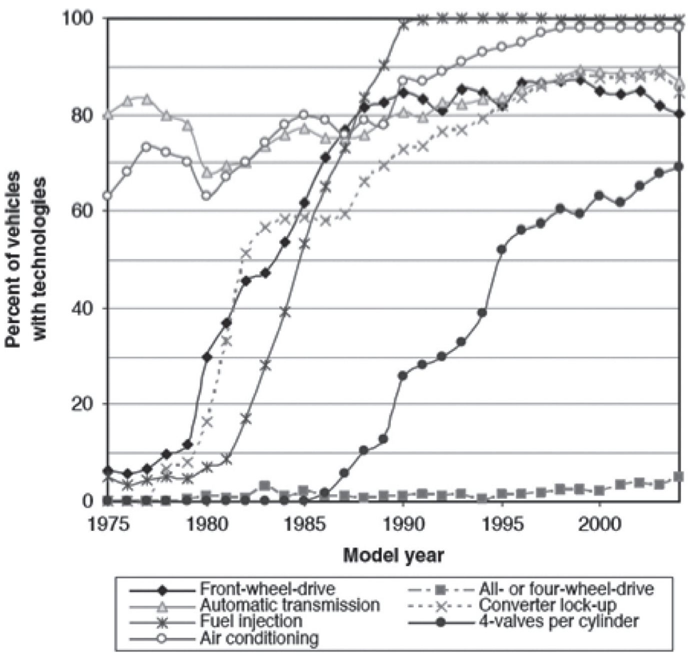


**Figure 24.7** | Diffusion of automotive technologies during implementation of US Fuel Efficiency (CAFE) standards. Source: Lutsey and Sperling, 2005. © National Academy of Sciences. Reproduced with permission of the Transportation Research Board.

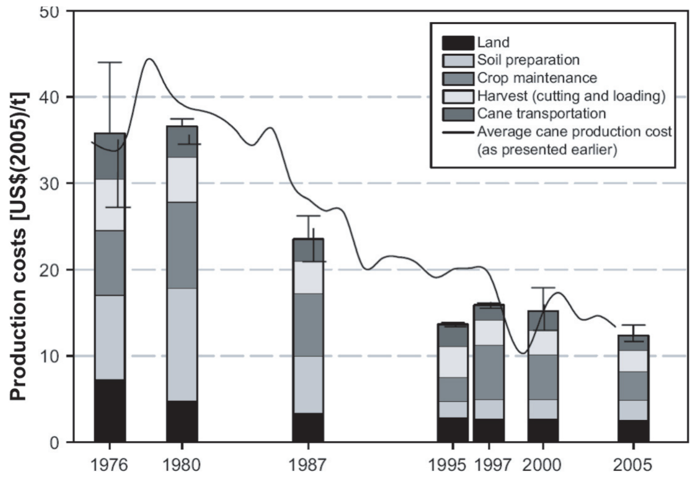


**Figure 24.8** | Decomposition of cost components and their improvements for Brazilian ethanol (cane production only). Source: van den Wall Bake et al., 2009.

price data, and also differences in load factors across technologies (e.g., nuclear's electricity output per kW installed is between a factor three to five larger than that of PV or wind turbine systems). Despite a wide range in cost trend experiences across technologies, two important observations stand out: (1) there is a marked contrast between nuclear showing persistent cost escalation versus the other non-fossil technologies, that generally show declining costs/prices with accumulated market deployment experience. (2) Improvement trends are highly variable across technologies and also over time. For some technologies (e.g. wind in the United States and Europe) historical cost improvements were temporarily reversed after the year 2003/2004 suggesting possible effects of ambitious demand-pull policies in the face of manufacturing capacity constraints and rising profit margins that (along with rising commodity and raw material prices) have led to cost escalations in renewable energy technologies as well.

## 24.4 Energy Technology Innovation Policy

### 24.4.1 Public vs. Private Actors: Roles and Differences

There are a multitude of actors involved in ETIS that either can be differentiated with respect to their role in a technology's life cycle (technology research, development, or adoption, i.e., the supply of and the demand for technology innovation) or with respect to their nature as public or private sector institutions (governments, firms, associations), or individuals (entrepreneurs, consumers). Moreover, the innovation actor landscape that has traditionally be defined within a national context is becoming increasingly globalized, considering the increasing role of multinational firms and direct foreign investments as sources of technological change, and the role of multilateral institutions (World Bank, GEF) and NGOs, which are increasingly involved in ETIS.

The role of these actors can vary considerably. A firm can be a developer of a particular technological innovation while at the same time an adopter for another innovation; their respective role as actors over a technology life cycle also changes. Actors are also extremely heterogeneous in terms of their technology knowledge and competence

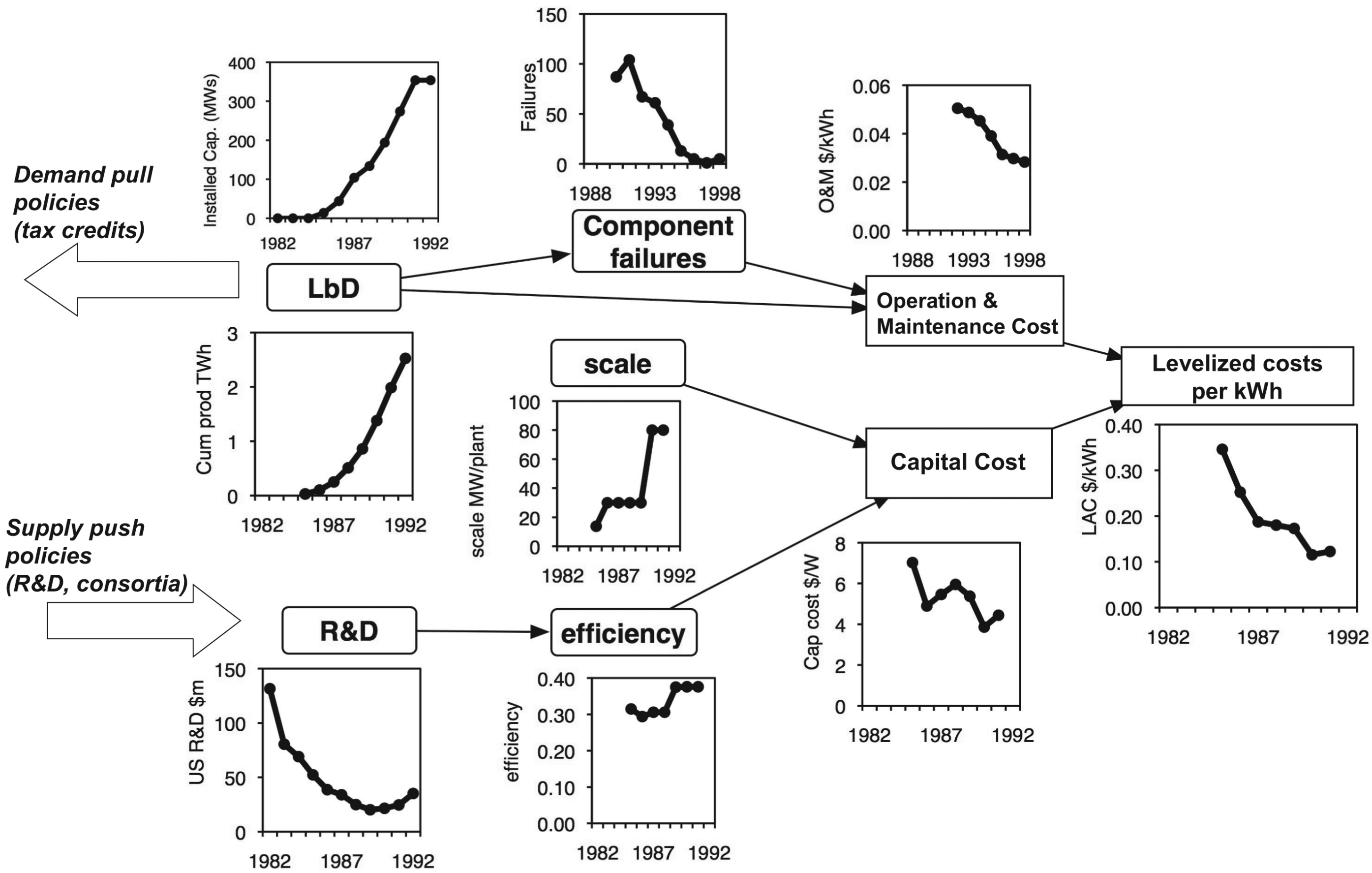


**Figure 24.9** | Causal link model diagram for cost reductions and technical improvements in early solar thermal electricity generation in the United States, 1982–1992. Source: *Solar Thermal* case study. Note: R&D = Research & Development, LbD = Learning by Doing.

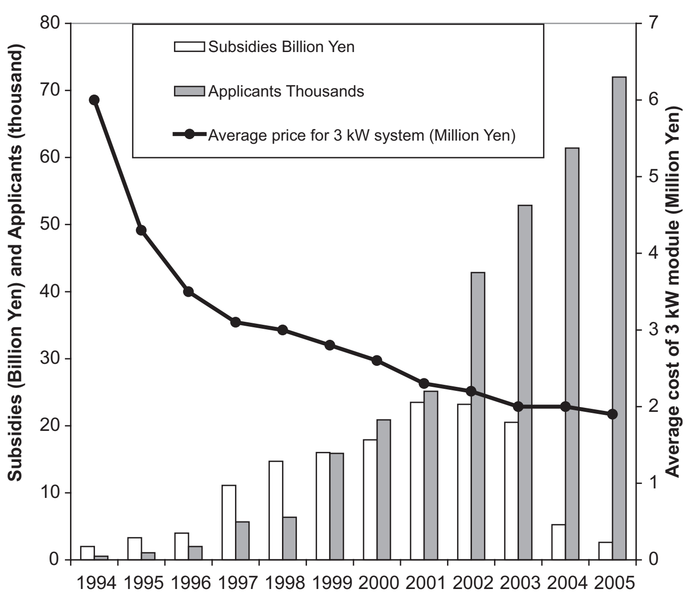


**Figure 24.10** | Japan subsidies and applications for rooftop PV systems versus average 3 kW module price. The 2005 data correspond to specific investment costs of $US_{2005}$\$5816/kW and the 2.6 billion yen subsidy to $US_{2005}$\$23 million. Source: based on Jäger-Waldau, 2006.

base and the resources they can mobilize for innovation (development or adoption), as well as in their characteristics (e.g., different discount rates applied to energy efficiency investments).

For the purpose of this chapter, the differentiation between public and private sector actors is of particular importance. Whereas private sector actors are the main actors of technological innovation in terms of performers of R&D, technology developers, and in manufacturing and marketing of technological innovation, they cannot influence associated (knowledge or environmental) externalities nor the incentive environment in which innovation takes place. This accords a special role to the public sector with respect to technology innovation policy and is reflected in traditional areas of public policy concern (see Section 24.4.2), including public R&D funding, incentives for private R&D, the setting of technology or environmental performance standards, and the general area of economic incentives for technology adoption (e.g., via taxes or subsidies).

Lastly, the literature on institutional innovation (e.g., Ruttan, 1996) is relevant here. Evolving institutional settings can be interpreted by themselves as forms of social "techniques" or innovation that can help to overcome knowledge asymmetries or split incentives that can hinder

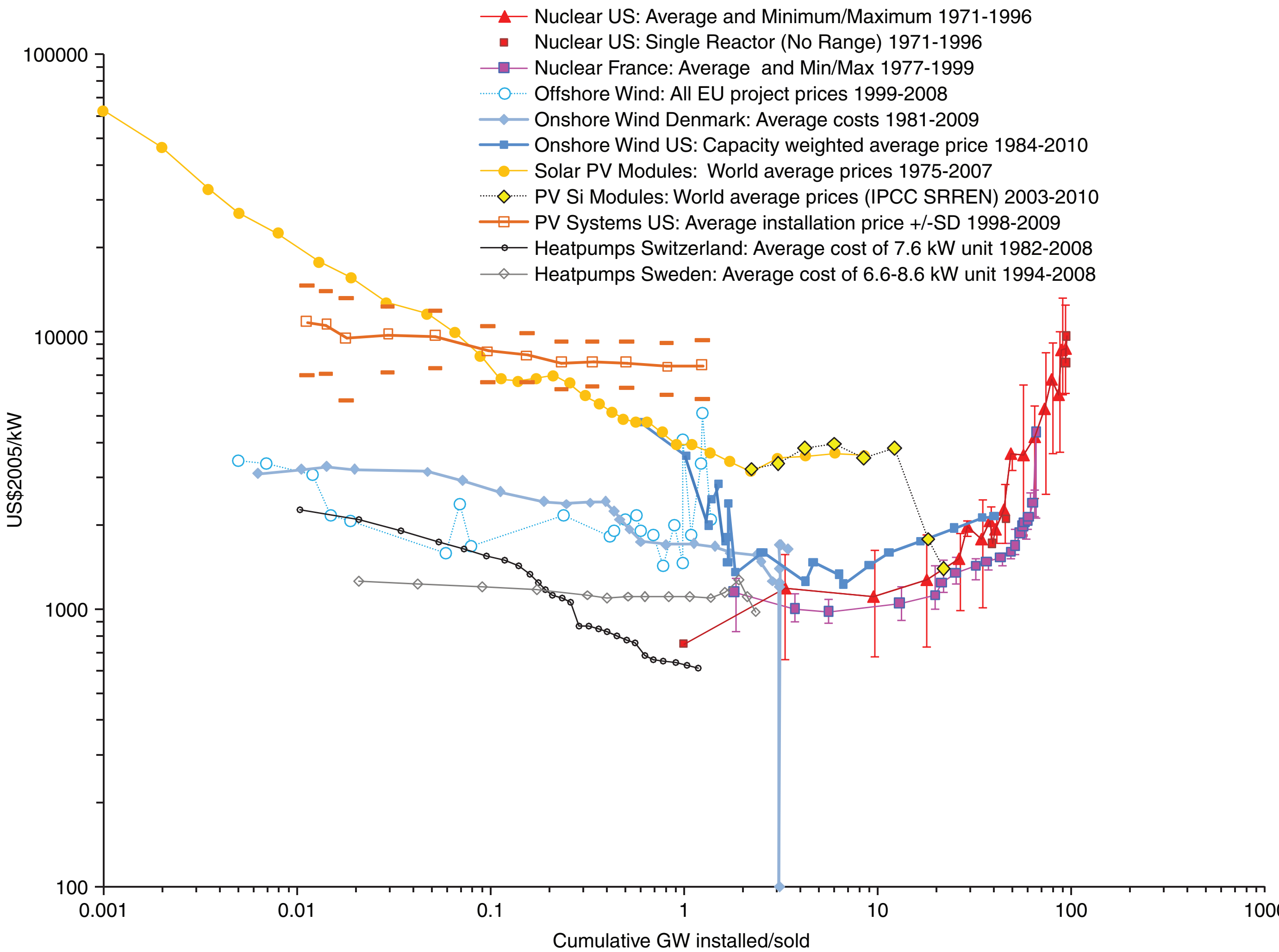


**Figure 24.11** | Chapter 24 Case Studies summarized: Cost trends of selected non-fossil energy technologies ($US_{2005}$\$/KW installed capacity) versus cumulative deployment (cumulative GW installed). Source: Chapter 24 case studies.

socially desirable technological innovation. For instance, energy service companies (ESCOMs) are an example of an institutional innovation in the form of new actors who can assist households or public sector entities, like schools, in the adoption of energy efficiency innovation.

## 24.4.2 Rationale for Public Policy

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

A private firm would endeavor to innovate in response to a perceived need in the marketplace or to create a new product to market to the world. Such profit-maximizing behavior is obvious and important because the global energy marketplace is indeed very large. The IEA estimates that investments in energy supply alone will cumulatively total US$22 trillion globally between 2006 and 2030 (IEA, 2007). Thriving businesses in the energy domain translates into economic development, economic growth, the maintenance and creation of jobs, high-technology domestic sales, and perhaps exports. ETI can also reduce the costs of delivering energy services to consumers, freeing them to save or spend money on other goods and services in the economy. An important question is whether or not the private sector invests sufficiently in ETI, and unfortunately the data do not yet exist to answer that question satisfactorily. Companies are not required to disclose information about their investments, and even if they did, it would be difficult to determine what fraction of the private-sector expenditures by automobile companies and other manufacturers of energy-consuming goods can be counted as efforts to improve the energy efficiency of products. It is also hard to define energy technology. Information on private-sector expenditures in the early-deployment phase is more readily available because venture capital (VC) and private equity investments, asset finance projects, and corporate finance deals are announced and tracked (e.g., Anadon et al., 2009; see also Section 24.6.2 in Appendix I).

There are reasons to believe that the private sector probably under-invests in ETI, both in comparison to historical R&D investment levels and in view of the social and environmental challenges related to the energy sector. First, what data exist indicate that investments are declining. According to one analysis of the US private sector using data from the National Science Foundation's annual survey of companies, private sector ETI investments fell approximately 20% during 1994–2004. The US electricity sector's R&D arm, the Electric Power Research Institute (EPRI), saw its budget decline by a factor of three during that time period (Nemet and Kammen, 2007). Also, companies are far more likely to invest in short-term RD&D projects that are likely to bear fruit in the near term than to invest in longer term, more fundamental R&D. This is especially true during times of broader economic turmoil or recession and energy price volatility. Such volatility leads to a "lumpy" pattern of investment on the part of the private sector, where big investments are followed by precipitous declines, and vice versa. Innovation requires sustained and steady "inputs" – people who are able to focus over the longer term on improving or inventing energy technologies, and adequate and stable resources to do so (Gallagher et al., 2006).

Turning to the particular rationales for government involvement in ETI, the first is to support, complement, and encourage the private sector's efforts because a vibrant energy sector in any economy will contribute to economic growth and prosperity. Second, energy services are fundamental human needs, and improvement of those services can better the human condition. If innovation reduces the costs of those services, consumer welfare and human well-being are improved. In poor countries, where millions still lack access to basic modern energy services provided by energy carriers such as like electricity, the government has an especially important role to play in developing appropriate technologies for rural energy users, and devising and implementing demonstration and deployment programs for better cookstoves, heating and building technologies, and so forth.

Government investment in ETI is also justified to make energy supply more reliable and secure; help the energy system emit fewer pollutants; and reduce the negative impacts of energy extraction, conversion, and use of water and land resources. In other words, market failures to protect the environment and enhance the security of a country help justify government involvement in the innovation process.

The last rationale for government policy for ETI is to overcome market barriers. Incumbent energy technologies or systems tend to have institutions, infrastructures, and policies that support them, providing barriers to entry for new technologies (sometimes called lock-in or path-dependence). There is also a famous valley of death between the invention phase of innovation and the deployment phase. This valley is really two valleys, because there are often difficulties moving from R&D to demonstration (which is expensive), and then again difficulties 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 lab to the market. In sum, policy can help push and pull advanced, cleaner, and more efficient technologies into the marketplace.

### 24.4.3 Models and Instruments of Policy

Policies for innovation can directly target the innovation process, support the innovation system, or unintentionally impact innovation while targeting an unrelated concern.

Direct policies for innovation vary according to their target and their timing during the innovation process. Policy is needed at each stage of this process (see the top of Figure 24.12 for examples). The role of government is typically viewed as being most evident at the earliest stage of basic science and research. However, together with the private sector, governments are also engines of applied energy R&D. But governments must also play an important role in leveraging private sector investment at the early commercialization stages by supporting demonstration activities (to reduce risks) and market formation (to underwrite demand). Finally, through regulations and other policies, including tax and fiscal policies, governments also strongly influence the diffusion of energy technologies.

There is often an intermediate stage between demonstration and diffusion that can be considered a market formation or early deployment stage. Here, government can play a critical role because policies are often needed to create an initial market to ease the passage of new energy technologies into the marketplace. First-of-a-kind technologies are often more expensive, and governments can create niche markets through procurement and other policies (e.g., feed-in tariffs or technology portfolio standards) to create demand for advanced or cleaner

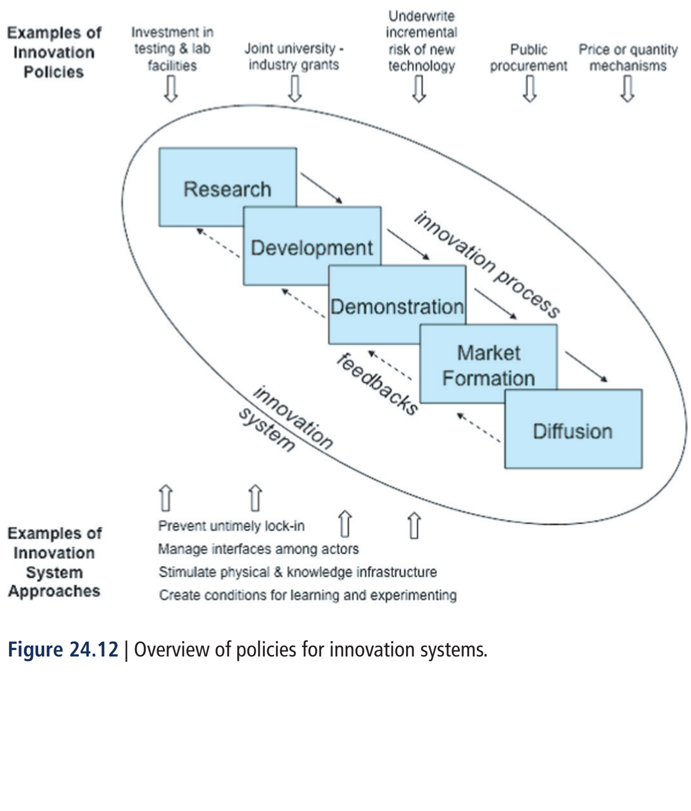


**Figure 24.12** | Overview of policies for innovation systems.

energy technologies. With this support, entrepreneurs can experiment and test the market. Technological learning occurs through experience. Even after the niche market has been exploited, policy intervention may be needed to broaden and deepen the market through the elimination of market hurdles, provision of information, tax incentives, or low-interest loans. At some point, a given technology becomes competitive in the marketplace, and the government can exit the market-formation stage. For new, cleaner energy technology 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). Because there are so many market distortions, technologies cannot be assumed to freely compete in the global marketplace.

The innovation process is situated within an overarching system comprised of the actors, institutions, and networks involved in developing and commercializing a technology (see Section 24.2 for details). Innovation policies must therefore also target the smooth functioning of the innovation system (see bottom of Figure 24.12). Although government policy affects all stages of innovation, rarely do we see evidence of comprehensive government strategies to optimize the efficiency of the ETIS. Instead, government policies persistently aim at isolated components of the system, such as support for R&D without regard to which policies are needed to maximize feedbacks in the system, or which market-formation policies will be needed if and when the technologies emerge in the demonstration phase.

Policies on issues such as education, taxes and subsidies, and market regulation can exert an important but indirect influence on 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.

Policies supporting the supply of innovations 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 roadmaps to guide the direction of innovation, and financial incentives such as tax credits for private investments. Not all innovation, however, derives from formal research and development activities. Problem solving and incremental improvements in existing technologies are also of importance and can be stimulated and supported by public sector policies that lead to the creation of outreach, extension, and technical support programs. Policies supporting the demand for innovations as commercialized technologies include demonstration projects, public procurement, market niche creation (e.g., supply obligations), 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 supply-push and demand-pull policies are context-specific complements rather than substitutes. Innovation success stories are typically characterized by comprehensive and consistent policy support through the entire innovation process (see Figure 24.12). Particular innovation policies must account for specific local conditions or be otherwise tailored to the technological or market characteristics of an innovation.

### 24.4.4 International Dimension to Energy Technology Innovation and Policy

International energy technology spillovers and feedbacks will depend on both local and global factors, and policy at both these levels is crucial. Energy systems and technologies are highly internationalized, and knowledge and learning in the energy sector has an intrinsic international dimension. Moreover, as shown in some of the case studies and the quantitative ETIS investment analysis (Appendix I), non-OECD countries have progressively invested in and developed capabilities in earlier stages of development of new technologies (e.g., China in coal gasification, India in wind turbines, and Brazil in biofuels). The globalization of technology has the potential to significantly increase the rate of energy innovation if international feedback and learning are properly enhanced.

The majority of energy technology is diffused through private means; it routinely flows through foreign investment, licensing agreements, and international trade. Each channel implies different modes of technology transfer and, depending on the effectiveness of local learning investment, different levels of local assimilation (Cohen and Levinthal, 1989). Many of these flows are actually intra-firm technology transfer, since energy firms are counted among the largest multinational corporations in the world, with very high indexes of internationalization (measured as share of affiliate sales on total sales; see UNCTAD, 2002). But this is not exclusive to the fossil energy industries: PV and wind turbine technologies were also developed as a result of experience and learning that crossed borders. But international inter- and intra-firm transfer do not occur without the appropriate systemic incentives, including subsidies, public R&D investment, tariffs, standards, resource mobilization, and the guiding action of policies and institutions.

Incentives for technology diffusion in general include market conditions and government policy, but cleaner energy technologies require normally explicit incentives. While the existence of more advanced and cleaner energy technologies has led many to believe that latecomer countries will leapfrog to such technologies (Goldemberg, 1998), this is by no means an automatic process. Rather, the process is predicated on developing technological capabilities (absorptive capacity) and appropriate market incentives for technology diffusion.

National policy incentives, coupled with either the financial resources to buy and/or the indigenous technological capabilities to make or assimilate advanced technologies, are required in this situation. Local policy incentives and institutions are crucial to overcome adoption hurdles, especially for cleaner technologies. The development of China´s automobile industry is one example. The Chinese government supported its firms to purchase automotive technology through licensing and joint venture arrangements, but for a long time failed to elicit pollution-control technology adoption due to the lack of pollution control standards until 2000. A lack of leapfrogging was observed with respect to pollution-control technology, but rapid leapfrogging occurred during the 1990s for automotive technology more generally in China (Gallagher, 2006). In the case of ethanol in Brazil, the government employed a comprehensive strategy involving standards, market incentives, RD&D investments, and human resource development to create a sugarcane-based ethanol industry (see the *Brazilian Ethanol* case study). In Mexico, opportunities were missed to cultivate a local wind industry and accompanying capability accumulation. Although the Instituto de Investigaciones Electricas (a public R&D center) had made the first steps toward developing wind turbine technology, the government failed to create incentives at the manufacturing stage, and opted for turn-key plant technology transfer (Borja-Diaz et al., 2005; Aguayo, 2008).

International policy also creates incentive frameworks for the 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., IEA, World Trade Organization, World Bank, and United Nations Development Programme). However, most of these are not oriented specifically to foster energy technology innovation. A current research gap is the dearth of studies examining the impact of these international policies and institutions on energy innovation. The effectiveness of international schemes like the Clean Development Mechanism and offset markets as energy innovation mechanisms remains unclear.

Adoption of energy innovations tends to proceed faster in late-adopting countries, but achieves lower technological levels than in inventor countries, as shown in the *Scaling Dynamics* case study. This is true also for traditional, carbon-intensive technologies. Most developing countries are currently experiencing a rapid transition into energy- and carbon-intensive modern energy infrastructures and fossil-fuel dependent end-use technologies, most notably the private automobile. Augmenting international spillovers and knowledge flows at early phases of scaling up could enable scope and scale economies in the formative phases of technology, accelerating technology improvement and pulling new technologies from their initial niches of application.

International knowledge spillovers through government-sponsored collaboration efforts seem weak compared to what is needed to foster a significant global energy transition. Perhaps the most prominent example of international energy technology collaboration among governments is the implementing agreements of the IEA. The IEA provides support for numerous international cooperation and collaboration agreements in energy technology R&D, deployment, and information dissemination (IEA, 2010). These agreements cover a broad range of technologies, but they strongly differ in the scope, stage, and level of commitment of the R&D process. Moreover, many are not really R&D collaboration projects, but simply institutional arrangements for information exchange or standardization. While non-member countries and international organizations may participate, OECD members' presence dominates (see Figure 24.13 below). There are other examples of government-supported international collaboration (e.g., the fusion reactor project ITER, or the Carbon Sequestration Leadership Forum), but their effectiveness remains to be assessed.

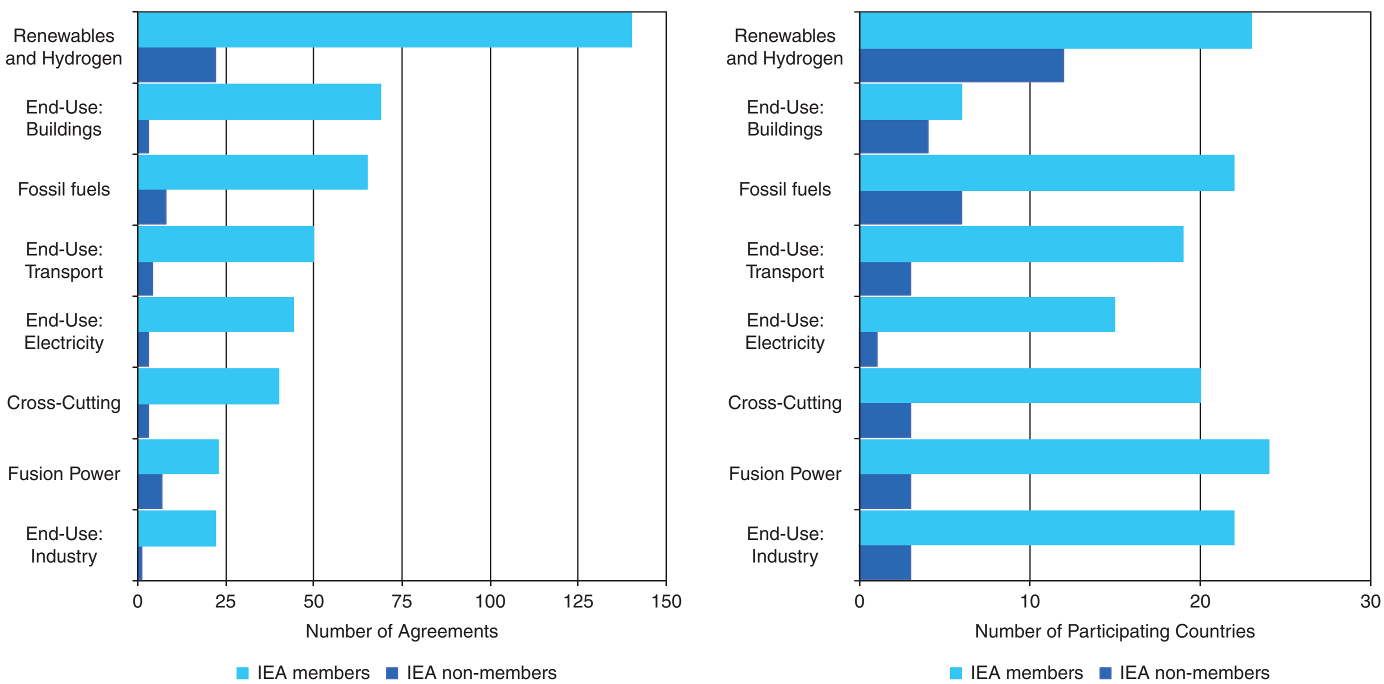


**Figure 24.13** | Examples of international technology cooperation via IEA agreements, by participating countries (IEA members and non-members), number of agreements covered (left panel) and number of participating countries (right panel). Note in particular the relative sparse participation from developing countries, which is less surprising considering the exclusive OECD membership of IEA. Source: based on IEA, 2010.

Another potentially important channel for international spillovers and technology transfer is government bilateral agreements. Their real impact on technology spillovers and advancement has not been assessed and will probably remain constrained by national interest issues and disagreement. These bilateral agreements are predominantly North-North, but there are examples of North-South cooperation, and most recently South-South energy technology flows, such as Brazil's set of agreements with 12 African and Caribbean countries for transferring sugar-based ethanol technology. Given their growing importance as both energy consumers and as energy technology providers, India and China have attracted most of the attention, spurring a constellation of binational dialogue and exchange programs such as the new United States-China Clean Energy Research Center, agreed to in November 2009 by President Barack Obama and President Hu Jintao. Again, these programs' effectiveness in fostering innovation and technology transfer remain to be evaluated.

### 24.4.5 Policy Design Guidelines/Criteria

#### 24.4.5.1 Introduction

The previous sections have outlined the main drivers of technological change embedded in a *systemic* conceptual perspective of the ETIS. The systemic perspective highlights that drivers and policies to stimulate technological change (innovation and diffusion) are closely interrelated. This section summarizes the main findings from the technology policy case studies of Chapter 24 that can guide the design of technology innovation and diffusion policies. In the view of the authors, these guiding principles for policy design carry more weight than the choice of particular policy instruments (including, e.g., externality pricing, preferential feed-in tariffs for emerging technologies, or various forms of subsidies or quantitative regulations such as technology performance standards) that are discussed in the various case studies. In other words, while the policy guidelines outlined below are considered generic and applicable across *all* technology fields and adoption environments, the choice of individual technology-related policy instruments needs to be tailored to technology- and locality-specific circumstances, but are invariably guided by the overarching general policy principles.

Ignoring the systemic characteristics of technological change often leads to a partial view and fragmented (even contradictory) policy frameworks. Although it is well understood that technology is fundamental to solving the energy challenges of our time, including climate change, energy security, and economic growth, what remains less clear is how to most effectively create and deploy new and improved technologies. There are no simple answers; innovation systems are highly complex and interconnected, meaning that decision makers must guard against overly simplistic responses that hide the need for flexible and broad policy approaches to meet energy innovation challenges. Included as boxes within the following sections are several stylized examples of these simplifications – or "policy myths"– and brief explanations of how such simplification might lead policy makers to actions that will not achieve their goals.

#### 24.4.5.2 Create Knowledge! Or: How to Enable Technological Learning while Learning about Technologies Yourself

One cannot influence the creation of technological knowledge in an effective way without knowledge of how the ETIS operates (and its institutions), the inputs it requires, and how to assess the effectiveness of innovation policies (outputs and "outcomes"). A special need in knowledge development relates to data on innovation activities themselves, which for the most part are poor, scattered, and incomplete. Informed innovation policy cannot be created in a knowledge vacuum. It needs to rely on data and appropriate metrics and indicators that can guide adaptive innovation policy design. For instance, our knowledge on technology-specific private sector energy R&D is woefully inadequate, implying that public and private sector innovation priorities risk being misaligned or even contradictory.

Research on energy innovation requires consistent, long-term, comparable, and more detailed data on innovation inputs and outputs, including information disclosure on policy programs. This information is critical for assessing not only the direction and rates of technological change and identifying needs in different areas of the innovation process, but also for evaluating society's response to energy challenges, including policies themselves. Policy makers need to communicate clearly strict quid pro quo conditions for policy support. For instance, direct subsidies on nascent technologies such as demonstration projects and niche market deployment need to be contingent on public disclosure and documentation of successes and failures in the deployment and performance of new technologies, in order to enable learning and the preservation of technology experimentation knowledge.

Decisions and choices that policy aims to influence depend on the structures in which actors are embedded. As technology systems develop, vested interests emerge, not only in the private sector and intermediate institutions but also in the policy-making realm itself. The risk of moral hazard and a poor ability to learn from mistakes can introduce rigidity and biases within the innovation system. This is why societies require reassessment and institutional learning at higher levels of the innovation system, in order to be able to learn and readjust policy objectives, priorities, and instruments. The need for independent and stable institutions that act as intermediaries between the twin vagaries of the policy and market environments, e.g., in the form of technology assessment institutions, cannot be stressed enough. Innovation policy needs institutional capacity for designing, implementing, and monitoring innovation policies, which is lacking in almost all countries, as well as at the international level.

#### 24.4.5.3 Assure Feedbacks! Or: How to Create/Enable Knowledge Flows for Technology Learning and Spillovers

Formal and informal information feedback processes are essential for sustained and successful innovation. This is well known and well cited in the literature, yet it has proven virtually impossible to institutionalize. Even this recommendation has sometimes been seen as an excessive burden on already over-worked public officials, NGOs, and contractors who have little interest in long-term monitoring (PCAST, 1997). Government can support these essential feedbacks in a variety of ways, but can also hinder – or even block – essential information and knowledge flows.

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 results communicated back to developers/manufacturers. The *Wind Power* case study illustrates the success of test stations in Denmark to support knowledge feedback and quality assurance. The results were widely spread, as networking between actors (i.e., manufactures) was also supported. The test station establishment resulted in essential knowledge and technology development. However, the case study of wind energy also illustrates the negative experience in the Netherlands, where the government supported competitiveness rather than networking. In the Netherland case, the test station environment did not support essential feedbacks and information exchanges between Dutch manufactures.

Niche markets and early market deployment can also provide essential feedbacks. For many new energy technologies, early experience in production and use, including experience in operation and maintenance (O&M), have been essential for successful development because experience is fed back into R&D and design changes. For example, wind turbines developed in the early 1980s were assembled from standard components, and feedback in use and O&M were essential for the development and tailoring of specialized wind turbine components; this in turn supported the development of specialized suppliers. Moreover, high costs related to production and O&M are important drivers for feedback and improvements of products and production processes. Another example for this type of essential market feedback is provided in the *Kenyan PV* case study of PV applications in rural Kenya (see Appendix II). Problems with quality in the PV systems were only revealed through extensive market deployment (and not in earlier demonstration stages or via traditional manufacturing quality control) and led to the subsequent improvement of the technology. Governments or NGOs can assist in this feedback process by providing documentation and public disclosure of market deployment experiences with novel technologies.

Feedback from niche markets and early markets are also important for the formation of the entire innovation system, taking into account not only the technology itself, but also actors and legal and economic frameworks. Essential feedback can be provided by evaluating the process of market formation. By evaluating how the system of innovation is evolving, e.g., the development of knowledge and actor networks, ongoing policy programs can be redesigned to improve in effectiveness and efficiency.

For both technology and market development, extended feedback loops could be achieved through international cooperation and experience sharing. Reporting is essential to overcome any discontinuities (for longer or shorter periods) in the support of technology and market development. Such international knowledge exchange initiatives (e.g., through some IEA programs) remain in their infancy.

#### 24.4.5.4 Globalize! Or: How to Devise Local Policies to Productively Harness the International Flow of Energy Technologies

Energy technologies are intrinsically international. They constantly flow in the private sector through international licensing agreements, joint ventures, direct investment, and trade. Feedbacks in the energy innovation process can and should occur across national borders. To encourage the development and deployment of advanced/new technologies, policies are often needed to create a coherent incentive structure. Local policies are also necessary to foster absorptive capacity to take advantage of technology and knowledge produced abroad.

Protecting intellectual property rights (IPR) is an important aspect of knowledge exchange, but not a sufficient condition – nor even the most important factor – for enabling the transfer of technologies and knowledge (see Box 24.1). Technology diffusion, both across industries as well as across countries, consists fundamentally of adapting existing solutions to new environments through an iterative process of knowledge exchange, revision, reconstruction, and improvement. Setting up the conditions for accessing and assimilating foreign technologies necessarily implies building a local system to produce and reproduce this knowledge.

Developing countries can access new energy technologies through external technology sources like specialized suppliers and multinational firms, or they can support indigenous development of advanced technologies by implementing a comprehensive strategy that includes policy support for human resource development, investments for RD&D, and market formation. Simply buying technologies from abroad is often insufficient because developing countries assimilate these technologies but not the related knowledge about how to adapt, reproduce, and improve upon them.

Naturally, the financial requirements for acquiring hardware, machinery, and equipment are a central aspect of international technology diffusion, especially in capital-intensive, large, and embodied energy technologies. International financial schemes and institutions play a role 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. Local and global efforts to mobilize the appropriate financial resources and schemes must be aimed at reducing the valley-of-death transit of clean, advanced, new energy technologies to enable technology and knowledge flows across borders.

Efforts to align national policies toward more effective technology transfer mechanisms must take into account both the predominance of private channels of technology transfer, as well as the role of public investment and incentives needed to provide a level playing field for advanced new clean technologies.

## Box 24.1 | How can we ensure that all regions and sectors have access to, and are using, the best technology?

Myths: *"You can just buy (transfer), whatever technology is needed."*

*"If we just fix IPR issues, technology will transfer seamlessly."*

*"If developing countries only had strong IPRs, technologies would transfer to their countries."*

*"If only international IPRs were weaker, developing countries would rapidly adopt new technologies."*

Technological capabilities and technology levels vary widely across regions. Given that the non-OECD regions will represent an increasing share of the global energy system, effective technology deployment within and to those regions will lay the foundation of growth that is consistent with energy-related objectives.

Patents and other Intellectual Property Rights (IPRs) instruments are not a sufficient condition for innovation or technology transfer. Technology is much more than the "blueprints" of information disclosed in a patent. There are plenty of other conditions and investment needs to be met. Income thresholds set up limits to the scale to which technologies can be applied, limiting their attractiveness. Specialized inputs and infrastructures must be timely and effectively supplied. Skills in operating and integrating complex systems need to be developed. Moreover, many innovations are not patented, and in many industries firms rely on other means for seizing technology advantages (Levin et al., 1987). This means that simply adjusting intellectual property rights will prove far from sufficient to bring about the necessary technology transfer.

The literature discussing the impact of IPR on energy technology transfer is scarce. There is a dearth of empirical or literature evidence that lacking IPR protection is a strong barrier to technology diffusion. In fact, there is emerging evidence to the contrary, i.e., other barriers such as capital costs, lack of infrastructure, lack of local policy incentives like performance standards, feed-in tariffs, and subsidies, and lack of financial resources are more important. In the case of PV and biofuels, for example, the high number of supplier firms and flexibility of sources will most likely reduce the space for monopolist practices in technology contracts. The same seems to be true in the more concentrated wind turbine industry, where developing countries' firms have developed local industries through licensing. However, IPR protections may be a barrier to industry entry for developing countries in the future (Barton, 2009), even when other entry barriers (manufacturing experience) may play a much larger role.

Patents build up incentives for innovation by providing means to control and shape technology transfer. The current global context is already one in which IPRs have been considerably strengthened by prohibiting or restricting compulsory licensing, reversing of burden of proof, and extending of patenting dimensions (Maskus, 2000). Many models on patents show that balancing a patent's dimension can actually reduce the social costs of IPRs, depending on the structure of demand (Nordhaus, 1969; Klemperer, 1990; La Manna, 1992). The resulting trend to maximize all dimensions of patents in TRIPS (Trade Related Intellectual Property Issues) and other trade related IPR frameworks have limited the scope for IPR policies to more rationally foster innovation and transfer by customized IPR systems that properly balance private and social costs.

#### 24.4.5.5 Be Stable! Or: How to Create Policy Stability and Credible Commitments on which Innovation Depends

Governments need to create expectations for actors in the innovation system that are stable and consistent over a multi-year period. Uncertainty in expectations about future policies increases the risk of investing in innovation for energy technologies. Because externalities are pervasive in the clean energy sector – due 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 several years in the future are uncertain, firms will discount the value of future policies and under-invest in innovation. Because technology development is in itself a risky endeavor, private sector energy companies will only respond to policies that are credible, last more than a few years, and have a reasonable degree of stability. Moreover, volatility can accelerate knowledge depreciation and loss. Technology policy can be dynamic and flexible to reflect new information, but broad goals must be consistent and funding levels for support of the various stages of the innovation life cycle need to be predictable for the private sector to engage and invest in the creation of new technological knowledge. For energy problems that cannot be solved quickly, patience and predictability are needed.

The case studies make clear the adverse effects of policy volatility and rapidly shifting priorities among policy makers, as well as successes that have resulted from a more recent shift to longer time horizons. R&D budgets have been notoriously volatile. The history of US energy R&D funding is not characterized by stable budgets, but by changes that are much larger than annual changes in economic activity and overall research spending. More than half the time, annual program budgets rose or fell by more than 10% (Nemet, 2007). Wind power, solar thermal electricity, and solar water heaters boomed in the early 1980s and then the industries were devastated by dramatic program cuts in the mid-1980s, even if partially restored soon thereafter. Innovation, job creation, and manufacturing dropped in the United States, and even 25 years later, the focus of activity on these "abandoned" technologies remains outside the country.

A more recent policy innovation has been the shift to policies that ensure stability by including time horizons that set expectations about the intensity of government activity, for example, over ten year periods. The Japanese New Sunshine Program in the 1990s set declining levels of subsidies over ten years. The California Million Solar Roofs Bill set subsidies for 10 years. Renewables obligations in many US states set levels 15–20 years in the future, usually with annual interim targets. An important cautionary note is that long term commitments like these often include clauses that allow loopholes for governments and actors to avoid meeting these commitments should compliance become more difficult than expected, for example through the ability to pay low penalties. A "safety valve" clause in cap and trade has a similar effect if not paired with a symmetric price floor. While the flexibility to change targets may have social benefits, it is important to understand the price paid in terms of reduced incentives for investment for private actors. The shift to longer time horizons for policy making has been an important development, but can also be undermined by implementation details allowing excessive flexibility in cases of nonattainment.

### Box 24.2 | How quickly can we move the energy innovation system? How long of a commitment to energy innovation is needed?

Myths: *"If we throw enough money at this, we can make it happen quickly."*

*"This is a man-on-the-moon project."*

There is no doubt that today's energy challenges call for quick action, and increases in government funding may play a key role in the strategy for solving these problems. In framing the energy challenge, many have evoked the memories of rapid, focused projects to achieve single national goals, such as the Manhattan Project in the United States to develop nuclear weapons, or the US effort to put a man on the moon in less than 10 years.

Although there is a need to pursue energy innovation more aggressively, energy embodies a far broader range of technologies and actors than a Manhattan Project. Virtually every citizen of the globe is an energy user, and therefore has the ability to choose technologies to deploy and fuels to purchase. Energy supplies are produced and provided by a vast range of actors and there is a wide range of supply sources: fossil fuels, bioenergy, nuclear power, solar power, wind power, and others. Each of these involves multiple technology competitions and opportunities for improvements. Historically, accelerated technology deployment programs relied on "selected" single-mission driven technology winners. Meeting future energy needs likely benefits by bringing multiple, competing technology options to the market.

Further, the challenges that face the energy system over the coming century will not be met within a decade. For example, climate change research indicates that the carbon dioxide ($CO_2$) emissions reductions required to stabilize $CO_2$ concentrations will be more stringent in the longer-term than in the shorter-term and reductions must continue indefinitely. The challenge for decision makers is to develop the support for a sustained, long-term effort to enhance energy innovation.

#### 24.4.5.6 Align Incentive Structures! Or: How to Avoid Confusing the Market

To maximize the effectiveness of ETIS, it is essential to align incentive structures and employ consistent policy signals. These alignments should be durable so that there is predictability over time for the ETIS. When there is inconsistency or lack of alignment, the efficiency and effectiveness of the system is undermined.

There are two types of alignment that must be considered: (1) alignment of incentives within a given innovation system; and (2) alignment of incentives for different innovation systems to encourage spillovers. To illustrate how to align a particular system, we can utilize the model of the growth phase of the technology life cycle. Aligned policies would include the development of an explicit strategy for supporting technologies that are invented through demonstration and testing, and formation of larger-than-niche markets to 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. Throughout the growth phase of a technology (or set of technologies), governments need to elicit information from actors and devise mechanisms for feeding that information to other actors and other stages of the innovation process. In other words, government often must facilitate the integration of supply and demand and overcome barriers to sharing information essential to the good functioning of energy markets.

When government fails to align the incentive structures for achieving desired outcomes, contradictions emerge and perverse outcomes flourish. Three examples are helpful to illustrate these contradictions.

The *US Vehicle Efficiency* case study on the CAFE standard and the *Hybrid Cars* case studies (see Appendix II) show that the main policy incentive for the development and deployment of energy-efficient vehicle technologies in the United States is the CAFE standard. However, the United States does not impose significant fuel taxes or any fees on the purchase of inefficient vehicles (though it provides a subsidy in the form of an income tax credit for the purchase of certain advanced technology vehicles like plug-in hybrids). As a result, manufacturers are encouraged to innovate only as much as the standard implies, and consumers have virtually no incentive to drive less or to purchase more efficient vehicles. The CAFE standard thus creates a floor for minimum levels of innovation, which implies that the policy mix is incomplete. As one would expect, vehicle miles traveled have steadily grown in the United States (especially because the cost per mile of driving is lower with the fuel efficiency standards), and there was an explosion in the purchases of large passenger cars and light trucks, which had a weaker standard. If the US government added a tax to the price of gasoline, it would help create consumer demand for more fuel-efficient vehicles, thereby facilitating the integration of supply and demand.

The large government investments into RD&D of fossil, fission, fusion, efficiency, and renewable energy technologies can be charitably labeled uncoordinated, and possibly characterized as completely at odds with the much larger government subsidization of the deployment of fossil-fuel technologies. In 2008, IEA member countries invested US$14 billion in energy RD&D, and US$1.6 billion in total for fossil energy technologies (IEA, 2009b). While fossil fuel subsidies may support the fossil fuel RD&D investments, they strongly distort the market for nonfossil energy technologies. US fossil fuel subsidies alone are at the level of approximately US$10 billion/year for traditional fossil fuels, according to a recent report (Adeyeye et al., 2009). Fossil fuel subsidies in the non-OECD countries are estimated to be approximately US$170 billion/year (IEA, 2006). Globally, subsidies to fossil fuels may be on the order of US$500 billion/year, of which about US$100 billion is estimated to be provided to producers (GSI, 2009).

For an example of the lack of policy coordination, consider the United States. There is little evidence in the United States of bureaucratic coordination at the federal level. R&D strategies and decisions are largely made by the Department of Energy in the Federal Executive Branch (although appropriation decisions for R&D are made by Congress, often in contradiction to the R&D strategies set forth by the Department of Energy). Congress, however, establishes the market formation policies – the subsidies, loan guarantees, tax credits, carbon taxes, and cap-and-trade systems. Sometimes the Environmental Protection Agency establishes the market formation or deployment policies (e.g., sulfur dioxide emission trading system; performance standards for power plants), but Congress usually confers this authority. In this system, it is difficult to map out and implement an efficient innovation strategy, much less insure that feedback loops are established and maximized.

Alignment of incentives for ETI probably cannot be achieved without an explicitly designed and implemented innovation strategy for energy technologies. Even with such a strategy, multiple objectives in a country's energy policy can cause a misalignment of incentives. A common misalignment is government making RD&D investments in energy efficiency while simultaneously subsidizing the price of retail fuels. 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.

#### 24.4.5.7 Be Systemic! Or: How to Address Innovation in a Comprehensive Way

Innovation policies tend to focus on specific technologies. A narrow technology focus runs counter to the systemic view of energy technology innovation developed throughout this chapter. As well as technology-specific innovation processes, the innovation system is comprised of actors, organizations, infrastructure, and institutions. Relationships and feedbacks between these various components of the innovation system underpin the drivers and mechanisms of innovation discussed in

## Box 24.3 | What mix of policy instruments would most effectively spur innovation?

Myths: *"The solution is a massive ramp up of R&D expenditures."*

*"If prices are right, innovation will take care of itself."*

It is well established that innovation takes place through a system of complementary actors and processes. Each or any of these processes may prove to be a choke point in the innovation system. Government-supported R&D is a core element of the innovation system, and many argue that government R&D expenditures should be increased in the face of our current energy challenges. However, government R&D is far from the only component of the energy innovation system.

Internalizing the costs associated with climate change and energy security to the feasible extent would provide more appropriate signals for technology deployment and private-sector innovation and investment activities. However, a wide range of market failures exist that prevent the private sector from investing in innovation in ways that are consistent with social needs, even if prices are right. Effective pricing is far from sufficient for a robust energy innovation system.

Decision makers find themselves in a situation where there is no single policy mechanism that will support a robust energy innovation system. The system must include a well-functioning and well-targeted government R&D program, but appropriate incentives through the pricing of externalities is also critical for producing demand signals that will induce learning and create incentives for private-sector R&D. A wide range of policy challenges remain regarding other core elements of a robust innovation system, including intellectual property rights and institutional structures to support widespread deployment of new technologies.

Section 24.2. Taken together, these components comprise the selection environment that shapes the outcomes of the innovation process.

A systemic approach to innovation policy requires a package of policy instruments that should adapt to changes and be geared toward triggering changes over time in the innovation systems. Policy packages may also differ from one innovation system to the next. Within these packages, policies must be aligned and consistent in their targets and objectives, as discussed above. Policy packages must also be broad in their coverage, supporting the successful functioning of the whole innovation system. A good example is the cooperation and knowledge feedbacks between different actors and institutions furthered by incentives for collaboration and mandates of information disclosures. Overall, the policy package needs to support knowledge development, feedback processes, and learning for the entire – or at least for the essential parts – of the innovation system. The *Wind Power* case study discusses the development of wind energy in Denmark and shows the success of a systemic approach that includes several actors (energy companies, wind turbine producers, smaller wind turbine owners) and the relationships between those actors, as well as essential institutional features (connection to the grid, spatial planning and permitting process). The *Japanese Efficiency* case study also illustrates this point nicely.

In the case of end-use technologies, actor-networks within innovation systems are often more complex, involving end-users, local authorities, wholesalers, retailers, branch organizations, consultants, installers, energy companies, architects, etc., as well as socially constructed norms, habits, routines, and values. Although these social institutions may 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. This can be attributed in part to the deep ideological, conceptual, and analytical differences between social innovation and technological innovation, which extend into the policy domain.

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.

The interdependence of innovation outcomes with social change also highlights the limitations of innovation policy, even when designed within this systemic perspective. Even comprehensive, aligned, and stable policy packages can never guarantee successful innovation outcomes due to irreducible uncertainties.

## Box 24.4 | Is innovation policy exclusively concerned with technologies?

Myths: *"The problem is technological. If we solve that, social change will follow."*

*"Technological change only arises in response to social needs."*

Technological and social change are interdependent. The success of technology-focused innovation processes, as well as the effectiveness of these policies, is conditional on supportive and adaptive social institutions. Participatory planning processes to foster the scaling-up and diffusion of wind power, and community-based organizations that promote energy efficient behaviors and technology adoption, are two current examples. Policies to support social innovations should be considered an integral part of an innovation system approach.

#### 24.4.5.8 Experiment! Or: How to Stop Worrying about Failure

The formative phase of a technology's life cycle concerns the transition from development to diffusion. The dynamics of energy technologies that have successfully diffused historically indicate the importance of building out large numbers of units as a key feature of this formative phase. (A unit refers to a steam turbine in a coal or nuclear plant, a wind turbine, a photovoltaic module, and so on.) From the perspective of governments, experimentation, debugging, improvements and learning possibilities are all proportional to the number of units built during the formative phases of a technology's life cycle. Granularity is therefore a key variable determining innovation and investment risks, as well as the extent of possible experimentation, improvements, and learning favoring smaller, unit-scale, MW-scale projects over larger, "lumpy" GW-scale projects.

The demonstration and early deployment of many units is a natural feature of modular, distributed technologies like residential solar hot water or PV systems, with relatively low capital requirements per unit (even if costs per unit of energy output/capacity might be high). The unit costs of modular technologies may be driven down during the early deployment and diffusion phases by manufacturing scale economies in addition to learning effects. However, the same tendency to focus initially on building out unit numbers is also observed in the histories of large, centralized supply-side technologies. Despite the apparent availability of unit scale economies (i.e., falling unit costs at larger unit capacities), formative phases were historically characterized by only incremental increases in unit capacity over an extended, decadal period. Considerable experience was 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 different units as a precursor both to widespread diffusion and to up-scaling (i.e., pushing technologies up the unit scale frontier). The hallmark of this approach to innovation is granularity: individual eggs in many small baskets. Note that granularity here refers to the formative phases of a given technology; design criteria for portfolios of technologies are addressed below.

Promoting substantial one-off increases in unit scale prior to numerous formative experiments in both precommercial (demonstration) and commercial contexts should therefore be considered a high-risk strategy. The comparative histories of wind power in Denmark and Germany support this cautionary note. Experimentation to generate knowledge on a technology's performance, efficiency, reliability, and other service attributes enhances the required capacity for capturing unit-scale economies. The design, construction, and operation of many different smaller scale units not only leads to incremental improvements and learning-related cost reductions, but also would appear to underpin the success of subsequent larger-scale units.

The importance of these formative experiments helps explain why the time period over which unit scale economies are captured does not appear to accelerate from early to late markets. Although large scale units may be transferable from early to late stage markets, the late stage markets need time to form the requisite institutional capacity to support these increases in unit scale. A context of international cooperation and knowledge transfer would, of course, support the aggregation of learning from experimentation processes running concurrently around the world.

Experimentation can and also perhaps should be multifarious, involving an array of different actors, forms, and stages of the technology's life cycle. In practice, many smaller scale variants of a technology may be pursued on parallel tracks by competing and heterogeneous commercial interests. This granular approach to innovation policy diversifies risk and reduces the consequence of failure.

Government's role should be to fill in the gaps by, for example:

- underwriting small-scale demonstration projects for socially robust innovations with less immediate or higher risk private returns;
- supporting variety in the early deployment phase by creating and protecting differentiated niches;
- reducing upfront capital barriers;

- managing the natural commercial tendency to rapidly confirm a dominant design that confers market advantages and potential cost benefits through scale economies; and

- avoiding over-emphasis on rapid unit scaling.

Failure is an inherent feature of a multifarious and granular portfolio of innovation experiments. Venture capitalists may build energy technology portfolios with an expected nine-in-ten failure rate, knowing that the one in 10 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. A shift in mindset is needed to recognize that perfect foresight and innovation are awkward bedfellows, not just in the early R&D phase, but also during the early deployment phase of experimentation with many unit numbers. Learning what does not work supports learning about what does work, and this in turn supports both diffusion and unit scaling. Building diverse portfolios of modular or smaller-scale technologies helps spread this risk of failure. Conversely, concentrating public resources on the scaling up of a particular technology (be it fusion power or GW-scale CCS projects) reduces portfolio diversity and magnifies the risk of failure.

#### 24.4.5.9 Focus on Technology Portfolios! Or: How to Not Pick a Winner, but to be Picky on your Picks

The broad range of necessary ETIs combined with inevitable innovation uncertainty suggests that innovation policies must consider not a random collection of innovations, but rather a wide portfolio of technologies.

Innovation portfolios reflect the combination of technology options pursued within the innovation system that reflects both their respective option value (i.e., societal/ environmental/ economic benefits in the case of successful development and diffusion) as well as their associated risks (e.g., innovation failure or investment risks).

In designing innovation portfolios, a number of basic criteria need to be taken into account:

1. The portfolio needs to reflect a blend of options comprising the entire energy system and spread the investments across many technologies and projects.

2. The innovation portfolio should encompass all salient elements of the technology development cycle and all different channels of technology knowledge creation, such as R&D. demonstration, niche market deployment incentives, and market creation measures.

3. 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 meaningfully only be considered in global innovation portfolios. A common thread in case studies on both historical as well as current energy technologies (compare the studies on *Hybrid Cars, Solar Water Heaters, Heat Pumps, Japanese Efficiency, Wind Power,*

### Box 24.5 | Are the technologies available that would be necessary to take action today?

Myths: *"No innovation is needed; all that's required is political will."*

*"We can't take action now because the needed technologies are not available."*

The full suite of technologies that will ultimately be deployed to address the energy challenges in the coming century is not currently available. Technology continues to advance and redoubled efforts to spur innovation will certainly lead to improvements in technologies over the coming decades. At the same time, there are numerous reasons to take action to deploy currently available technologies today: innovation systems are most effective when there is communication between technology users and developers; a range of non-technology factors are associated with the broad deployment of many technologies, and these can take years to develop; capital investments today may preclude effective action in the future; and in many applications, there exist technologies that could have dramatic near-term effects, such as end-use technologies.

Decision makers find themselves in a situation where a wide range of beneficial actions are possible today to deploy existing technology, yet not all technologies are ready for deployment. The challenge for decision makers is to implement policies that will allow some technologies to develop further before moving from the laboratory to the field, and experimentation and feedback with other technologies at a small scale. These policies should support the private sector's role in deploying still other technologies at a large scale if they are clearly proven at smaller scales.

*Solar PV,* and *Kenyan PV* with the *US Synfuels* and *French Nuclear* case studies) is the importance of granularity. Smaller unit scales of energy technologies (e.g., the size of a one MW wind turbine compared to 1000 times larger typical size of a one GW nuclear reactor) not only result in lower innovation failure risk[16] for a given project, but also in lower barriers to innovation adoption in case of successful demonstration. Technology policy can also profit from granularity, as enabling the spreading of innovation risks across a broader range of a multitude of smaller-scale innovations without requiring the premature selection of few capital intensive innovation projects, preemptying decentralized market-based decision processes. It is not coincidental that granular, smaller-scale innovations in energy end-use technologies have been the dominant source of technological advance in energy systems historically and will likely remain so in the future.

4. In portfolio design, the inherent tension between the desirable goal of maintaining technological diversity and the equally desirable goal of improved economics through standardization and technology focus needs to be considered.

5. The core element of a broad-based innovation portfolio is that policy makers need to be pickier with their technology picks. 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 complement private market technology innovation biases against large-scale, investment-intensive technologies that might be crucial in addressing broader social and environmental goals. While resource limitations inevitably require focus on a few strategic technologies, there is a downside: decision makers need to be aware of the pressures to concentrate capital-intensive, high-risk innovation projects (potential innovation "lemons") in the domain of public sector innovation portfolios, implying higher risks that the public sector disproportionally shoulders. The result is an invitation for public support for high-risk innovations or bad business practices (e.g., according a quasi-monopoly to private sector-advanced technology options that capitalize on the economic rents from lavish public subsidies, without "delivering" in terms of much needed technology innovation, such as persistent cost improvements of new energy technologies).

6. Innovation portfolio design ideally includes a blend of the respective options values of technologies, both from a demand-pull and a supply-push perspective. Policy makers also need to be explicit on their underlying risk measures and criteria that enter innovation portfolio design to enhance the legitimacy and transparency of the resulting resource allocation across options and measures.

7. The importance and complexity of these portfolio decisions will require more expertise within governments, as not all technology decisions can (or should) be made by the private sector. Fortunately, formal scientific tools for innovation portfolio design and analysis are becoming increasingly available (cf. the *Technology Portfolio*s case study). These tools can help move the discussion on innovation portfolios to more rational ground, but the further development of these tools requires continued policy and funding support much like energy technologies themselves, as well as an institutional locus for their application.

16 Given equal probability of failure of two innovation projects, the one with smaller unit scale and hence lower total costs (millions as opposed to billions of dollars) results in lower innovation risk (defined as failure probability times [economic] consequences, i.e., loss of investment).

### 24.4.6 Conclusions: Generic Characteristics for Energy Technology Innovation Policies

Energy systems consist of interconnected technologies, knowledge bases, and practices that are interdependent and operate in dynamic ways. They are simultaneously embedded into prevailing economic incentive structures and broader social contexts. To be effective, innovation policy must be conscious of these interdependencies across time, space, and actors, and act coherently. Isolated policies acting in only one realm of the market (for example, by stimulating niche markets through tariff policies under a cost buy down paradigm) will not yield strong innovation if not accompanied by coordinated and aligned support for R&D and demonstration projects. Likewise, an isolated technology push focused on R&D without regard to the economic and institutional incentive structures and barriers prevailing in energy markets will be counterproductive for innovation, effectively curtailing the essential feedback and learning from market deployment on which R&D so critically depends.

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. Resource and financial hurdles are, for example, of a very different type in R&D phases than in demonstration and early deployment stages; as market formation advances, the need for agents' coordination also changes in nature and degree. Policies for preserving variety or accelerating standardization are extremely sensitive to the state of development of the technology.

The dynamics of technology over time require the attention of innovation policy to development times and feedback processes. Technology research 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. Since 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. Long-term planning and policies that persist before being able to reap economic,

### Box 24.6 | How should policy focus and resources be allocated across technologies?

Myths: *"All technological options will be needed everywhere."*

*"We need a balanced portfolio."*

*"Technological failures are a sign that mistakes have been made."*

*"We'll need as much diversity as possible."*

*"Technology X is the answer."*

There is a strong tendency for decision makers and technology advocates to focus on a single technology as being the key to meeting energy challenges – the "silver bullet" approach. This single technology focus is a result of both a lack of understanding of the complexity of the global energy system and the tendency of technology experts to support the continued expenditures on single technologies. However, research has consistently indicated that a broad and diversified portfolio is critical to provide options throughout the energy system, to allow for experimentation, and because history has shown that technological expectations are often wrong. A necessary condition for a successful innovation system is the exposure of nonproductive avenues for innovation and the ability to drop these avenues from the portfolio.

At the same time, a diversified portfolio is not necessarily an effective portfolio. There exist a wide array of possible diversified portfolios, and the need for diversity does not obviate the need for decision makers to identify avenues that are most promising and or lacking in effort and adjust the portfolio appropriately. Further, there are many avenues of investment for which increased effort is an obvious need.

The challenge for decision makers is the management of diversified portfolios. This requires institutional structures that are capable of effectively collecting and synthesizing information, robust in the face of necessary technological failures, and capable of adjusting as information changes.

social, and environmental returns are key to ETI. To be consistent in time, policies should be adaptive, flexible, and patient during the early phases of technology development to preserve technological variety, with efficiency assessments and selection of programs/projects in later stages.

The inherent, strong uncertainty that characterizes early phases of innovation calls for flexible institutional mechanisms that are able to actualize expectations regularly. However, as the technology 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 towards standardization, and be able to switch policy priorities over time, but in a predictable, consistent manner.

Knowledge is a crucial factor in innovation, and its nature critically influences policy outcomes. Systemic approaches particularly emphasize the fact that learning processes in innovation occur at many different levels and flow in multiple directions. Knowledge develops and accumulates through a range of complementary processes and activities, which in turn condition the future absorptive capacity for new technological knowledge. Supporting and facilitating these complementary learning processes is a crucial complement for innovation policy, unfortunately too often ignored. The quasi-public and distributed nature of knowledge, together with the strong positive feedbacks between different knowledge bases, call for adequate, timely policy support to these activities, which are easily screened out by market processes. At the same time, policy design should reflect the understanding that knowledge can become obsolete and experience can be lost. Innovation policy is incomplete if it does not adequately address the conservation of memory and a continuous renewal of the knowledge base, which is particularly threatened by stop-and-go erratic policy support.

## 24.5 Conclusions

### 24.5.1 Research, Data, and Information Needs

A number of important gaps in data, information and research were identified in the above assessment. Addressing these issues is not only of academic interest but equally critical for improved technology innovation policies, and hence is of greater societal relevance. Ten important areas are summarized here, regrouped into two broad categories: data and information, and research needs. A central theme is the need to develop better indicators and quantitative data as well as operational models and criteria to answer the core questions of technology innovation policy regarding effectiveness, i.e., what is the most appropriate policy instrument for a particular purpose, what resources are required, and what are the likely response times of the innovation system to policy interventions?

#### 24.5.1.1 Data Needs

In terms of data, four 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 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 on joint technology development collaborations; and
- 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.

#### 24.5.1.2 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 available or to be developed data sets;
- operational measurement models that describe knowledge depreciation in R&D and LbD processes; and
- criteria for the selection of technology specific case studies especially in a comparative context across countries and across technologies.

#### 24.5.1.3 Research Needs

In terms of research, this assessment has identified the following areas:

- the development of conceptual models that answer the question of how measurable inputs and outputs of innovation systems relate to each other;
- the development of a "meta-theory" of technological change that enables to establish appropriate *ceteris paribus* conditions to be able to compare and assess the dynamics of change and of policy effectiveness across different technologies and development/adoption environments; and
- comparative assessments of the effectiveness of alternative policy instruments aiming at influencing individual components or the entirety of ETIS.

### 24.5.2 Conclusions on Energy Technology Innovation

Substantial and accelerated innovation is essential to respond to the sustainability challenges of energy systems at all levels, including the local, national, regional, all the way up to the globe scale. Further, 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, driving and embedding factors that need to work hand in hand in the development, testing, and ultimate selection and adoption of new innovations.

A core message of this chapter is that the drivers of innovation, as well as the policies that support it, are complementary rather than substitutable for each other. This requires attention to fundamental innovation, or technology push, which needs to be coordinated with efforts to facilitate the expansion of the market opportunities – demand pull – that move innovations from laboratory to cost-effective deployment. As such, the energy sustainability challenge requires changes in whole innovation *systems* rather than simply more independent, individual innovations.

The synthesis of the available literature and case studies suggests that successful innovation systems and their supporting policies are characterized by three main features: alignment, consistency, and patience.

Alignment (i.e., comprehensive and contradiction-free) means that the various forces and policies that drive innovation are considered holistically and not from the perspective that any single driver can substitute for the (lack of) other drivers. Accelerated R&D in new energy technologies without economic incentives for ultimate adoption of the innovations will not yield the much needed change to redirect energy systems toward sustainability.

Likewise, consistency of policies and drivers is key. Incentive structures need to remain stable and not at odds with each other. All innovation actors (researchers, industry suppliers, and customers, the end consumers) rely on predictability and consistency of the innovation environment; otherwise the costs of taking the inevitable innovation risks become prohibitive. An important task for research is to provide a framework that can be used to examine energy and carbon outcomes of innovation policies, including the relative benefits and costs of policy tools aimed at the expansion of the low-carbon energy sector.

Finally, patience is needed. The time lags between basic and applied research, development and testing, market introduction, and ultimate diffusion and the required feedbacks to earlier innovation stages in the process are substantial. Joint expectations (or visions) need time to emerge and accommodating social and institutional settings need time to develop. The international dimension in the development and diffusion of innovations also requires patience.

Innovation and technology policies also can no longer remain fragmented, *ad hoc*, and concentrated on individual technological options. A much more strategic and long-term approach is required to harness the potentials of well-functioning ETIS. Goals and objectives, weighting of different (sometimes conflicting) objectives, strategies and implementation plans to be followed, evaluation criteria for continued reassessment, etc., all need to be formulated to involve relevant stakeholders and take account of international developments. Above all, this requires institutional innovations as, at present, corresponding institutional frameworks and learning capabilities are insufficiently developed. Successful examples such as the Japanese national system of innovation can provide inspiration, but institutional solutions need to be custom-tailored to their specific national or regional circumstances.

A paradigm for a strategic and long-term approach to ETIS is the concept of adaptive/policy learning. Strategies and policies need built-in mechanisms to assure flexibility and the ability to adjust courses of actions and policies to reflect new developments, in order to be able to react to and correct for unanticipated outcomes and surprises. There is an inherent tension between the desired criteria of flexibility/adaptability on one hand, and the equally desirable criteria of alignment, consistency, and patience on the other. These seemingly contradictory objectives can and should be reconciled, but it will involve an open institutional and policy architecture that can mobilize collective learning processes and widely shared strategic goals.

Openness implies increased sharing of data and experience and non-exclusive networks of actors, nationally as well as internationally. In short, much higher levels of cooperation and knowledge exchange are needed to address the potential tensions between national policies and an increasingly globalized ETIS landscape via formal and informal information sharing, cooperation, and coordination agreements. Existing institutional solutions such as the IEA or the International Renewable Energy Agency can serve as useful entry points, but must be expanded to become both truly international and comprehensive in terms of their energy systems perspective, in particular in moving away from the traditional energy-supply bias to include energy efficiency and conservation in a more integrated way.

As daunting as the agenda for a systemic, consistent, and aligned long-term technology policy framework may appear, improvements can be implemented gradually. An illustrative roadmap for action over time consistent with the dynamics of capital stock turnover rates in energy systems is given in Table 24.9.

**Table 24.9** | Illustrative roadmap for the development of a systemic, aligned, and consistent policy framework for energy technology innovation and diffusion matching policy approaches to realistic timescales of outcomes.

| Timescale of Policy Outcome | Examples of Policy Approaches |
|---|---|
| short term<br>(e.g., to 2020)<br>capital stock additions (some) | create, stimulate and protect market niches around performance advantages of new technologies<br>deploy market-ready, clean technologies through credible and stable incentive mechanisms<br>develop long-term technology innovation and market deployment strategies in a consultative process, creating "joint expectations"<br>reduce/eliminate direct or indirect subsidies for technologies not aligned to long-term technology strategy and portfolios<br>use "sunset" clauses for planned retirement of depreciated, inefficient, or polluting capital vintages |
| medium term<br>(e.g., to 2050)<br>capital stock additions (all), capital stock turnover (some) | expand public and private R&D investments stably in diversified portfolios designed to manage risks and corresponding with end-use needs<br>underwrite many granular and multifarious technology demonstration and learning cycles<br>support disclosure, interaction, and feedback between innovation system actors<br>engage in multiple international collaborative projects to further knowledge dissemination and technology spillovers<br>align innovation and market deployment incentives (e.g., recycling externality pricing revenues back to R&D and market deployment incentives) |
| long term<br>(e.g., to 2100)<br>capital stock additions (all), capital stock turnover (all) | set long-term targets with appropriate monitoring and enforcement mechanisms to sustain shared technology expectations<br>maintain portfolio diversity to prevent premature lock-in or standardization<br>set technology standards for the gradual phase out of "bridging" technologies |
| throughout (present-2100) | create and nurture formal and informal institutional settings for technology assessment, evaluation, portfolio design, and knowledge sharing |

### 24.5.3 What is New?

At the end of any assessment, it is legitimate to ask: what's new? Readers will undoubtedly form their own opinions, but the (subjective) perspective of this chapter's writing team is summarized below.

As a first, the chapter provides a synthetic overview of the resource requirements (in terms of investments) of the entire energy technology innovation and diffusion process. This assessment thus includes new data, including R&D expenditures in emerging economies, a summary synthesis of diffusion investments, and novel first-order estimates of end-use technology investments for which information has been lacking to date. Notwithstanding the key role of innovation in the front end of the technology life cycle, the numbers nonetheless confirm the predominance of assuring an appropriate incentive environment for the adoption of innovations, where typically 80–90% of financial resources need to be mobilized. The numbers also confirm the critical importance of energy end-use and related technologies in ETIS that need to be better reflected in R&D and market deployment incentives and new business models.

The chapter also contains a rich set of new case studies on energy technological change, which are both novel in their scope and constitute a useful resource for research as well as policy learning. The case studies represent new, original research and are unusual for a major international assessment such as the GEA. However, the fact that they could be conducted even under extreme resource constraints points to the wide interest and collaborative spirit of the technology community, which can be harnessed further to improve knowledge exchange and learning for successes and failures, moving technology policy forward.

The chapter also opens the "black box" of technological innovation and change. It analyzes the "finer grain" underlying the change in the multitude of attributes and drivers of innovation: new knowledge, but also knowledge depreciation, economies of scale, linkages and spillovers to other sectors, phenomena of increasing returns inherent in knowledge generation and in infrastructure-intensive interconnected systems such as energy, as well as resource constraints and (relative) input prices. The new findings, while tentative, again confirm the importance of alignment and consistency under the overall umbrella of the complementarity of policies/measures/incentives rather than their substitutability. These findings add a new dimension to naive perceptions of the prevalence of either supply push (e.g., accelerated, stepped-up R&D programs) or demand pull (e.g., "cost buy down" in new technologies) that have characterized much of the literature and policy debates to date.

Finally, this chapter introduces the novel concept of "granularity." Historically, successful innovations are characterized by a prevalence of a multitude and a diversity of "small" (locally adapted) solutions to problems that occur even at a global scale, as opposed to singular, large-scale, planetary solutions (be it geo-engineering, solar power satellites, or a single design for a nuclear fusion reactor). "Granular," small scale innovations offer the potential of multiple and repeated experimentations, learning, and adaptation to diverse adoption environments. An example is the dramatic difference in industrial and managerial experience that stems from building and operating a million wind turbines, as opposed to some 1000 nuclear reactors. From that perspective, the critical innovations paving the way to energy sustainability will reside in energy end-use (e.g., efficiency) and locally adapted supply options (e.g., in smaller-scale renewables) that are in stark contrast to the prevalence of a uniform, global technology landscape that has characterized the fossil fuel age.

## 24.6 Appendix I: Investments into ETIS

### 24.6.1 RD&D Investments

R&D expenditures at the macroeconomic level are routinely collected by national and international statistical agencies (see OECD, 2007). The data usually differentiate by funding source (public versus private sectors); by R&D performing institution (government laboratories, universities, or by private firms); and, finally, by broad economic sector. Methodologies, data collection, and compilations are well established (OECD, 2002).

Energy-related or technology-specific RD&D data are not reported separately in these macroeconomic statistical frameworks, creating formidable data challenges. For a concise review of data sources, methodological issues, and limitations of energy RD&D data, see Dooley (2000). Energy- and technology-specific RD&D data are available for public sector expenditures in member countries of the IEA (IEA, 2009b), but information on non-IEA countries (Brazil, China, and India, or Russia, to name the most important ones) and especially for private sector energy RD&D are extremely fragmented and sparse. Evidence suggests that the IEA public sector energy RD&D statistics may cover only about a quarter of all energy-related RD&D globally, where private sector RD&D and increasingly non-IEA countries substantially contribute to energy RD&D. This assessment therefore includes an effort to compile national energy RD&D data on the emerging economies of BRIMCS (Brazil, Russia, India, Mexico, China, and South Africa), conducted by a team of researchers at Harvard University (Kempener et al., 2010b; see the *Emerging Economies R&D* case study summarized in Section 24.7.8) that also includes (albeit incomplete) coverage of private sector RD&D in these countries. For private sector energy RD&D in OECD countries, this chapter could only draw on the survey conducted by the World Energy Council in 2001 (WEC, 2001) for a sample of OECD countries. More recent international comparative data are simply unavailable.

#### 24.6.1.1 Public Sector Energy RD&D

Figure 24.14 summarizes the trends in public sector energy RD&D since 1974 in IEA member countries and contrasts it with total public RD&D

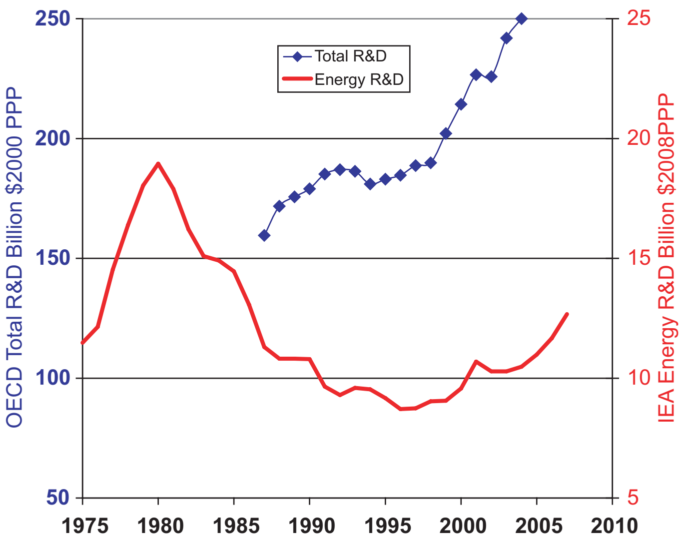


**Figure 24.14** | OECD public R&D expenditures ($US_{2000}$$ PPP) versus public sector energy R&DD in IEA countries ($us_{2008}$$ PPP). Note the factor of 10 difference in the scale of the two expenditure categories and the opposing time trends since 1985. Source: Doornbosch and Upton, 2006 (in $US_{2000}$$ PPP); IEA, 2009a (in $US_{2008}$$ PPP).

expenditures. While total reported energy technology RD&D expenditures by definition include demonstration investments in addition to R&D expenditures, little detailed data are available. IEA (2009b) reports a total of some $550 million[17] at purchasing power parities (PPP) for seven countries for which such data are available. The United States represents the bulk of this figure, with approximately $444 million development expenditures, corresponding to some 4% of total public energy technology RD&D in all the IEA member countries in 2008. Hence, it is fair to say that public energy RD&D expenditures are in fact mostly R&D expenditures with little expenditure on technology demonstration proper.

A defining characteristic of energy RD&D is both its comparably small magnitude (5% of total government RD&D), as well as its boom and bust cyclical nature, characterized by rapid expansion in the wake of the oil crises of the 1970s, its subsequent collapse (with corresponding impacts on knowledge depreciation), and only gradual recovery after the year 2000. This is in stark contrast to the continually expanding overall R&D budget in IEA member countries. These trends are extensively discussed in the literature (Dooley and Runci, 2000; Doornbosch and Upton, 2006) and have been referred to repeatedly as "R&D under-investment" by researchers (e.g., Nemet and Kammen, 2007) and business executives (e.g., AEIC, 2010).

Figure 24.15 summarizes the historical evolution of IEA member country energy RD&D by broad technology class, illustrating a third area of concern: asymmetries in public energy RD&D portfolios (see Box 24.7 on RD&D Portfolios). Total public sector RD&D in IEA member countries in 2008 amounted to some $12.7 billion (PPP). Close to $5 billion was spent on nuclear (fission and fusion), $3 billion on "other" energy technologies (hydrogen; electric power outside renewables, fossils, and nuclear; electricity transport and distribution; as well as basic energy research), and about $1.5 billion on fossil fuels and energy efficiency, respectively (for a tabular overview for IEA countries see Box 24.7. For BRIMCS countries, see overview in Section 24.7.7).

As discussed above, comparable internationally 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 OECD countries. Given that this is no longer the case, enlarging global energy RD&D reporting systems remains a critical task. The Kempener et al. (2010b) energy RD&D survey on BRIMCs countries, suggests that public energy RD&D in the six BRIMCS countries amounted to some $2.7 billion dollars[18] in aggregating national data sources, compared with US$4.4 billion public energy R&D in the United States in 2008 (IEA, 2009b). The case of BRIMCS countries also illustrates the fact that the traditional distinction between public (i.e., government) and private (privately-owned companies) sectors as sources of RD&D funding becomes increasingly blurred. Whole or partially state-owned enterprises (e.g., national oil and gas companies, utilities) constitute an important part of the energy sector in developing and emerging economies and also in many OECD countries. The RD&D expenditures in state-owned enterprises are strongly determined by national governmental policies. Combining public and semi-private energy RD&D, BRIMCS countries have a total current energy RD&D budget of some $15 billion (PPP), about equal to the entire public sector energy RD&D expenditures in IEA member countries ($13 billion, PPP) and still about half of the combined public and private energy RD&D in OECD countries (estimated here at approximately $25 billion). A commonality in the energy RD&D budgets of IEA member countries and BRIMCS countries is the dominance of fossil fuel and nuclear technologies, which currently receive some $11 billion (PPP) in total RD&D funding, or some 75% of total energy RD&D in BRIMCS countries. IEA member countries invest close to 50% of their public energy RD&D investments in these technologies (>$6 billion; $10 billion when private RD&D investments are included).

### 24.6.1.2 Private Sector Energy RD&D

The situation with respect to data availability of private R&D expenditures is dire. The Directorate General for Research of the European Commission states, "Despite the growing need, statistics on energy R&D expenditures in the private sector remain a problem" (EC, 2005).

17 2008 International $. The R&D expenditure data in this section are expressed throughout in terms of purchasing power parity (PPP) in order to improve comparability across very different economies. One drawback of PPP is, however, that simple ex post adjustments to a common base year (2005 in GEA) are not possible for international, cross-country statistics. Differences to 2005$ PPP should however be minor. PPP values are denoted here simply as "$" to differentiate them from the US$.

18 Data limitations preclude a comparison for an identical base year. Instead, the totals reported aggregate national statistical data for reporting years that vary between 2004 (China) to 2008 (Brazil, Russia, India, and South Africa). Numbers are expressed in terms of PPP.

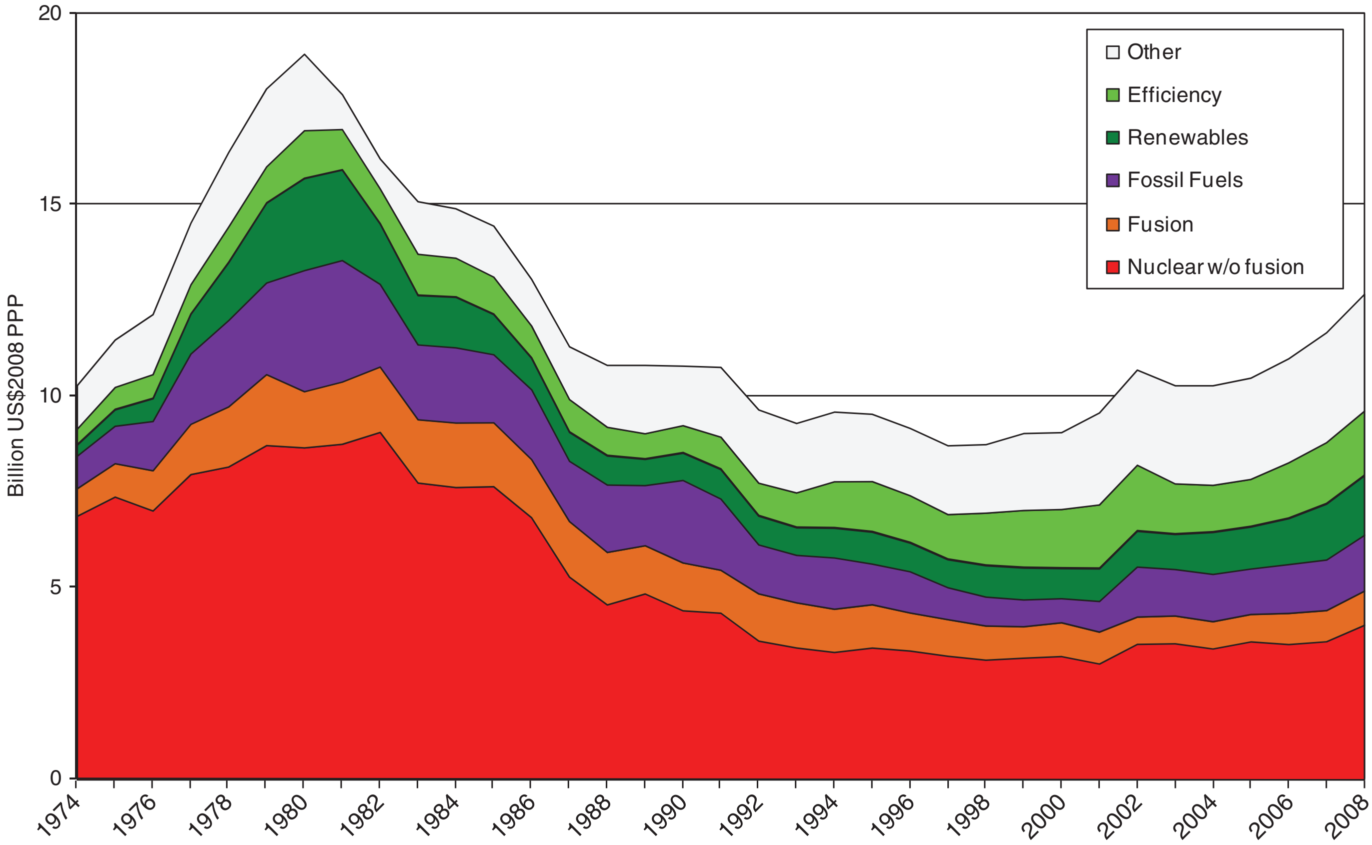


**Figure 24.15** | Public sector energy RD&D in IEA member countries by major technology group 1974–2008 (in $US_{2000}$$ million PPP). Source: data based on IEA, 2009a.

Macroeconomic RD&D statistics by broad economic sector are available for a sample of 19 OECD countries in the OECD Structural Analysis database (OECD, 2009). However, the latest year reported is 2002. Data for other countries are not collected and available in any internationally comparable form. In 2002, business enterprises excluding extractive industries (coal mining; oil and gas extraction) performed R&D equivalent to $433 billion (PPP in 2000$) in the sample of 19 OECD countries provided. The only sectorial breakdown available that bears directly on the energy sector are "coke, refined petroleum products and nuclear fuel" ($2.7 billion) and "electricity, gas, and water supply" ($2 billion), with an OECD total of energy-related private sector RD&D of less than $5 billion (PPP). Of course, RD&D performed in the manufacturing sector has a bearing on energy use, e.g., such as in electrical machinery ($13 billion), motor vehicles[19] ($50 billion), or aircraft ($20 billion; see NSF, 2010). How much of the RD&D performed in these sectors is energy-related remains unknown.

19 The six automobile manufacturers listed among the top 25 global corporations in 2006, performed between US$4.6 billion (Honda) to US$7.5 billion (Toyota) in R&D, with a total of some US$39 billion. Other corporations, whose R&D is likely to include an important energy component are Siemens (US$6.6 billion), Samsung (US$5.9 billion) Matsushita (US$4.9 billion), Sony (US$4.6 billion), and Bosch (US$4.4 billion) (NSF, 2010). This listing alone suggests that in terms of private energy-related RD&D, energy end-use technologies are most likely to be of much greater importance than energy supply.

The only available survey of private sector RD&D specific to the energy sector is the study conducted by the World Energy Council (WEC, 2001), covering the period 1997–2000 for a sample of seven OECD countries, which are summarized in Table 24.10. In addition to the WEC survey, the most recent private sector RD&D data for the United States for 2004 (NSF, 2009) are listed for comparison.

The information available on total OECD private sector energy RD&D from 1993–2000 amounted to some $12 billion annually. The technology-specific breakdown is too incomplete and the data too old to warrant a detailed discussion. However, it is noteworthy that with the exception of Japan, private sector R&D on energy efficiency appears either to be unrecorded or, when subsumed under the "other" (or unaccounted for) category, remains extremely small outside Japan. Thus, the sparse available data suggest that also private sector energy R&D seems to follow the supply side (fossil and nuclear) over-emphasis apparent in public sector R&D in OECD countries.

For non-OECD countries, the Kempener et al. (2010b) survey on BRIMCS puts the OECD numbers in perspective (for a detailed breakdown, see the table in Section 24.7.7). The information available on investments in energy RD&D in the BRIMCS countries by the private sector and state-owned enterprises also amount to about $12 billion (PPP 2008), albeit based on more recent data (2004–2006).

## Box 24.7 | R&D Portfolios

How can we assess current energy technology R&D portfolios, i.e., the technologies we invest in, with the technology investments needed for an energy sustainability transition?

One way is to describe alternative futures through the scenario technique and use models to calculate the future market potential of specific energy technologies. This potential can be contrasted with public sector energy R&D spending (see the *Technology Portfolio* case study based on Grubler and Riahi (2010) and summarized in Appendix II below).

Given that the future is inherently uncertain, one needs to explore a wide range of possibilities, i.e., a reasonable number of scenarios. The results of these scenarios can be analyzed to derive "need-based" technology portfolios that can guide RD&D allocations across technology fields. A large-scale scenario study (Riahi et al., 2007) explicitly addressed the question of how the portfolio of GHG mitigation technologies changes as a function of the representation of salient uncertainties including energy demand, resource constraints, availability and costs of technologies, and the magnitude of GHG emissions constraints. For the quantification of the respective role of individual groups of technologies in the entire GHG emission reduction portfolios, the concept of mitigation "wedges" (Pacala and Socolow, 2004) was used. A mitigation wedge as defined in Riahi et al., 2007 is simply the contribution to the cumulative emissions reduction over the period 2000–2100 that a particular option provides compared to a baseline scenario. First, three baseline scenarios without GHG emissions constraints were compared to corresponding hypothetical baselines that assume a "frozen" state of technology in the year 2000 (i.e., no technological change/improvements). Then, for each baseline scenario a range of increasingly stringent GHG emissions constraint scenarios are calculated (constraints vary from as low as 450 ppm $CO_2$-equivalent GHG concentration by 2100 all the way up to 1390 ppmv-equivalent). Additional model sensitivity analyses then explored the impacts of the unavailability of particular technological options (e.g., nuclear or CCS). The calculated aggregated technology specific GHG mitigation "wedges" are summarized in Figure 24.16, showing mean as well as minima/maxima across all scenarios explored. The ranking of different mitigation options is quite robust across the scenarios explored, with energy efficiency and conservation being the single most important option with typically >50% contribution and nuclear with a typical 10% contribution to cumulative 2000–2100 emission reduction. The results are representative of other modeling studies, e.g., as reported by the Energy Modeling Forum (EMF-22) where the maximum share of nuclear energy ranges between 11–12% (Calvin et al., 2009) to 9–14% (Gurney et al., 2009) by the end of the 21st century.

It is also instructive to compare the calculated future mitigation potentials of technologies with RD&D expenditures, summarized for the total of all IEA countries above. A *significant mismatch in R&D portfolios* in favor of nuclear and to the detriment of energy efficiency and conservation emerges. Nuclear received well above 50% of all cumulative (1974–2008) R&D expenditures, with energy efficiency receiving less than 10%, whereas their respective role in the GHG mitigation portfolios is exactly the inverse. To put these numbers into an absolute perspective: cumulative public R&D into energy efficiency totaled some 38 billion $\$_{2008}$ (in purchasing power [PPP] terms), which is lower than total cumulative expenditure into fusion energy ($41 billion PPP). Current R&D levels into renewable and CCS (which is subsumed in the "other" category above that includes *inter alia* also hydrogen, fuel cells, and basic energy research) are also much lower than a future "need-based" analysis suggests, albeit the mismatch is less striking than the one comparing energy efficiency to nuclear.

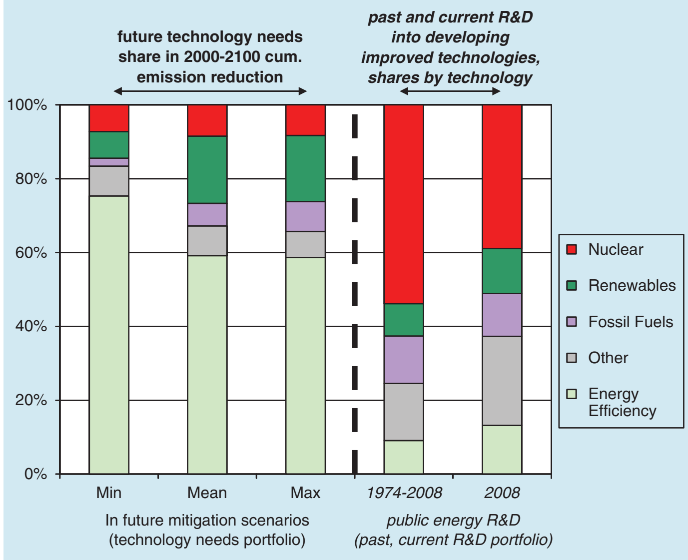


**Figure 24.16** | Distribution of past (1974–2008) and current (2008) public sector energy technology R&D portfolios in member countries of the IEA (right) versus portfolios of future GHG mitigation needs (min/mean/max, left) derived from an extensive scenario uncertainty analysis. Source: adapted from Grubler and Riahi, 2010.

Were current energy technology R&D portfolios to represent the respective "option value" of alternative technologies in a climate-constrained world, one would have to increase current R&D into energy efficiency by at least a factor five or by some $6 billion PPP per year (thus not proposing a reduction in nuclear R&D). Given that improved energy efficiency has multiple public benefits beyond climate change (e.g., less energy use, reduced local air pollution, and lessened import dependence) even more ambitious increases in public energy R&D budgets for energy efficiency would be justified.

**Table 24.10** | Private sector energy RD&D, selected OECD countries from WEC (2001) survey (in billion $US_{2001}$\$[22]). Also, for the US latest available data for 2004 (NSF, 2009) are shown for comparison.

| Billion US$ | US | *US* | Japan | Korea | Sweden | France | Denmark | Spain | Total |
|---|---|---|---|---|---|---|---|---|---|
| in year | 2000 | *2004* | 1997 | 1998 | 1997 | 1998 | 1993 | 1998 | ~2000 |
| Efficiency | | | 6.10 | | | | | | **6.1** |
| Fossil fuels | 0.81 | *1.04* | 0.84 | 0.03 | | 0.56 | | | **2.2** |
| Nuclear | 0.03 | *0.03* | 1.00 | | | 1.17 | | | **2.2** |
| Renewables | | | 0.29 | | | | | | **?** |
| Other or non-spec. | 0.36 | *1.21* | | 0.03 | | 0.05 | | | **?** |
| **Total** | **1.20** | ***2.28*** | **8.6** | **0.06** | **0.1** | **1.78** | **0.08** | **0.08** | **11.9** |

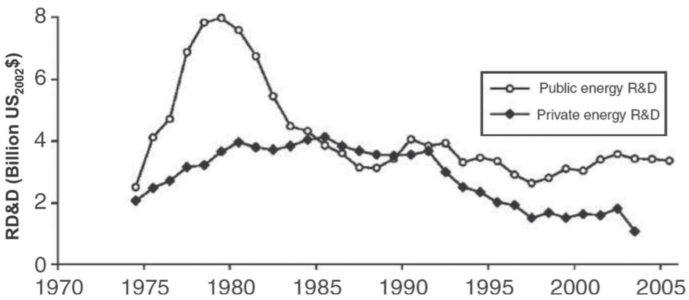


**Figure 24.17** | Trends in US public and private energy RD&D (billion $us_{2002}$\$[20]). Source: Nemet and Kammen, 2007.

There is evidence from the United States that private sector energy RD&D appears to follow comparable trends as public R&D (Figure 24.17), as both are influenced by rising and falling oil prices. One interpretation of these joint trends is "that the 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" (Nemet and Kammen, 2007). By analogy, the same influences also appear at work in periods of declining public R&D budgets. The available empirical evidence at present appears insufficient to support the often advanced argument of "crowding-out" effects, i.e., expanded public sector R&D would substitute (crowd-out) private sector R&D (e.g., Popp, 2006).

#### 24.6.1.3 Total Energy RD&D

Based on the limited data available, the order of magnitude estimate of global energy RD&D amounts to some \$50 billion (PPP) with some \$15 billion in public sector RD&D and up to \$35 billion by the private sector. About half of all energy RD&D is spent on fossil fuels and nuclear according to this assessment. The Sustainable Energy Finance Initiative's (SEFI) estimate (UNEP/SEFI/NEF, 2009[21]) of global RD&D into sustainable energy of some \$12.4 billion for the year 2005 (including \$6.8 billion private and \$5.6 billion public sector RD&D) is insufficiently documented to allow a more in-depth comparison, but are likely to represent an optimistic estimate.

### 24.6.2 Market Formation Investments

Market-formation investments include public and private investments in the early stages of technological diffusion and are sometimes also referred to as "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 that may take advantage of markets created by government policies, such as renewable performance standards or price instruments like carbon taxes.

Market-formation investments in the energy sector as a whole are difficult to track, because many transactions are unreported, ways of measuring market-formation investments are not yet harmonized internationally, and efforts to track such investments are only relatively recent.

#### 24.6.2.1 Analysis of Market Formation Sustainable Energy Investments

- Market formation investments in sustainable energy (solar, wind, biofuels, biomass and waste-to-energy, marine and small-hydro, geothermal, efficiency, and other low-carbon technologies/services) can be measured by activity in three main asset classes: venture capital/private equity; new listings on public markets; and asset finance. Figure 24.18 shows the distribution across the three asset classes with total investments across all regions growing

20 To convert to $US_{2005}$ \$ multiply by 1.09.

21 The Sustainable Energy Finance Initiative is convened by UNEP, with participation from Bloomberg New Energy Finance (NEF): www.sefi.unep.org/.

22 These rather outdated (but only available) data are presented here mainly for illustrative purposes. In order to avoid confusion, currencies have not been converted to the more recent GEA base year of 2005.

## Box 24.8 | How large are the investments in sustainable energy?

It has been reported that over US$200 billion in investments have been made into sustainable energy,[23] and in 2008, this grew to US$223 billion (UNEP/SEFI/NEF, 2009). However, as a leading indicator for the growth of sustainable energy infrastructure, the total US$223 billion is misleading because it includes a number of transactions – a full 30% – that are purely financial, such as mergers and acquisitions (M&A), refinancings, and buyouts. These transactions represent changes in ownership rather than input investments into energy technologies.

Figure 24.18 shows a breakdown of the US$223 billion in investment transactions in 2008 for sustainable energy as tracked by UNEP/SEFI/NEF,[24] and maps them against the categories of RD&D and market formation used in this chapter. By doing so, a clearer picture of the scale of input investments into the sustainable energy technology system emerges. Technology-specific (as opposed to ownership changes represented by some US$67 billion for mergers and acquisitions) investments amounted to a total of some US$$_{2008}$160 billion. RD&D (public and private) made up US$18 billion, with the bulk of the investments (US$141 billion) classified as market formation investments into sustainable energy technologies.

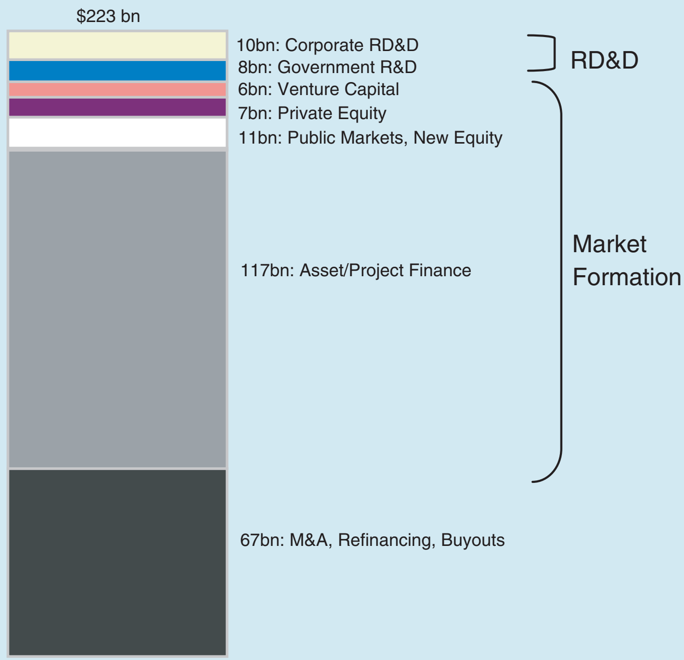


**Figure 24.18** | Investments into sustainable energy in 2008. Data source: SEFI/UNEP/NEF, 2009.

at a compound annual growth rate (CAGR) of 63%/year between 2004 and 2008.

- The largest asset class within market formation investments is asset finance, which includes the building of new assets financed via either project finance or balance sheet/syndicated equity. While often investing in quite large and more mature technologies, asset finance investments in sustainable energy are counted here as part of "market formation" because they are highly dependent on governmental subsidies and incentives such as tax equity credits or feed-in tariffs. The amounts also include estimated investments for small-scale and residential installations of sustainable energy technologies such as biodigesters, micro-wind turbines, and solar hot water systems.

- Brazilian ethanol was excluded from market-formation investment totals, as these investments are no longer substantially supported by government subsidies (see the *Brazilian Ethanol* case study). The net effect of doing so was to reduce the total amounts invested by US$17.2 billion for 2004–2008 and US$8 billion in 2008 across all asset classes. (These investments are included in the diffusion investment category in this assessment, summarized in Section 24.6.3 below.)

- The technology sector attracting the most investment for 2004–2008 is wind. Wind-related investments grew at an AGR of 51%/year in this period.

- Investments into energy efficiency are small (~2%).

- The regions that saw the most investment were OECD countries, notably Europe, at 45%, and North America, at 30%, of total investments for the 2004–2008 period.

#### 24.6.2.2 Spotlight on Venture Capital and Private Equity (VC/PE) Energy Investments

While often characterized as investing in highly risky assets, VC/PE investors typically invest after a good deal of technology risk has already

23 "Sustainable energy," according to UNEP/SEFI/NEF, includes: solar, wind, biofuels, biomass and waste to energy, marine and small-hydro, geothermal, efficiency, and other low-carbon technologies/services. It excludes large-scale hydro (>50MW) and all nuclear power.

24 Figure 24.18 includes both project finance for large scale installations and small scale and residential installations as estimated by UNEP/SEFI/NEF.

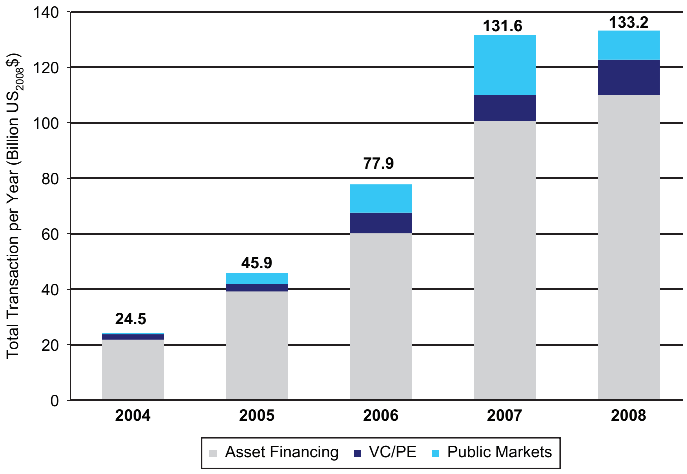


**Figure 24.19** | Yearly investments in market-formation for sustainable energy technologies 2004–2008 (total transaction/year in billion $US_{2008}$\$). The total market formation investments in 2008 exclude US\$8 billion in Brazilian ethanol (classified here as diffusion investments) from the total of US\$141 billion reported in Figure 24.18. Source: O'Rourke, 2009; UNEP/SEFI/NEF, 2009; bloomberg new energy finance database (courtesy of ERD3 Project Harvard; NEF/SEFI, 2009).

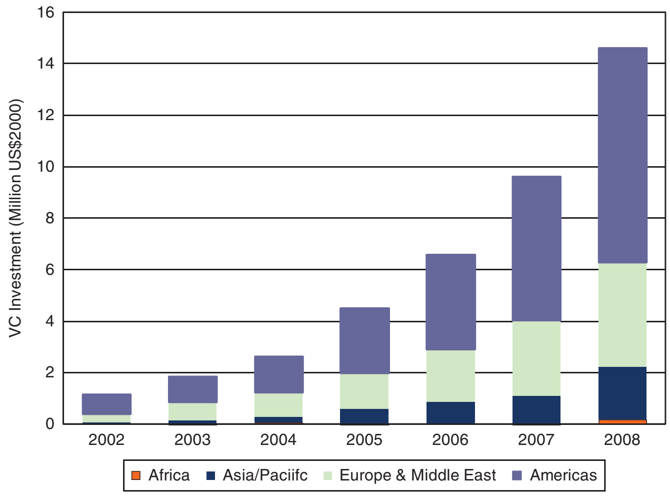


**Figure 24.20** | Total amounts of VC/PE in energy by year and region (in 1000 $US_{2008}$\$). Sources: O'Rourke, 2009; Bloomberg New Energy Finance database (courtesy of ERD3 project harvard; NEF/SEFI, 2009); Thomson Reuters Venturexpert Database (Thomson Financial, 2009).

been mitigated, when markets for the new technologies are somewhat defined, and when the entrepreneurial company is formed and functioning. VC/PE investors hope to profit from the rapid scaling up of the technology in formative markets, at which point they can sell their equity stake at a high multiple on what they initially invested (see also the *Venture Capital* case study summarized in Section 24.7.8).

Compared to coal, oil and gas, and nuclear energy, sustainable energy technologies are less mature technologies, and VC/PE capital and skill can help accelerate the transition from demonstration to market adoption.

The following investment amounts build upon the UNEP/SEFI/NEF data presented above by adding fossil-fuel technologies and installations with data gathered from the Thomson/Reuter's VentureXpert database (Thomson Financial, 2009). Total amounts and numbers of investments are likely to be higher than what is listed here because investments made by VC/PE funds into energy technology companies forming new markets are often not publicly reported, and investments made by angel (individual) investors are also not reliably reported, even if such investments serve as an important source of capital for both very new and later stage venture companies with energy technologies.

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. Figure 24.20 illustrates the recent growth of VC investment into both fossil and non-fossil energy technologies following the regional disaggregation given in the original data source.

- Between 2002 and 2008, at least US\$40.88 billion was invested by VC/PE investors into energy technology firms; in some 2,375 transactions.

- In 2008, the total amount of energy (fossil and non-fossil) investments made by professional VC/PE investors worldwide was US\$14.6 billion. This grew from some \$1.14 billion in 2002.

- The compound annual growth rate (CAGR) for the 2002–2008 period is 53%/year for the total amounts invested and 26%/year for the number of investment rounds ("deals") made.

- The bulk of the investment went into North American and European companies with non-fossil-based energy generation technologies. This uneven distribution reflects both the limited availability of data outside North America and Europe, and the limited availability of professional VC/PE in some regions of the world with other forms of financing more common such as family-firm or investments made by large corporations.

Figure 24.21 shows that the majority of investments made by VC/PE investors are in sustainable/renewable energy generation and end-use efficiency technologies over fossil fuels and power generation technologies. Specifically:

- solar energy-related technology companies have attracted the highest amounts of investments overall, representing some 30% of global energy VC for the whole period. Solar investments grew particularly rapidly between 2005–2008 in terms of numbers of deals and total amounts invested; and

- "end-use efficiency" (such as smart energy metering in buildings, demand response software systems, high efficiency lighting, etc.) also grew in the period, totaling US\$5.5 billion for the period.

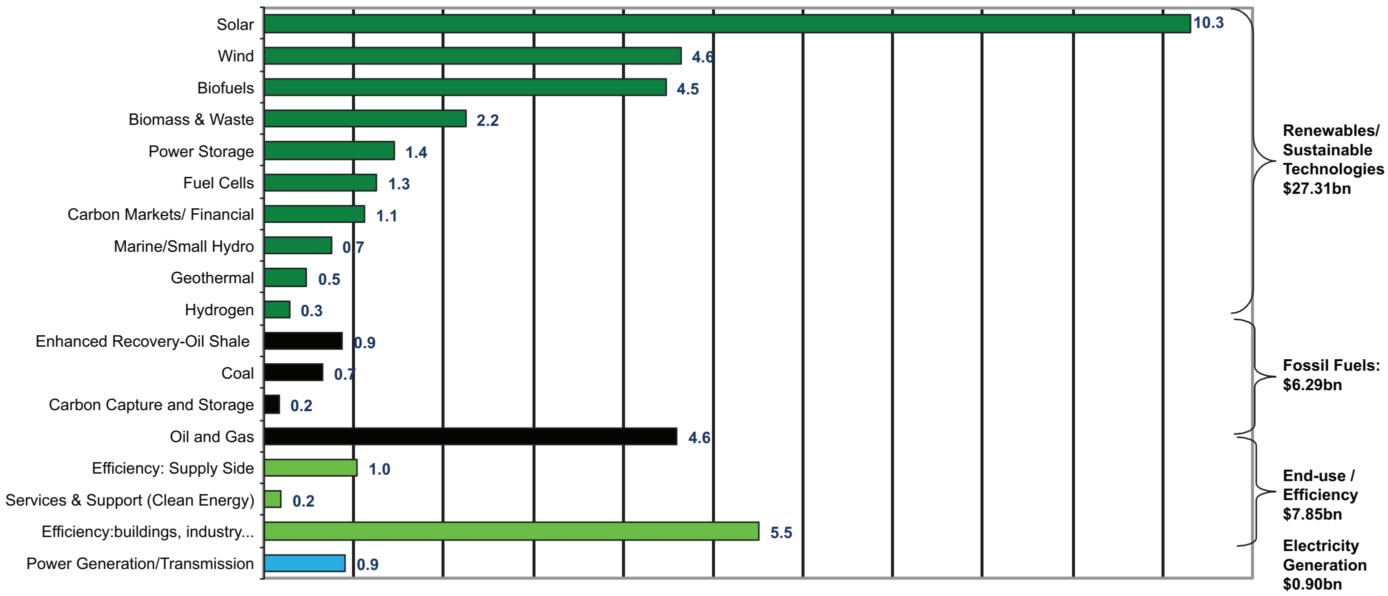


**Figure 24.21** | VC/PE investments in energy technologies by technology cluster between 2002–2008 in billion $US_{2008}$$. ("Biofuels" category excludes investments made into Brazilian ethanol companies, accounted for diffusion investments in Section 24.6.3 below.) Source: O'Rourke, 2009; Bloomberg New Energy Finance database (courtesy of ERD3 Project Harvard; NEF/SEFI, 2009); Thomson Reuters Venturexpert Data Base (Thomson Financial, 2009).

## 24.6.3 Diffusion Investments

Energy sector diffusion investment data are sparse and not collected systematically nationally or internationally. Modeling studies, as well as limited survey data, allow estimates of energy-supply investment levels, but energy end-use investment data are almost entirely lacking. Instead of concluding with the simple statement of data unavailability, this assessment explores some of the reasons for the lack of data and aims to provide at least some plausible estimates of orders of magnitude to provoke discussion and subsequent research in this extremely under-researched and under-reported area.

### 24.6.3.1 Energy Supply Investments

Data on energy supply investments are extremely limited, so the literature typically relies on model estimates (multiplying statistical data and/or estimates on capacity expansion with average technology-specific investment costs to derive total energy supply investments) or limited surveys. Energy supply modeling studies have become available since the mid-1990s in academia (e.g., Nakicenovic and Rogner, 1996; Nakićenović et al., 1998; Riahi et al., 2007), as well as from the work of the IEA, particularly the World Energy Investment Outlook (IEA, 2003); the Energy Technology Perspectives (IEA, 2006; 2008b); and the recurrent projections of IEA's World Energy Outlook (e.g., IEA, 2006; 2007; 2008a; 2009a), which also contain unique survey data on energy supply investments, particularly in the oil and gas industry. A common feature (and drawback) of all modeling studies is that energy sector investments are not reported for their corresponding base year values, but instead as cumulative totals of the projection horizon of typically 30 years. 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 and a comparison among the different studies an almost impossible task.[25] In the assessment below, we summarize available information by drawing on the only modeling study that has disclosed its underlying base year energy investment numbers (Riahi et al., 2007)[26] and the surveys reported in IEA's WEO (IEA, 2006; 2008a; 2009a). Because of the significant price escalation observed for energy sector investments (particularly for oil and gas since 2004), the Riahi et al. (2007) estimate (that refers to year 2000 investments and price levels) can be considered a lower bound, assuming recent price escalations will not remain permanent. Conversely, the IEA numbers can be considered as an upper-bound estimate of investments in energy supply (see Table 24.11).

Despite differences in estimated supply-side investments per category, the available data suggest a likely order of magnitude of energy-supply

25 Therefore wherever possible, underlying investment numbers of modeling studies should be made publicly available.

26 Numbers have been published in an interactive web-based database. Base year data refer to capacity additions and price levels for the year 2000 but were expressed in $US_{1990}$$. These were converted to the GEA standard of $US_{2005}$$ using the US GDP deflator multiplier of 1.4. However, despite being expressed in $US_{2005}$$, price levels remain that of the year 2000, as energy sector-specific price deflators are not available internationally.

**Table 24.11** | Range of energy supply investments in Billion US$_{2005}$\$. (T&D: transport and distribution of electricity).

| | | LOW[1] | HIGH[2] |
|---|---|---|---|
| | | 2000 prices & activity | 2005–07 prices & activity |
| FUELS | UPSTREAM: | | |
| | Exploration fossil fuels | n.a. | 40 |
| | Extraction fossil fuels | 180 | 180–360 |
| | DOWNSTREAM†: | n.a. | 100–140 |
| | Synfuels, fossil | 1 | 7 |
| | Biofuels | 20 | n.a. |
| | Other | 20 | n.a. |
| TOTAL FUELS | | >220 | 300–550** |
| POWER | Electricity generation: | | |
| | Fossil | 110 | n.a. |
| | Non-fossil | 100 | n.a. |
| | Total | 210 | 220–300 |
| | T&D | >>70 | ?-230-? |
| TOTAL POWER | | >500 | 450–520* |
| TOTAL SUPPLY INVESTMENTS | | >720 | 750–840* |

* Total minima/maxima ranges are not additive from (sub-)component min/max ranges.
** Mimima excludes exploration while maxima includes exploration.
† Downstream includes refining, pipelines etc.
1 Riahi et al., 2007.
2 IEA, 2006; 2008a; 2009a.

side investment of some US$_{2005}$\$700 billion/year that could extend to some US\$840 billion in 2007/2008, considering the higher ranges reported in the literature. Investments are dominated by electricity generation and transport and distribution (T&D), with some US$_{2005}$\$500 billion. Fossil fuel supply, particularly the "upstream" component (i.e., exploration and production), accounts for US\$250[27]-400 billion, mostly for oil and gas.

Renewables that figured prominently in market formation investments discussed above are minor players under the market conditions characterizing current diffusion investments. Liquid and gaseous biofuels account for US\$20 billion, including US\$8 billion for Brazilian ethanol (UNEP/SEFI/NEF, 2009). Large-scale hydropower (<US\$100 billion for annual capacity additions of between 25–30 GW) make up a maximum of 17% of current supply-side investments.

27 Taking the Riahi et al. (2007) estimate of US\$220 billion, complemented by not reported investment categories, the estimated grand total includes US\$230 billion for fossil fuels and US\$20 billion for biofuels.

Major uncertainties include the accounting for oil and gas exploration activities (at some US\$40 billion) that are, strictly speaking, not energy technology investments. When categorized as RD&D activity for future oil/gas reserves – as is the practice by some companies – oil and gas exploration would represent the single largest RD&D spending in the energy technology field. Major differences also exist for electricity transport and distribution infrastructure investments for which only modeling study data are available and estimates differ by about a factor of three. The IEA WEO 2008 projection of average annual electricity T&D infrastructure investments of US\$230 billion over the period 2007–2015 appears extremely high, and is comparable to the corresponding electricity generation capacity expansion investments. Lastly, it is interesting to note that no studies available report actual data for current investments in nuclear energy (even though nuclear figures prominently in future projections). According to IEA (2002; 2009a), installed nuclear capacity expanded by 20 GW between 1999 and 2007. IEA (2008a) reports an increase from 358 to 376 GW between 2000 and 2006, which yields an average annual net increase in nuclear capacity of between 2–3 GW, mostly in Asia where investment costs are comparatively modest at an estimated 1500–2500 \$/kW (see Chapter 14). This suggests current investments of between US\$3–7.5 billion/year for nuclear reactors, which makes this the only technology in which RD&D investments *exceed* diffusion investments. (Given its technological maturity of over 40 years since its first market introduction, nuclear can reasonably not be considered a technology in its market formation stage, where such an investment pattern would be both possible and plausible.)

The assessment of the nuclear industry in terms of technological and investment risks by markets, as reflected in actual technology investments, departs markedly from the overemphasis of nuclear in public RD&D portfolios. This misalignment suggests two critical questions for technology policy. First, is the public sector energy RD&D confined to investments in innovations that ultimately find little market appeal? Alternatively, given the heavy emphasis of public RD&D on nuclear, is the public sector providing sufficiently consistent market deployment incentives so the heavily subsidized technology finds market applications?

Evidence regarding the time trend of supply-side energy investments is scarce in the literature. An intriguing empirical finding from the United States, however, shows a significant decline in energy supply-side investments as a share of sector revenues for electricity generation in the second half of the twentieth century (Figure 24.22). The declining investments (as a share of revenues) in the US electricity sector suggest a substantial thinning of resources available for capital turnover and diffusion of new technologies as a twin result of slowing demand growth and energy sector deregulation and liberalization. At present, it remains unclear if this trend is a specific phenomenon of OECD countries or of US electricity supply (an increasingly deregulated sector). However the example supports the conclusion that better current and longitudinal data on energy sector investments are needed for improved decision-making.

This assessment of diffusion investments has focused on the global level for the simple reason that regionally disaggregated investment survey data are lacking. Modeling studies suggest that current (year 2000) energy supply-side investments are distributed about 60:40 between Annex I and non-Annex I countries, as defined by the United Nations Framework Convention on Climate Change (UNFCCC, 1992). Short-term projections (e.g., to 2030 by IEA, 2009a) suggest roughly a 50:50 split between energy supply investment needs between Annex I and non-Annex I countries, for a global total of cumulative energy supply investments 2008–2030 of some $US_{2008}$$25 trillion.

### 24.6.3.2 Energy End-use Investments

The decentralized nature of these investments by private households (and their corresponding classification as consumer expenditures rather than investments) and by firms (whose energy-specific investments go unrecorded) explains the absence of energy end-use investment numbers in the literature. The small-scale nature and formidable definitional

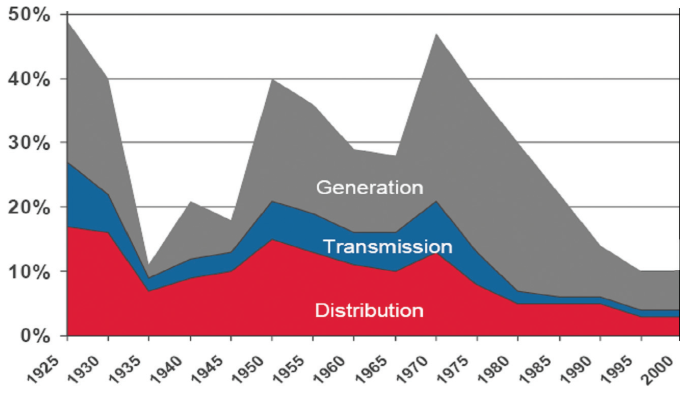


**Figure 24.22** | Declining investments (as share of revenues) in the US electricity sector, 1925–2000. Source: modified from EPRI, 2003.

challenges[28] of these numbers also contributes to their absence. This lack of data, even model estimates,[29] introduces a serious challenge in both energy modeling and policy, because the potentially largest source of energy demand (and emissions) reduction is either entirely ignored or assumed to cost nothing. Customary energy and climate policy models deal with energy end-use costs by either "assuming away" missing data by exogenous (and policy independent) autonomous energy efficiency trends or by considering investment costs for the incremental component of energy end-use investments related to improved energy efficiency, which in itself provides a formidable definitional and data challenge.

To address this gap, Chapter 24 presents the first global, bottom-up estimate of total investment costs in energy end-use technologies. Volume data (production, delivery, sales, and installations) and cost estimates to approximate total investment costs in 2005 are estimated in both end-use technologies and their specific energy-using components.[30] Low and high sensitivities around central estimates are included, taking into account uncertainties in both volume and cost assumptions. The intention is to provide a first order, educated guess point of comparison with supply-side investments. Supporting data and a discussion text are posted on the GEA Chapter 24 website[31]

28 For instance, it is far from trivial to discern the energy component in the total investments of a new building. Depending on where the systems boundary is drawn, one could look at the heating and air conditioning system, including that part of the building structure that determines its energy use (insulation, windows). Indeed, the entire building structure may be considered.

29 Some studies include incremental energy end-use technology investments associated with additional energy efficiency gains above a typical "business as usual" scenario (e.g., IEA, 2009a). Apart from introducing additional definitional ambiguities (i.e., what constitutes incremental investments), the modeling is usually only done for a few technologies (e.g., transport), which limits its usefulness to inform policy.

30 Available data do not allow a further disaggregation into those subcomponents of investments on energy efficiency improvements, which remains an important future research task.

31 See www.globalenergyassessment.org.

to document the assumptions underlying the estimates below, solicit feedback and comments, and invite further research in this critical area (See also Wilson and Grubler, 2011).

To ensure comparability between supply-side and demand-side investments, a common definition of the unit of analysis is needed. Supply-side investments are quantified at the level of the power plant, refinery, or liquefied natural gas terminal. These are complex, integrated technological systems with energy conversion technologies at their core. These energy-converting components are configured within their corresponding technological system to provide a traded energy carrier to intermediate users (utilities, fuel distributors, pipeline, or shipping companies).

The logical demand-side analogues of these technological systems are the aircraft, vehicle, refrigerator, and home heating system. Although generally less complex, each of these technological systems similarly has an energy conversion technology at their core (i.e., the jet engine, internal combustion engine, compressor, boiler). In addition, each is configured to provide a useful service to final users.

With demand-side technologies, however, this definition of the unit of analysis is problematic. Investments in (and performance of) end-use technologies are dependent on investments in associated infrastructure such as airports, roads, and buildings. Is it meaningful to quantify the investment cost of a home heating system without quantifying the investment cost of a home and the insulation level that determine the dimensioning of the home heating system in the first place? Is the end-use technology to consider a boiler or a building?

Although the same issue exists on the supply-side, it is largely addressed by additionally quantifying investment costs in associated transmission and distribution infrastructures in policy models, as comprehensive statistics are also lacking on the supply side. The problem on the demand side is that the same approach would result in a sum of the total investment costs in all building structures, roads, railways, ports, airports, industrial machinery, equipment, and appliances. Such an exercise would amount to a *reductio ad absurdum.*

A pragmatic pathway out of this system boundary ambiguity is to provide a range of estimates for a range of system boundaries of energy end-use technologies. An initial broader definition and data set describes end-use technologies as the smallest (or cheapest) discrete purchasable units by final consumers. This implies boilers and air conditioning units not houses, and dish washers and ovens not kitchens. A second, narrower definition and data set describes the specific energy-using components of these end-use technologies. This implies engines in cars, and light bulbs in lighting systems. Table 24.12 summarizes these distinctions for the technologies analyzed. In some cases (e.g., industrial motors, mobile heating appliances), a distinct energy-using component was not identified.

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. The breakdowns of these totals by technology are given in Table 24.13 and Table 24.14.

It should be emphasized that these investment cost ranges are rather *underestimates*, as many end-use technologies are omitted from the analysis. Although the principal end-use technologies in terms of the costs of their energy-using components (not the technologies themselves) are captured, investment costs in many technologies cannot be quantified. These include all propeller-based and noncommercial aircraft; helicopters; all military technologies; mass transit systems (whose costs are extremely site specific); heating and cooling systems in commercial and institutional buildings (new build and retrofits); water heaters; information and communication technologies; small appliances; other consumer electronics; and all industrial equipment and processes other than motors (e.g., blast furnaces, pulp mills, cement kilns). With the exception of industrial plants, the inclusion

**Table 24.12** | Summary of technologies and components included in estimates of energy end-use technology investments.

| End-Use Service | End-Use Technology | Energy-Using Component |
|---|---|---|
| mobility | commercial jet **aircraft** | jet **engine** |
| mobility | **vehicles** (cars and commercial) | internal combustion **engine** |
| space conditioning | **central heating systems** (boiler/furnace, ducts/pipes, radiators, controls, energy supply infrastructure network connections for new systems) | **boiler** or furnace |
| space conditioning | **air conditioning systems** (AC unit, ducts, controls, energy supply infrastructure network connections for new systems) | air conditioning **unit** |
| space conditioning | **mobile heating appliances** (e.g., portable convection / fan heaters) | same definition as technology |
| lighting | **lighting** (light bulb and fixture) | light **bulb** |
| food storage and cooking | large **household appliances** (fridges, freezers, clothes washers and dryers, dish washers, cookers) | compressors, motors, fans, heating elements |
| various (e.g., processing) | industrial motors | same definition as technology |

**Table 24.13** | Estimated investment costs in selected end-use technologies (in billion $US_{2005}$\$).

| End-Use Technologies in 2005 | low sensitivity | central estimate | high sensitivity |
|---|---|---|---|
| | *in billion $US_{2005}$\$* | | |
| Commercial jet aircraft | 12 | 28 | 50 |
| Cars | 540 | 758 | 1194 |
| Commercial vehicles | 270 | 427 | 672 |
| Buildings (retrofits) – central heating systems | 47 | 250 | 979 |
| Buildings (new) – central heating systems | 33 | 93 | 248 |
| Mobile heating systems | 2 | 4 | 5 |
| Buildings (retrofit) – air conditioning systems | 9 | 42 | 137 |
| Buildings (new) – air conditioning systems | 7 | 20 | 41 |
| Lighting | 17 | 38 | 83 |
| Large household appliances | 45 | 75 | 124 |
| Industrial motors | 2 | 6 | 16 |
| **GRAND TOTAL COSTS** | **984** | **1741** | **3549** |

**Table 24.14** | Estimated investment costs in "energy-using components" of selected end-use technologies (in billion $US_{2005}$\$).

| Energy-Using Components of End-Use Technologies in 2005 | low sensitivity | central estimate | high sensitivity |
|---|---|---|---|
| | *in billion $US_{2005}$\$* | | |
| Commercial jet aircraft | 3 | 7 | 13 |
| Cars | 36 | 76 | 159 |
| Commercial vehicles | 27 | 57 | 119 |
| Buildings (retrofits) – central heating systems | 13 | 52 | 158 |
| Buildings (new) – central heating systems | 9 | 20 | 41 |
| Mobile heating systems | 2 | 4 | 5 |
| Buildings (retrofit) – air conditioning systems | 5 | 21 | 69 |
| Buildings (new) – air conditioning systems | 4 | 10 | 20 |
| Lighting | 12 | 27 | 59 |
| Large household appliances | 11 | 18 | 53 |
| Industrial motors | 2 | 6 | 16 |
| **GRAND TOTAL COSTS** | **124** | **298** | **712** |

of these categories should not substantially increase the investment cost range for energy-using components, as suggested by back-of-the-envelope sensitivity analyses; however, they would substantially increase the investment cost range for end-use technologies in their broader definition.

Given the definitional problems described above, the appropriate point of comparison for estimates of supply-side investment costs is a range spanning the narrow category of "energy-using components" at the lower end, to the broader category of "end-use technologies" at the upper end. Taking also into account the extent of end-use technologies missing from this analysis, *the range of demand-side investment costs is conservatively in the order of US\$0.3–4.0 trillion.* This compares with supply-side investment costs on the order of US\$0.7 trillion/year.

Although the two ranges span the same orders of magnitude, the upper bound of demand-side investment costs is four times higher than its supply-side equivalent, recalling also that this is likely a (potentially substantial) underestimate. Interestingly, this result aligns with the IEA's estimation that demand-side investment needs exceed supply-side investment needs by a factor of 4 to 5 in the IEA climate policy scenarios (IEA, 2008b). Disaggregating the data by region shows that approximately two-thirds of the end-use investments in 2005 are in Annex I countries; the remaining one-third are in developing economies.

## 24.7 Appendix II: Summaries of Case Studies of Energy Technology Innovation

### 24.7.1 Grand Designs: Historical Patterns and Future Scenarios of Energy Technological Change[32]

The case study reviews patterns, drivers, and typical dynamics (rates of change) in energy systems from a historical as well as futures (scenario) perspective. From a historical perspective, two major energy transitions, each of which took up to a century to unfold, can be identified: the phase of growth in coal-fired steam power, and its subsequent displacement by oil and electricity-related end-uses and technologies (Figure 24.23). Similar far-reaching future transitions are also described in the scenario literature as a function of alternative assumptions on rates and direction of inventive activities and performance and cost improvements of new energy technologies.

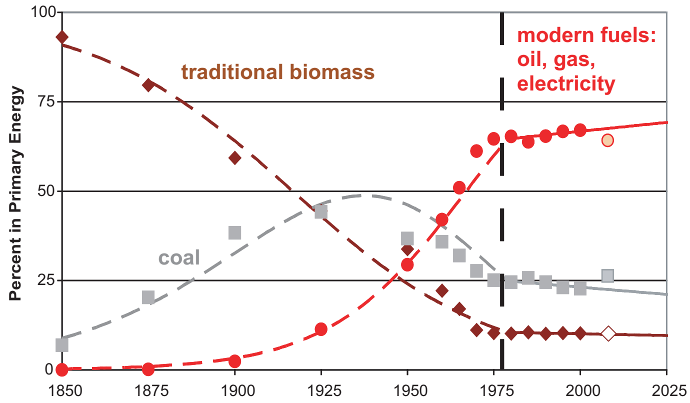


**Figure 24.23** | Two "grand" transitions global energy systems measuring market shares in total primary energy use, 1850–2007 (preliminary data) of biofuels, coal, and modern energy carriers (oil, gas, electricity). Note in particular the long period of initial slow market penetration of new technologies and the significant slow-down of historical technology dynamics after 1975.

**Summary Points**

- Technological and social innovations have been core drivers of historical energy transitions and remain so in future scenarios.
- Energy history and future are characterized by four "grand" patterns of technological change in energy systems:
  - clustering and spillover effects dominate over singular technologies;
  - performance dominates over costs in the early phases of technology development;
  - end-use applications dominate over energy supply; and
  - time constants of change are substantial, spanning from many decades to a century.
- There is evidence that, contrary to the historical evidence and popular conception, rates of systems transitions have substantially slowed since the 1970s.

### 24.7.2 Historical Scaling Dynamics of Energy Technologies[33]

The twentieth century has witnessed extensive diffusion of many supply-side and end-use energy technologies as part of a wholesale transformation of the energy system. Entire industries have grown, but so too have the size of technologies at the "unit" level (e.g., the rated capacity of a steam turbine or a car engine). Analyzing these historical growth dynamics at both the industry and unit level reveals some general patterns that appear robust across very different energy technologies. First, increases in unit size generally follow a period of experimentation with many smaller-scale units. This is particularly the case for technologies like nuclear or wind power with clear economies of scale at the unit level. Second, the extent to which an energy technology industry grows is consistently positively related to the time duration of that growth. These and other findings have important implications for policy, not least in striking a cautionary note on pushing for significant jumps in technology unit size before a formative phase of experimentation and learning with smaller-scale units has been completed.

**Summary Points**

- Growth of energy technology industries comprises a *formative* phase, then a *scaling* phase that precedes or is concurrent with an *industry growth* phase.
- The formative phase involves many smaller-scale, granular units with only small increases in unit size. The scaling phase sees large increases in unit sizes, particularly at the scale frontier, and a large increase in numbers of units. The industry growth phase is driven by large numbers of units at larger unit sizes and describes the maturing industry.
- Experimentation with many smaller-scale units tends to precede substantive increases in unit size. The formative phase following an energy technology's introduction into the market is an often lengthy process of testing and experimentation with many small-scale units, which allows technologies to be "debugged" through a process of "designing-by-experience" (Ruttan, 2001). Successful experimentation, improvements, and learning appear to be critically determined

32 Arnulf Grubler.

33 Charlie Wilson.

by the granularity and the associated smaller financial and innovation failure risks of smaller-scale unit projects. Resulting learning effects lead to cost and performance improvements, but also facilitate the subsequent capture of unit scale economies as the industry matures.

- The relationship between the extent and the time duration of an industry's growth is consistent for different energy technologies. It is intuitively obvious that the extent of growth should correlate positively with the time period over which that growth occurs (notwithstanding the many factors that affect diffusion rates). However, the consistency of that relationship for very different energy technologies is surprising. The case study also identifies an important learning externality for later adopting regions that achieve generally faster diffusion compared to leading innovation centers. Compared to historical dynamics, future scenarios reviewed were generally found to be conservative in their technology scaling and market expansion assumptions.

### 24.7.3 Technology Portfolios[34]

The case study reviews a range of methodologies and model-based applications that can assist policy decisions under (inevitable) technology innovation uncertainty.

One possible approach is based on scenario analysis. As an example of that method, a detailed scenario exercise performed at IIASA explores uncertainties in main scenario drivers of future greenhouse gas (GHG) emissions (energy demand, resource and technology availability, etc.) and extent of future climate constraints (represented through a range of stabilization targets). The study identifies energy efficiency and conservation as the single most important, and also the most robust, technology option across all scenarios. This result is in stark contrast to past and present public sector R&D portfolios, which continue to be dominated by nuclear R&D at the expense of energy efficiency.

A second analytical approach is based on a portfolio theory that helps capture the benefits from (technology) portfolio diversification in the framework of risk-averse decision-making. An example modeling study suggests that risk aversion leads to higher adoption rates of currently higher-cost energy technology options such as modern biomass and renewables, but also CCS. The modeling study also suggests higher short-to-medium term investments into advanced technologies under risk aversion. It is also possible to not only consider variance as a risk measure, but take into account the risk of high impact tail events. For example, a risk premium of only about 1% of total energy expenditures was found to decrease the value of the 99$^{th}$ percentile extreme event by more than a factor of two. Diversification thus not only reduces the mean of risk exposure but drastically lowers the tails of extreme and undesirable outcomes.

Portfolio theory and scenario analysis can also be used in combination, where scenario analysis provides the basis for describing the uncertainty space and portfolio-based approaches then help to identify optimal risk hedging strategies and resulting technology portfolios.

**Summary Points**

- Formal tools, e.g., scenario analysis and portfolio theory, are increasingly available to move technology policy decisions (e.g., R&D, or early niche market investments) onto a more rational ground.

- A generic pattern from modeling studies that applies these methods to the field of energy technologies involves *portfolio diversification* and *enhanced experimentation* with earlier niche market investments, the extent of which depends on the (user specified) degree of risk aversion in addition to the underlying innovation uncertainty distributions.

- A comparison of technology portfolio scenario studies with past and current energy R&D portfolios reveals that the latter are highly biased, with energy efficiency/conservation underrepresented and nuclear R&D overrepresented in comparison to their respective option values in a climate-constrained world.

### 24.7.4 Knowledge Depreciation[35]

The case study first reviews the sources of knowledge depreciation that consist of knowledge lost (e.g., due to staff turnover), as well as knowledge made obsolete (e.g., due to rapid innovation). The literature of typical knowledge depreciation rates is reviewed and the limited examples related to energy technologies are discussed in more detail. Illustrative calculations show the implications of knowledge depreciation for two groups of energy technology innovations: nuclear power and energy efficiency based on public energy R&D statistics of IEA member countries (Table 24.15).

**Summary Points**

- Knowledge depreciation rates – characterized by high staff turnover – can be substantial, reaching 100%/year in service industries. In the energy technology field, knowledge depreciation rates range from 10%/year (wind turbines) to 30%/year (solar PVs) due to technological innovation-induced knowledge obsolescence.

34 Sabine Fuss and Arnulf Grubler.

35 Arnulf Grubler and Gregory Nemet.

**Table 24.15** | Current (2007) and cumulative (1974–2007) R&D expenditures of IEA member countries in $US_{2007}$\$ billion and estimate of remaining knowledge stock, assuming an average knowledge depreciation rate of 20%/year.

| | current R&D | | cumulative R&D | | remaining knowledge capital stock | |
|---|---|---|---|---|---|---|
| | $10^9$ $US_{2007}$\$ | % | $10^9$ $US_{2007}$\$ | % | $10^9$ $US_{2007}$\$ | as % of cum. R&D |
| Energy efficiency | 1.6 | 13.1% | 38 | 8.8% | 7 | **18.4%** |
| Fossil fuels | 1.4 | 11.5% | 55 | 12.8% | 6 | **10.9%** |
| Renewables | 1.5 | 12.3% | 37 | 8.6% | 6 | **16.2%** |
| Nuclear fission | 3.7 | 30.3% | 194 | 45.1% | 18 | **9.3%** |
| Nuclear fusion | 0.9 | 7.4% | 42 | 9.8% | 4 | **9.5%** |
| Others | 3.1 | 25.4% | 64 | 14.9% | 13 | **20.3%** |
| Total | 12.2 | 100.0% | 430 | 100.0% | 54 | **12.6%** |

Source: IEA, 2008b and authors' calculation.

- With knowledge depreciation, continuous knowledge recharge through sustained and stable R&D and niche market deployment efforts becomes critical.

- The *pathway* (stable, gradually rising) of policy support is as – if not more – important than the *absolute level* of policy support when characterized by "boom and bust" innovation investment cycles.

- Erratic policy support leads to substantially higher knowledge depreciation, even under otherwise high support levels. Estimates of the energy technology R&D knowledge stock for IEA member countries suggest that nuclear has suffered substantially more from knowledge depreciation than energy efficiency, which is characterized by much lower but more stable R&D expenditures.

### 24.7.5 Metrics for Assessing Energy Technology Innovation[36]

Assessing the performance of energy technology innovation processes or systems is complex. There are different assessment methods or approaches – both qualitative and quantitative – as well as many different assessment metrics, which are reviewed in more detail in the case study. These metrics are proxies for innovation inputs, outputs, and outcomes that are either intangible (e.g., knowledge stock, practical problems and solutions) or tangible (e.g., scientists, laboratories, installed technologies). *Input* metrics describe financial and labor inputs to the innovation process (e.g., R&D investments). *Output* metrics describe defined products of the innovation process (e.g., cost reductions). *Outcome* metrics describe broader energy sector or economy-wide impacts of the successful diffusion of innovations into the marketplace (e.g., reduction in emissions intensity).

36 Charlie Wilson.

Energy technology innovation is characterized by a mixed, staged involvement of both public and private resources, and an interdependent set of time-lagged processes linking innovation inputs to outputs. In other fields, econometric techniques are commonly used to evaluate outcome metrics such as net social returns on R&D. However, their application to date in the energy field has been limited due to data constraints, as well as the lack of consensus on objectives. Unanswered questions include: does successful energy technology innovation reduce energy or carbon intensity? Reduce unit costs? Reduce the cost of final service provision? Improve security, reliability, and flexibility? Increase option value?

Cross-country comparisons using both quantitative and qualitative approaches are complicated by the absence of standardized data, local specificities in energy technology innovation systems, and confounding factors such as labor cost differentials, intellectual property rights systems, and economic structure.

**Summary Points**

- Assessments of energy technology innovation can be qualitative, quantitative, or a combination of both. Qualitative assessments often complement the analysis of time series data by adding analytical rigor and depth.

- Assessments typically center on a particular technology within a national context, and/or focus on the effectiveness of innovation policies.

- Metrics of energy technology innovation relate to either *inputs*, *outputs,* or broader *outcomes* of the innovation process. With the partial exception of technological learning rates, there are no metrics that comprehensively link inputs to outputs and outcomes.

- The lack of available and reliable data on innovation inputs and outputs hampers standardized and cross-comparable assessments of energy technology innovation systems across technologies and countries.

**Table 24.16** | Energy Technology R&D in China in 2004 (in million Yuan) by institutional actor, performer, and funding source (> symbols indicate incomplete reporting). See also Table 24.17.

| R&D performed by | | | | Technology Areas | | | | |
|---|---|---|---|---|---|---|---|---|
| | *funded by* | basic research | end-use & efficiency | fossil fuels | electric power | T&D | others & unspec. | Total |
| Nat'l Program Energy Research | *Government* | 1274 | | | | | 785 | **2059** |
| Institutions of Higher Education | *Government* | | | | 744 | | 187 | **931** |
| (Public) R&D Institutions | *Government* | | | 21 | 199 | | | **220** |
| | *Enterprises* | | | 78 | 127 | | | **205** |
| | *Total* | | | 99 | 326 | | | **425** |
| *Subtotal (R&D performed by public sector)* | | *1274* | | *99* | *1070* | | *972* | ***3415*** |
| R&D by Industry | *Government* | | 78 | 878 | 146 | 83 | | **1185** |
| | *Enterprises* | | >>1873 | 14382 | 5092 | 2753 | | **>>22227** |
| | *Total* | | >>1951 | 15260 | 5238 | 2836 | | **23334** |
| **Grand Total** | | **2548** | **>>1951** | **15359** | **6308** | **2836** | **972** | **>28700** |
| | *incl. Gov't funded* | *2548* | *78* | *899* | *1089* | *83* | *972* | ***5669*** |

### 24.7.6 China: Energy Technology Innovation Landscape[37]

The case study provides a first-time comprehensive (even if in some aspects, incomplete) overview of the entirety of the energy technology innovation landscape in China. Major programs, institutional actors, funding sources, and R&D allocation by broad technology groupings are outlined and draw on data for the year 2004 (Table 24.16). Mechanisms for setting innovation and R&D priorities as well as strategic and priority areas for China's ETIS are outlined.

**Summary Points**

- Energy technology R&D in China is both substantial and expanding rapidly. The survey is partially incomplete, as it does not cover R&D in the automotive and other end-use technologies (e.g., appliances) industries. Nevertheless, the survey indicates a total resource mobilization of greater than RMB29 billion in 2004 for energy technology R&D. This translates to either $3.5 or $9.4 billion, based on either market or purchasing power exchange rates, respectively, and compares to a total public energy R&D budget of the United States of US$5.6 billion in the same year.

- Despite its unique feature as a largely centrally planned economy, energy technology R&D in China (not unlike in OECD economies) is dominated by industry, which performs 88% of R&D. Largely government owned enterprises also provide for some 85% of all energy technology R&D funding in China.

- The energy technology portfolio (again, not unlike in OECD countries) is dominated by supply-side options, even considering incomplete data available for end-use technologies such as the automotive sector. Within energy supply technologies, fossil fuel-related technologies account for more than 50% of all energy R&D, followed by electric power and T&D with more than 30% of all energy R&D.

### 24.7.7 Energy R&D in Emerging Economies (BRIMCS)[38]

This case study provides an overview of energy RD&D expenditures of six major emerging economies referred to as BRIMCS: Brazil, the Russian Federation, India, Mexico, China, and South Africa. For comparison purposes, corresponding US data are also included. The data summarized below synthesizes a wide array of sources that have to date not been compiled in a consistent fashion. RD&D expenditures are differentiated by broad technology group as well as by funding source based on the most recent published data available in each country (Table 24.17). Funding sources include (federal) government or 100% state-owned enterprises (SOE), as well as other sources such as local governments, partially-owned SOEs, private industry investments, or NGOs.

37 Kejun Jiang.

38 Ruud Kempener, Laura Diaz Anadon, and Kelly Sims Gallagher.

**Table 24.17** | Energy RD&D in BRIMCS countries (Million US$ at PPP).

| in Million 2008 PPP $Int* | Fossil (incl. CCS) | Nuclear (incl. fusion) | Electricity, transmission, distribution & storage | Renewable energy sources | Energy Efficiency | Energy technologies (not specified) | TOTAL |
|---|---|---|---|---|---|---|---|
| United States – Gov't | 659 | 770 | 319 | 699 | 525 | 1160 | 4132 |
| United States – Other** | 1162 | 34 | *no data* | *no data* | *no data* | 1350 | 2545 |
| Brazil – Gov't | 79 | 8 | 122 | 46 | 46 | 12 | 313 |
| Brazil – Other | 1167 | *no data* | *no data* | *no data* | *no data* | 1844 | 1351 |
| Russia – Gov't | 20 | *no data* | 22 | 14 | 25 | 45 | 126 |
| Russia – Other | 411 | *no data* | *no data* | *no data* | *no data* | 508 | 918 |
| India – Gov't | 106 | 965 | 35 | 57 | *no data* | *no data* | 1163 |
| India – Other | 694 | *no data* | *no data* | *no data* | *no data* | *no data* | 694 |
| Mexico – Gov't | 140 | 32 | 79 | *no data* | *no data* | *no data* | 252 |
| Mexico – Other | 0.1[1] | *no data* | *no data* | *no data* | 263[3] | 19[4] | 282 |
| China – Gov't | 6755 | 12 | *no data* | *no data* | 136 | 4900 | 11803 |
| China – Other | 289 | 7 | *no data* | *no data* | 26 | 985 | 1307 |
| South Africa – Gov't | *no data* | 133 | *no data* | *no data* | *no data* | 9 | 142 |
| South Africa – Other | 164 | 31[2] | 26 | 7 | *no data* | *no data* | 229 |
| BRIMCS – Gov't | 7100 | 1149 | > 259 | > 117 | > 208 | >4966 | > 13799 |
| BRIMCS – Other | 2724 | >> 38 | >> 26 | >> 7 | > 289 | > 1696 | > 4781 |
| BRIMCS – Grand Total | 9824 | > 1187 | > 285 | > 497 | > 497 | > 6662 | > 18580 |

* Data from United States, Brazil, Russia, India, China and South Africa are based on 2008, data from Mexico is from 2007.

** United States data on industry expenditure is from 2004 (NSF, 2009).

1 Based on PEMEX's fund for Scientific and Technological Research on Energy.

2 Based on total non-governmental investments into PBMR Ltd.

3 Based on 2005 R&D expenditure in car manufacturing industry (CONACYT, 2008).

4 Based on 2005 R&D expenditure in utilities sector (CONACYT, 2008).

> These cumulative values are based on data from only three to four BRIMCS countries, so actual expenditures are likely to be higher.

>> These cumulative values are based on data from two BRIMCS countries or less, so actual expenditures are expected to be much higher.

Source: Chapter 24 case studies and Kempener et al., 2010a.

**Summary Points**

- Public energy RD&D in BRIMCS countries is substantial and amounts to some $14 billion in PPP terms, slightly above the entirety of the public energy R&D budget of all IEA member countries combined (some $13 billion in PPP terms). Including non-governmental R&D funding sources, total R&D in BRIMCS countries is estimated to total nearly $19 billion.

- The significance of energy RD&D expenditure in BRIMCS countries challenges the traditional view that new energy technologies are predominantly developed within OECD countries and points to the need to include the BRIMCS countries in regular international statistical reporting and in a comprehensive global strategy to promote energy technology innovation.

- BRIMCS countries' energy RD&D data show that fossil fuel and nuclear energy receive the highest level of RD&D support, with renewables and energy efficiency highly underrepresented both in expenditures and statistical reporting.

### 24.7.8 Venture Capital in the Energy Industry[39]

Access to capital is a major enabler to the scale and speed of technological innovation as produced by entrepreneurs. Entrepreneurial firms face a multitude of risks and barriers. For those working with new technologies, technological, market, and financing risks are paramount. Venture capital (VC) is a source of capital that is willing to finance companies in this risky

39 Anastasia O'Rourke.

stage of the technology life cycle. By investing equity in such risky companies, VC investors are often considered "technology gatekeepers" who have helped to select and create "waves of technological innovation" that have transformed industries (Florida and Smith Jr., 1990).

The case study reviews recent trends in energy VC investments by category and region, drawing on and synthesizing a large body of literature and statistical information that has to date not been available in the public domain. There has been a dramatic growth of VC investment in clean energy technologies since the mid to late 2000s. Detailed statistical trends are presented in the VC case study.

**Summary Points**

- In 2008, the total amount of energy (fossil and non-fossil) investments made by professional VCs worldwide was US$15.5 billion.
- The compound annual growth rate (CAGR) for the period 2004–2008 is 22%/year of the number of investment rounds (deals) and 45%/year CAGR for the total amounts invested.
- The bulk of the investment went to North American and European companies with non-fossil-based energy generation technologies (solar; biofuels and biomass) and to storage technologies (particularly batteries). Significant investments were also made in end-use energy technologies such as smart energy metering in buildings, demand response software systems, or high-efficiency engines.
- While growth in VC investments has been dramatic, VC makes up only a comparatively small portion of all the capital employed to launch energy technologies into the market worldwide.
- Other niche-market investments in energy are needed as well. These include investments made at a very early stage by private individuals (angel investors); large company internal investments; investments in late-stage growth and private equity (primarily using debt instruments); project finance (also debt, often used to build larger-scale energy production facilities such as wind farms); and finally, investments in energy-technology firms that are listed on various public markets.
- The contribution of VCs to all private investments in energy combined sits at approximately 10%, according to data from New Energy Finance (IEA, 2009a; UNEP/SEFI/NEF, 2009).

### 24.7.9 Hybrid Cars[40]

This case study reviews the available literature on the development and deployment of hybrid-electric vehicles (HEVs), and particularly examines the role of government in this history. Three country-specific case studies are provided for Japan, the United States, and China. Key factors in the development and deployment of HEVs are identified and discussed.

Some governments are interested in promoting HEVs and other alternatives to conventional internal combustion (IC) engines because of concerns about oil security, air pollution, and global climate change. HEVs achieve greater fuel efficiency than conventional IC vehicles, although the extent of improvement in efficiency depends greatly on the configuration of the specific HEV system.

The three case studies below show that the drivers of invention did not substantially differ among the three countries, but the policy mechanisms and incentives for deployment diverged significantly. In all three countries, the governments originally pushed harder for alternative automotive technologies other than hybrids, such as pure electric vehicles or hydrogen-fuel-cell vehicles. In some cases, private firms made R&D choices that do not appear to have been strongly influenced by public policy, other than to provoke the firms to explore fuel-efficient technologies. In other cases, government policies appear to actually have turned firms away from HEVs. Once HEVs emerged in the marketplace, however, the government response was completely different in the three countries, especially in terms of the extent to which each government was prepared to support their transition through the "early deployment" phase of innovation to facilitate widespread market diffusion.

**Summary Points**

- Policy for government investments in the RD&D of advanced-vehicle technologies was initially poorly coordinated, with policy for the early deployment of these technologies in all three countries. Japan and the United States reactively established policies to support the early deployment of HEVs once they were introduced to the market, but Japan implemented much more effective policies to support commercialization than the United States.
- Hybrid car consumers are clearly responsive to increased gas prices and other fiscal incentives, including sales tax reductions or exemptions and feebate schemes, and they also appear to buy hybrids out of concern for the environment or energy security.
- Leadership within firms appears to have been a major factor in explaining the relative success among the firms in developing and commercializing HEVs.
- Political and economic factors, most prominently the concern about energy security, were initially the main drivers for government technology policy and investments in advanced vehicle technologies in Japan, the United States, and China.

40 Kelly Sims Gallagher.

### 24.7.10 Solar Water Heaters[41]

The experience of innovation policy related to solar water heaters in the United States is a story of policy intermittency. A key general finding is that bad outcomes are often not easily forgotten, and can have substantial spillover effects on other technologies. This presents a challenge to the need to support experimentation and intelligent failures.

Solar water heaters (SWH) use a working fluid to absorb sunlight and provide heating and hot water in residential and commercial settings. The technology is currently cost effective, especially in large installations with high demand for hot water. Real-time electricity pricing is considered a potential boost to SWH. China is by far the world's largest market for solar water heaters. An important historical episode for this technology was the programs in the United States in the late-1970s and early 1980s. The biggest technical improvement was the advent in the 1970s of selective coatings, which would absorb more sunlight. Since then, the technology has been rather stable, with some improvements in lifetime and reliability. The key period of R&D investment was in the 1970s at national laboratories and universities. The subsidies in the 1980s were not monitored. There was rampant abuse of subsidies in the 1980s, and many installations leaked and caused extensive damage to structures far in excess of the cost of the water heater itself. The response was to avoid the technology for many years; the US industry went from US$1 billion/year in 1982 to US$30 million/year in the late 2000s. Hundreds of firms went out of business. As a result, much of the learning gained in the period of rapid deployment was lost. The perception of poor reliability persists and has proven difficult to overcome – bad news lasts. An exception to this general policy failure has been a program in Hawaii that makes consumer rebates contingent on an inspection that occurs one year after installation.

**Summary Points**

- A large, high-profile failure in the early stage of the US SWH industry has proven extremely difficult to overcome.
- For several years after this failure, the technology was not trusted.
- Experience was lost with the collapse of the industry.
- Verification is essential and not expensive.
- Inspection and verification have proven successful in Hawaii.
- Both R&D and incentives placed excessive focus on collector units rather than on system integration.
- Lack of involvement of utilities and builders appears to have hurt the industry.

### 24.7.11 Heat Pumps – Innovation and Diffusion Policies in Sweden and Switzerland[42]

Innovation and diffusion policies for the development and introduction of heat pumps provide an interesting case study on policy learning. Heat pumps have been supported by several countries since the 1970s as a strategy to improve energy efficiency, support energy security, reduce environmental degradation, and combat climate change. Sweden and Switzerland have been essential to the development and commercialization of heat pumps in Europe. In both counties, numerous policy incentives have lined the path of technology and market development. Early policy initiatives were poorly coordinated but supported technology development, entrepreneurial experimentation, knowledge development, the involvement of important actors, the formation of essential associations and organizations, and early market formation. The market collapse in the mid-1980s could have resulted in a total failure – but did not. The research programs continued in the 1980s, and a new set of stakeholders formed – both publicly and privately funded researchers, authorities, and institutions – and provided an important platform for further development. In the 1990s and 2000s, Sweden and Switzerland introduced more coordinated and strategic policy incentives for the development of heat pumps. The approaches were flexible and adjusted over time. The policy interventions in both counties supported essential learning, successful development and diffusion processes, and cost reductions of the heat pumps. The assessment of innovation and diffusion policies for the heat pump systems can be used to illustrate some general policy conclusions.

**Summary Points**

- The assessment shows the need for strategic, *long-term*, and *continuous* support. First attempts to introduce a new technology failed, and continuous support was needed to overcome initial shortcomings. Technological change takes considerable time.
- The combination of policy instruments may have to change and the government's approach should be *flexible*. The policy intervention may initially allow uncoordinated intervention to support entrepreneurial testing, but then should be developed into credible, stable, and transparent strategies that allow industry to make long-term investments.
- The policy interventions need to be *system-oriented* and consider both the development of the technology and its emerging market. In

41 Gregory Nemet.

42 Lena Neij, Bernadett Kiss, and Martin Jakob.

other words, R&D is important as a part of the policy strategy, but not enough.

- The assessment indicates a need for *testing and certification* processes to support technical quality and create credibility and legitimacy. R&D initiatives and subsidies require testing and certification to support a stable market development.

- The support of networking to improve strategic integration and the use of learning and to ensure feedback and spillover effects seems essential.

### 24.7.12 Role of Standards – The US CAFE Standard[43]

In 1975, the US government passed the Federal Automotive Fuel Efficiency Standards, which specified mandatory levels of miles per gallon of gasoline consumed for new vehicles averaged across each manufacturer's vehicle fleet. The required Corporate Average Fuel Efficiency (CAFE) standard increased from 18 miles per gallon (13 liters/100 km) in 1978 to 27.5 miles per gallon (8.6 liters/100 km) in 1985. The standard was effective in meeting its goals; actual fuel efficiency has never fallen below the government requirement. In fact, actual fuel efficiency has almost always exceeded the mandatory level. This over-compliance, combined with the collinear rise in the price of gasoline during the period of escalating standards, suggests that prices have played a role in motivating efforts to improve fuel efficiency, not the CAFE standard alone. The standard for passenger cars has remained the same since 1985, while actual efficiency has improved slightly. The standard will rise to 30 miles per gallon (7.8 liters/100 km) in 2011. Standards also exist in Europe, China, Japan, Australia, and Canada, and are well in excess of US requirements – by nearly 100% in the cases of Japan and the European Union.

The CAFE standard has affected the rate and direction of technological change in vehicles. End-use efficiency has improved almost continuously for the past 30 years. This rise in efficiency was used to accomplish different ends during the period of policy escalation (1975–1985) and after it (1986-present). In the first period, efficiency improvements were directed toward improving miles per gallon. After 1985, almost all of the efficiency improvements were used to increase other attributes, including acceleration, towing capacity, and vehicle size. Energy conversion efficiency has improved in drive trains, engines, drag, and rolling resistance. Drive train and engine energy conversion efficiency improved from 1975–1985; efficiency improved at the rate of 2–3%/year. After 1985, efficiency improvement slowed to about 1%/year, although that rate has increased since 2000. The continuity of this improvement makes it difficult to attribute to CAFE. However, consideration of what end-use characteristics these efficiency gains were used for is revealing; from 1975–1985, vehicle weight dropped by about one-third and acceleration remained the same. After 1985, when CAFE standards stopped rising, efficiency improvements were used to power increasingly heavier vehicles that could accelerate considerably faster. It needs to be noted that the CAFE standards did not apply to all road vehicles, excluding in particular light duty trucks, which incentivized a change in the composition of the road vehicle fleet towards pick-up trucks and, later on, Sport Utility Vehicles (SUVs) with much higher gasoline consumption CAFE regulated passenger cars.

**Summary Points**

- CAFE standards had a real effect on technological change.

- The improvement in miles per gallon was accomplished not only by a shift to lighter, less-powerful vehicles, but also by the adoption of new energy-efficient technologies.

- Attribution of these changes to the regulations, rather than to gasoline prices, is less clear since the two are so well correlated.

- Standards that apply only to parts of the technological artifacts in use risk behavioral responses from manufacturers and consumers that can go against the original intention of the efficiency regulation.

- The effectiveness of CAFE may actually have been important after 1985 when it served as a fuel economy floor in the face of persistently low gasoline prices.

### 24.7.13 Role of Standards – The Japanese Top Runner Program[44]

In 1998, Japan initiated a unique program – the Top Runner Approach – to improve the energy efficiency of end-use products and to develop "the world's best energy-efficient products." Under this program, the most energy-efficient product on the market during the standard-setting process sets the Top Runner Standard for all corresponding manufacturers and products.

The Program started with nine products: room air conditioners, fluorescent lighting, television sets, copying machines, computers, magnetic disk units, video cassette recorders, refrigerators, passenger vehicles, and freight vehicles. The scope was reviewed every two to three years and gradually expanded to include 21 products by 2009. It is now considered one of the major pillars of Japanese climate policy. The case study examines 12 years of the program's experience. It first reviews the structure of the Top Runner Approach and then illustrates its impacts. It

43 Gregory Nemet.

44 Osamu Kimura.

also discusses issues associated with the approach, and concludes with some implications.

**Summary Points**

- Dynamic, continuously adjusted standards have been successful in accelerating the trend of energy efficiency improvement in many end-use products, such as room air conditioners and passenger vehicles. In these cases, the standards provided a clear direction for product development by aiming at higher energy efficiency and eliminating low-efficiency products from the market.

- The case study illustrates that ambitious policies that match market conditions and technological conditions can work well to induce remarkable energy efficiency improvements. Because such conditions depend on the country and the phase of technological development, careful design and adjustment are required for effective policy making.

- Some preconditions may be necessary for success of the Top Runner Approach. One is the Japanese market structure, which is dominated by a limited number of domestic producers. Another precondition is the existence of cost-effective potentials for efficiency improvement. Last, the specifics of the Japanese systems of innovation, in which public and private sectors cooperate largely through informal networks in the dynamic standard setting and implementation process, may be a further precondition for success. When these conditions were met, the Top Runner Approach resulted in a substantial outcome in terms of efficiency gains.

- Although the achievement of the Top Runner Approach is remarkable, there remain some issues for policy consideration. The largest one is the lack of explicit consideration of potential impacts on consumers in the standard setting process. Because the approach is based on the Top Runner products on the market, price increases due to energy efficiency improvements are not explicitly considered. This might lead to product prices too high for consumers to achieve pay back within the lifetime of the product.

### 24.7.14 Comparative Assessment of Wind Turbine Innovation and Diffusion Policies[45]

Wind turbines have become a mainstream technology – a first choice for many when investing in new electricity generation facilities. This comparative case study addresses how governmental policy has been formulated and formed to support the wind turbine innovation process. Three innovation stages and corresponding innovation strategies are identified. First is the stage of early movers in the 1970s and early 1980s, covering pioneer countries such as Denmark, the United States, Germany, the Netherlands, Great Britain, and Sweden. Second, the stage of booming markets in the 1990s, guided by the successful Danish innovation path of the 1980s, is described. Third is the stage of emerging markets in the 1990s and 2000s, including countries such as India, China, and Korea. Within these different periods, common key elements in governmental policy strategies can be identified as essential for a sustainable and successful innovation process.

**Summary Points**

- Support for diversity in technology and market formation is essential. The experience of wind turbine policy intervention shows the importance of applying a diversified technology portfolio. Moreover, the study illustrates the difficulties in foreseeing the drivers and trends of any given technology and the need to provide subsidies for implementation to many actors.

- RD&D is fundamental but not enough. In many countries, wind energy innovation was initially supported through RD&D only and the innovation process was envisioned to be linear. However, the RD&D funding alone did not bring about any commercial applications.

- To support technology innovation, quality assurance is essential. An important component of the innovation path of wind turbines was the development of a certification process.

- Support for innovator interaction and networking is essential. However, models for interaction and networking have only gradually developed over time and have been designed differently in different countries.

- Support requires a systemic approach. The case of wind energy shows that governmental policy needs to support the development of the entire innovation system, i.e., the development of the turbines and its infrastructure, but also the involvement of actors, necessary networks, and institutions.

- Support needs to be stable and continuous. The history of wind turbines development is long; it started in the 1880s. Many failures have occurred over time. The continuous support allowed knowledge creation and learning, as well as essential market formation that paved the successful innovation path of onshore wind energy and that now is the basis for the development of offshore wind energy.

### 24.7.15 Comparative Assessment of Photovoltaics (PV)[46]

A variety of factors, including government activities, have enabled the two order-of-magnitude reductions in the cost of PV over the past five decades. Despite this achievement, the technology remains too expensive

45 Lena Neij and Per Dannemand Andersen.

46 Gregory Nemet.

compared to existing electricity sources in many applications, such that widespread deployment depends on substantial future improvements. No single determinant predominantly explains the improvement to date; R&D, economies of scale, learning-by-doing, and knowledge spillovers from other technologies have all played a role in reducing system costs. Moreover, interactions among factors that enable knowledge feedbacks – for example, between demand subsidies and R&D – have also proven important.

Conversion efficiency, economies of scale, and the emergence of sequential niche markets have been important factors accounting for the impressive cost reductions in PV. Improvements in electrical conversion efficiency have been important to cost reductions, accounting for about one-third of the decline in cost over time. R&D, especially public sector R&D, has been central to this change. Deployment of PV has benefited from a sequence of niche markets where users of the technology were less price sensitive and had strong preferences for characteristics such as reliability and performance, which allowed product differentiation. Governments have played a large role in creating or enhancing these niche markets. Increasing demand for PV has reduced costs by enabling opportunities for economies of scale in manufacturing. Japan's program was especially innovative in that it took not only a long time horizon but also set a declining subsidy such that it fell to zero after the 10 years of the program. This provided not only expectations of demand, but also clear expectations of future levels of subsidy. The Renewable Energy Law in Germany in the 2000s successfully replicated many of the features of Japan's program.

**Summary Points**

- An array of supporting policy instruments is required: R&D, demand subsidies, etc.
- Timing matters: the question of when to switch from a focus on R&D to deployment is important.
- Much of the success of multiyear demand-side programs (in Japan and Germany) is because these programs created long-term expectations of future demand that enabled large investments in manufacturing facilities, which brought down costs through economies of scale.
- R&D support also needs a long-term commitment, whether through budgets or grants spanning multiple years, or supporting policies. Examples of supporting policies include Japan's Sunshine Program and the United States' Project Independence, which demonstrated commitment by making this area of work a serious national priority.
- Niche markets have been crucial, although they are most effective when not government supported.
- The success of new technological generations may require renewed R&D support even while markets for the existing technology are expanding.

### 24.7.16 Solar Innovation and Market Feedbacks: Solar PVs in Rural Kenya[47]

The solar PV market in Kenya is among the largest and most dynamic per capita in the world. Over 30,000 systems are sold each year. Much of this activity is related to the unsubsidized, purely free market sale of household solar electric systems, which account for an estimated 75% of solar equipment sales in the country. Solar is the largest source of new electrical connections in rural Kenya.

Despite this undisputed commercial success, product quality has been a significant concern (Jacobson and Kammen, 2007). Quality problems emerged first with the amorphous silicon solar modules that entered the Kenyan market in the early 1990s. This situation created a serious problem in the market, as many potential solar customers were unable to determine which brands performed well and which did not. Through independent testing in 1999, underperforming suppliers and models were identified and consequently withdrawn from the market, but quality problems resurfaced after 2004.

In response, the Kenya Bureau of Standards (KBS) moved to formulate and enforce quality standards for both amorphous and crystalline silicon PV modules. Currently, the KBS requires that import companies secure a certificate that validates their product conforms to the respective Kenyan standards prior to bringing the modules into the country. This certificate of conformity must be issued by an accredited laboratory. No such facility exists in Kenya, so this testing needs to take place in laboratories in Europe, North America, and Asia.

**Summary Points**

- Product quality assurance and standards constitute an important element for the diffusion of new energy technologies, particularly for decentralized systems like solar PV that are installed at residential sites by local businesses relying on imported modules.
- The recurrent emergence of quality problems in the Kenya PV market confirms that the issue of product quality control cannot be solved decisively by one-time testing efforts or focusing on the improvement of individual low-performing brands. Rather, institutional solutions that persistently require high performance for all brands are needed to ensure quality.

47 Daniel Kammen.

- The formulation, implementation and enforcement of product quality standards requires appropriate local institutional capacity, which needs to be developed and maintained for each market.

- The potential market feedbacks between end-users and suppliers of energy technologies can be weakened when testing stations are only available overseas.

### 24.7.17 Solar Thermal Electricity[48]

Solar thermal electricity (STE) production technology has improved through a combination of learning-by-doing and R&D investments. Even though R&D levels for this technology were small (even declining) relative to other energy technology programs, these programs played an important role in making full use of the knowledge gained through experience in manufacturing, installation, and operation of these facilities. R&D helped codify and document the often-tacit knowledge that accrued to operators through experience. As a result, this knowledge could be shared across firms and even across countries. It also preserved at least some of the value of the knowledge over time – especially during more than a decade of stagnation in the 1990s, when essentially no large plants were built worldwide. The rebirth of the STE industry during the 2000s indicates that at least some of this knowledge accumulated in the 1980s informs current designs and operation.

Most of our historical knowledge about technical change in STE comes from the 350 MW (mostly troughs) systems that were deployed in California in the 1980s. Since the mid-2000s, a new round of installations has begun, primarily in Spain and the southwestern United States. These installations encompass all three types of STE systems: troughs, concentrators, and dishes. By the end of 2010, total STE capacity neared 1 GW, and several additional GW (>2 in Spain, >3 in the United States) are likely to break ground in 2011. A distinguishing feature of STE, relative to other renewables, is that STE requires big, risky investments. Early investors may have to "eat between one and three US$200 million plants" before improvements enable profitable operation. A policy implication is that the scale of technology requires different types of incentives from smaller-scale renewables such as PV. Two policy instruments are driving a resurgence in STE installations over the past 10 years: (1) California's aggressive renewables obligation, possibly increasing to 33% by 2020; and (2) Spain's feed-in tariff. Complementary policies, such as loan guarantees and tax credits, have driven investment as well.

**Summary Points**

- Interaction between learning-by-doing and public R&D investment – even if small – was important for the substantial decline in operating costs of STE systems.

- This technology appears to be one for which higher R&D could not have substituted for deployment; learning by doing was essential.

- Initial investments required were large, and chunky, due to scale. Firms knew they would need to absorb losses on the first few plants – a classic valley of death problem that was eventually overcome by the alternative energy bubble on Wall Street in the 1980s. As a result, early plants needed both guaranteed tariffs and capital cost subsidies.

- Part of the value of the R&D investment was the formal documentation of cost improvement efforts, which was publicly available and nonproprietary.

- Technically, the 1980s California (solar energy generating system) plants have been successful. They steadily improved their performances, are still providing power two decades after they were installed, and provide the basis for newly designed plants in Spain and California. The failure of the company that built them was due to falling energy prices and consequent changes in policy rather than technical problems, illustrating the substantial market risks associated with policy intermittency.

### 24.7.18 The US Synthetic Fuels Program[49]

In response to the drastic oil price increase in the wake of the oil crises in 1979, subsidies for the demonstration and deployment of synfuels – a supply-side technology – received a rare confluence of support from the US government and energy experts (Deutch and Lester, 2004). The policy objective was to ameliorate the energy-security consequences and macroeconomic effects of the US dependence on imported oil by using the country's extensive coal, heavy oil, and oil shale deposits. Given estimates that synfuels would cost only US$60/barrel against the backdrop of (erroneously) projected rapid further increases in oil prices, the demonstration and deployment of synfuels production capability was seen as a major backstop or insurance policy (Deutch, 2005). The US Congress created the Synthetic Fuels Corporation (SFC) in 1980 and gave it the ambitious mandate to achieve production of 0.5 million barrels/day by 1987, and 2 million barrels/day by 1992. The goal of producing 2 million barrels/day in 1992 would have replaced over one-quarter of US crude oil and petroleum product imports, implying a scaling-up to one-quarter of the entire market in only 12 years, which was clearly unrealistic. Five and a half years later, and after expenditures of billions of dollars, the program was terminated without achieving its production goal (Gaskins and Stram, 1991).

**Summary Points**

- Deterministic cost-benefit analysis should not be the only measure used to make policy decisions when there is deep uncertainty

48 Gregory Nemet.

49 Laura Diaz Anadon, Gregory Nemet, with contributions from Bob Schock.

associated with market conditions (future oil prices) and technical feasibility. Policies aimed at providing insurance against a risk that does not materialize do not necessarily imply a policy failure.

- The mandate to meet ambitious production targets in relatively short timeframes regardless of market conditions and with little technical information was highly risky, partly because of the high expenses involved and partly because it was not accompanied by a long-term vision and corresponding innovation patience.

- Deciding when there is enough technical information to move from applied R&D to demonstration and deployment (or, in the SFC case, production) is difficult, yet crucial. This is especially the case in a situation in which the market and political environments change quickly. In large technology demonstration efforts, a good management and evaluation system is necessary to allow for timely decisions about whether and when to redefine program goals.

- Boom and bust cycles of support should be avoided, as they disrupt the innovation process, result in knowledge depreciation, and deter wider engagement in the enterprise.

- Policy backlash – the risk aversion induced by generalizing the experience of perceived failure of one program to unrelated programs – can have important and long-lasting effects.

### 24.7.19 The French Pressurized Water Reactor Program[50]

The case study reviews the French nuclear Pressurized Water Reactor (PWR) Program as an example of successful scaling-up of a complex and capital-intensive energy technology. Starting in the early 1970s, France built 58 PWRs with a total gross installed capacity of 66 GWe. On completion in 2000, they produced some 400 TWh/year of electricity, or close to 80% of France's electricity production. The institutional setting is characterized by a number of features. These include a high degree of standardization; external learning via the use of proven US reactor designs under a Westinghouse license; high regulatory stability; the effective absence of any public opposition; and a powerful national utility, ÉDF (Électricité de France), which acted both as *principal* and *agent* in reactor construction. The case study reviews the economics of this successful scale-up of nuclear reactor technology, identifying a significant cost escalation in real-term reactor construction costs, but also a remarkable stability in reactor operation costs. This cost stability is particularly noteworthy considering the need for load modulation in a system relying as heavily on base-load nuclear as in the case in France.

**Summary Points**

- Even under a most favorable institutional setting, earlier hopes of significant declines in nuclear reactor construction costs did not materialize, illustrating a case of negative learning much like the example of the United States (although cost escalation in France remained substantially below US trends).

- The case study thus demonstrates the limits of the learning paradigm: the assumption that costs invariably decrease with accumulated technology deployment. Not only do nuclear reactors across all countries with significant programs invariably exhibit negative learning (cost increase rather than decline), but the pattern is also quite variable, defying approximations by simple learning-curve models.

- While reactors' real construction costs increased steadily, their *operating* costs remained low and flat in France, as well as for many reactors elsewhere. Perhaps nuclear's "valley of death" is its inherently high investment costs and their tendency to rise beyond economically viable levels. The success of ÉDF in combining principal *and* agent in the construction process, which limited price escalation trends (especially in comparison to the US experience), could be an option worth considering for minimizing cost escalation. Conversely, this logic may suggest that competitive nuclear power is unlikely to be achieved in a private free market, which instead is tending to produce the rapid innovations that now competitively challenge nuclear power.

- The case study also provides valuable lessons for energy technology and climate policy. Cost projections of novel technologies are an inherent element in any climate change policy analysis. The case study confirms the earlier conclusion of Koomey and Hultman (2007) that projections of the future need to be grounded much more firmly within the historical observational space. Climate policy analysis must include a wider variation in cost uncertainties, as revealed by past experiences, than has previously been assumed in policy analysis and models.

### 24.7.20 Ethanol in Brazil[51]

Brazil's first ethanol program (PROALCOOL), launched in 1975, was a direct response to the dramatic rise in imported petroleum prices in 1973. The military government of the time saw this as a challenge to Brazil's financial stability and energy security, since the country imported 80% of the fuel used by its transport sector. Moreover, Brazil had extensive sugar plantations that were facing increased challenges to their exports from European Union trading preferences with the African, Caribbean,

50 Arnulf Grubler.

51 Paulo Teixeira de Sousa Jr. and Lynn Mytelka.

and Pacific Associated States – ACP countries – and the emergence of corn syrup and other close substitutes for sugar.

PROALCOOL was initially a classic import substitution policy. Subsidies were used to expand ethanol production, then in its infancy, and to induce users to shift to dedicated engines for ethanol that could handle a gasoline blend with more than 5–10% ethanol. When gasoline prices fell a few years later, those who had shifted were left paying the higher costs of ethanol, while the original problem of oil imports remained.

In this changed context, the government decided to invest in the research needed for Brazil to become a more efficient ethanol producer and thus be in a position to eventually eliminate subsidies. At the core of this process was a research partnership that brought together the Brazilian Agricultural Research Corporation and Copersucar, a cooperative of sugar mill and ethanol plant owners. Between 1975 and 2002, ethanol production increased from 0.6 to 12.6 million cubic meters and the price paid to alcohol producers dipped below that of Rotterdam gasoline prices (Goldemberg et al., 2004). By early in the new millennium, increasing yields and reduced processing costs (van den Wall Bake et al., 2009) had eliminated the need for subsidies. The decision to develop flex-fuel engines, in collaboration with foreign-owned automobile producers, strengthened the domestic auto industry and led to a dramatic shift in consumption habits and practices, thus further building the market. Introduced in 2003, flex-fuel vehicles accounted for 81% of the light vehicle registrations by 2008 (ANFAVEA, 2008).

Five policy lessons emerge from the Brazilian ethanol experience:

- First, developing a portfolio of fuel options was important for Brazilian development more broadly.
- Second, domestic research was a major contributor to the positive development outcome over the longer term.
- Third, building coalitions among interested parties helped to sustain long-term development efforts.
- Fourth, sugar cane was grown on large plantations, concentrated heavily in a single state. This left few opportunities for small holders and meant transporting ethanol elsewhere around the country with potentially negative effects on net $CO_2$ benefits.
- Fifth, ethanol from sugar cane tended to maintain the structure of large-scale, concentrated production. Lessons such as these have been applied in the development of the biodiesel sector. A variety of inputs have been identified for biodiesel and several of these are available in most regions and can be grown by small holders and processed and distributed locally.

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