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Historical Characteristics and Scenario Analysis of Technological Change in the Energy System

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Introduction

Technological change is widely recognized as the main driver of long-term economic growth (Solow, 1957) and of development in general (Freeman and Perez, 1988). Contrasting perspectives persist on the relationship between technological, institutional, and social change. “Technological determinism” depicts technology as the main agent of change. “Social constructivism” depicts the shaping of the technological landscape by social forces. The perspective of this chapter is that these dichotomies cloud complex interdependencies. Technologies and their institutional and social settings coevolve. Change in these different arenas is mutually dependent, mutually enhancing, mutually dampening. Regardless of these particular perspectives, scholars agree on the importance of technological change in historical energy transitions and on future scenarios of energy system transformation (Grubler, 1998; Nakicenovic et al., 2000; Smil, 2003; Halsnæs et al., 2007).

Studies of past energy transitions, as well as technological successes stories, provide many insights relevant to mitigating climate change, providing universal access to modern forms of energy, ensuring secure markets and supply chains, and reducing air pollution and human health impacts (Johansson et al., 2012). These challenges of a future sustainable energy transition will require substantive innovation and technological change across all regions, particularly in developing countries. Historically, the emphasis of energy-related development has begun by addressing energy poverty, then on building up

infrastructure as part of industrialization, then on widening access, and finally on tackling the environmental externalities associated with growth in energy use and consumption (Grubler, 1998). The overriding question for developing countries is how to move from this historical pattern to an integrated, concurrent approach dictated by the sheer magnitude of numbers as well as energy access and climate stabilization objectives (Metz et al., 2007). While the difficulties of such an integrated approach are significant, especially in view of capital constraints and often weak institutional capabilities, the benefits of a sustainable energy transition are substantial (Johansson et al., 2012).

Here we review historical evidence on the dynamics and characteristics of technological change and diffusion, focusing on the energy system. Alongside this historical emphasis is an analysis of how technological change is represented in future scenarios. Both sources of evidence are used to draw implications for the ongoing development and diffusion of clean energy technologies. Important differences in context and needs mean global and universal policy prescriptions are inappropriate. Rather, generic policy design criteria are recommended to support effectively functioning clean technology innovation systems.

Historical dynamics of technological change in the energy system

Historical energy transitions

Global energy use has grown by a factor of 25 over the last 200 years. This increase, far in excess of the roughly seven-fold increase in population over the same period, constitutes the first major energy transition: from penury to abundance. The transition in the *quantity* of energy use is closely linked to corresponding transitions in the *quality* of energy used and the *structure* of the energy system. Quantitative and qualitative transitions have been driven to a large extent by technological change but they are far from complete. Some 2 billion people continue to rely on traditional patterns of energy use: noncommercial biomass as the principal source of energy; no access to electricity; and levels of energy use characteristic of preindustrial societies (some 20–50 gigajoule³ [GJ] primary energy per capita). Indeed, over the entire twentieth century, energy use in industrialized countries has been persistently *above* the levels seen in developing countries despite accounting (currently) for one-seventh of the global population. This situation reversed after 2000. Strong energy demand

growth in developing countries, particularly China, coupled with stagnant, even slightly decreasing energy use in industrialized countries linked to the recession, have meant developing countries now account for over half of global energy use, or 276 exajoules (EJ) of a global total of 530 EJ in 2009 (Grubler, 2008; BP, 2010; IEA, 2010). Scenarios suggest that by 2100, developing countries could account for between two-thirds to three-quarters of total global energy use.

Although energy use has increased in industrialized and developing countries over the past 200 years, the underlying driving forces have been radically different. Historically, increasing energy use has been weakly related to population growth. Nearly exponential increases in energy use in industrialized countries contrasts with comparatively modest, linear increases in population. In developing countries, the reverse is true: nearly exponential increases in population yielding—up to 1975—a linear increase in energy use. Since 1975 (and especially since 2000), the increasing *per capita* energy use characteristic of industrialized countries is taking shape in developing countries. These historical differences are explained by the nature of the industrialization process of industrialized countries—income growth, fueled by technological change, leading to affluence and high levels of material (and energy) consumption. The historical record suggests that many developing countries are now at the beginning of a long, decadal development path with increasing levels of energy use as incomes rise. Conversely, in many industrialized countries, per capita energy use since 1975 has remained remarkably flat despite continuing growth in per capita income, suggesting an increasing decoupling of the two variables.

Although the pattern of increasing energy use with economic development is pervasive, there is no unique and universal “law” governing their relationship over time and across countries. There is a persistent difference between development trajectories spanning the extremes of highly energy intensive (e.g. the United States) to highly energy efficient (e.g. Japan). The concept of “path dependency,” discussed further below, helps to explain these differences in energy use patterns among countries and regions even at comparable levels of income.

Two major transitions have shaped the *structure* of the global energy system and the *qualitative* dimension to energy use since the onset of the Industrial Revolution (Nakicenovic et al., 1998). The first is characterized by the emergence of steam power relying on coal that helped to overcome the constraints of preindustrial energy systems including the limited availability of mechanical power, low-energy densities, and the lack of ubiquitous and cheap transport systems (see also Landes, 1969). This first energy technology transition took well over a century to unfold: between the late eighteenth century until the 1920s

when coal-based steam power was over two-thirds of the global energy system. The second energy technology transition is characterized by the displacement of the previously dominating coal-based steam technology cluster by electricity (drives, light) and petroleum-based technologies (automobiles, aircraft, petrochemicals). This second transition is far from completed: some two billion still lack access to modern energy services provided by electric appliances and end-use devices (Johansson et al., 2012).

These historical energy technology transitions are characterized by various “grand” patterns of technological change, each of which is discussed in the sections that follow:

- i. end-use applications drive supply-side transformations;
- ii. performance dominates cost in the initial market niches;
- iii. technologies do not change individually, but cluster and “spillover”;
- iv. the time constants of technological change are long, decades not years;
- v. experimentation and learning precede “up-scaling” and widespread diffusion;
- vi. the magnitude and rate of expansions in energy conversion capacity are inversely related;
- vii. diffusion in late adopter regions is faster than in initial innovator regions, but saturates at a lesser extent.

End-use applications drive supply-side transformations

Neither of the two major energy technology transitions since the Industrial Revolution were driven by resource scarcity or by direct economic signals such as prices, even if these exerted an influence at various times (Grubler, 2008). It was not the scarcity of coal that led to the introduction of more expensive oil. Instead, these historical shifts were, first of all, technological, particularly at the level of energy end-use. The diffusion of steam and gasoline engines and of electric motors and appliances can be considered the ultimate driver, triggering important innovation responses in the energy sector and leading to profound structural changes in the energy supply. The history of past energy transitions thus highlights the critical importance of end-use technologies, consumers, and the demand for energy services such as heating, lighting, mobility, and power.

Stationary steam engines in industry and agriculture and mobile steam engines on ships and locomotives were the dominant markets for this new technology. Small by comparison were the coal mines and the coking and town gas plants

that represented the emerging cluster of a coal-supply technology. In the case of electricity, the first innovation leaving Thomas Edison's R&D laboratory in Menlo Park was the incandescent light bulb. In the technology language of today, a demand innovation—the electric light bulb—triggered a host of supply-side innovations—electricity generation, transport, and distribution.

The size of end-use markets and the volume of applications dwarf their supply-side counterparts. Reliable historical records for the United States describe the evolution of energy technologies and illustrate the importance of energy end-use.

By the beginnings of the US steam age in the 1850s, the dominant energy technologies were the simple conversion devices of ovens, furnaces, and boilers, which converted chemical energy in the forms of fuel wood and coal into heat. Horses were the dominant transport technology converting chemical energy (feed) into mechanical energy, with five-fold greater capacity than the first stationary steam engines. By 1900, close to the peak of the coal/steam transition, thermal conversion in boilers and furnaces accounted for 90 percent of the 1,000 GW of installed conversion capacity in the United States. A hundred years later, this total had grown to some 34,000 GW or 120 kW per capita, ten times the level of 1850. This spectacular expansion has been marked by the electrification of homes and industry, and the striking 1,000-fold increase in energy conversion capacity enabling private mobility. Today, car and truck engines comprise nearly three-quarters of all energy conversion capacity in the United States, exceeding the thermal capacity of electric power plants by a factor of around 10.

Performance dominates cost in initial market niches

Initially, new technologies are attractive not cheap. New technologies when introduced are crude, imperfect, and expensive (Rosenberg, 1994). Performance initially dominates economics as the driver of technological change. New energy technologies are attractive for their ability to perform a particular task or deliver a new or improved energy service. This is often circumscribed by a specific set of needs in a particular context: a market “niche.” End-users in such niches are generally less sensitive to the effective price of the energy service provided or have a higher willingness to pay for its performance advantages (Fouquet, 2010). Costs will often only start to fall meaningfully after an extended period of commercial testing, learning, efficiency gains, and other incremental improvements. The concurrent establishment and growth of an industrial base drives costs down through standardization, mass production, and economies of scale. Only then

are new technologies able to compete with incumbent technologies on a cost basis, driving their widespread diffusion.

Initial steam engines were, by any standards, inefficient and extremely expensive. The first atmospheric steam engines had thermal conversion efficiencies of only 1 percent, consuming some 45 pounds of coal per horsepower delivered (Ayres, 1989). It took a century to boost their thermal efficiency to around 20 percent in a successive stream of innovations. It took another century again to reach the current steam turbine efficiency of 40 percent. The initial costs of steam engines in the mid-eighteenth century amounted to a phenomenal US\$12,000 per kW (in 2003\$) (Crafts, 2004) in an economy a factor of 130 smaller than today with per capita incomes around US\$1,500 (in 2003). Yet despite their high inefficiency and high cost, the modest performance benefits of steam engines in terms of power output and density meant they began substituting for the incumbent power providers—horses and water. After an extended period of experimentation and development, costs of steam engines started to come down during the mid-nineteenth century, 100 years after their introduction. By the beginning of the twentieth century, costs had fallen to below US\$3,000 per kW (in 2003).

In spite of initial high costs, a similar pattern in the adoption of new energy technologies is found in the introduction of electricity and electric appliances for light and motive power (Devine, 1983; Smil, 2000). Fouquet (2010) compares the drivers of fourteen energy transitions in the means of providing heat, light, mobility and power in the UK over the past millennium. In the majority of cases, better or different energy services drove the transition: “The steam engine enabled entrepreneurs to boost production, not limited by humans or animals or by the location of flowing water. Electricity radically altered the production process from belts centrally driven by a steam engine to numerous machines . . . potentially controlled by the worker. Railways and cars transformed the provision of transport services, allowing a faster service and a more flexible and private form of transport respectively. Gas lighting was easier to use and less dangerous. Electric lighting was much easier to use.” (Fouquet, 2010, pp. 6591–92).

Major energy transitions are associated with step-changes in both the quality and the quantity of energy services provided through end-use technologies. Though transitions may be catalyzed by innovations that create new, better or qualitatively different energy services, transitions are subsequently driven and sustained by dramatic falls in the effective cost of providing energy services. (Fouquet and Pearson, 2007; Fouquet, 2010). Any efficiency gains are then overwhelmed by increases in energy service demand and a corresponding

expansion in the volume and pervasiveness of end-use technologies (Haas et al., 2008).

Technologies do not change individually but cluster and “spillover”

No individual technology is able to transform large and complex energy systems. The importance of single technologies arises in particular through two effects: “clustering,” or combinations of interrelated technologies, and “spillovers,” or applications outside the configuration, use, sector or geography for which a technology was initially devised. In other words, technologies act more effectively as families or “gangs,” not as individuals.

Technology researchers have introduced the concept of “general purpose” technologies to describe the synergies of technologies deployed in a variety of applications promoting knowledge spillovers and market growth, with corresponding economies of scale (Lipsey et al., 2005). Steam is a prominent historical example. Stationary steam engines were first introduced in the eighteenth century for dewatering coal mines. Stationary steam power subsequently spilled over to drive mechanization in manufacturing (e.g. textiles) and agriculture (e.g. threshing) and also to mobile applications such as railways and steamships. Perhaps the exemplar of a general purpose technology whose importance is founded on clustering and spillover effects is electricity, the “greatest engineering achievement of the 20th century” (US_NAE, 2003). Information and communication technologies (ICTs) are the clearest current example of a general purpose technology (Basu and Fernald, 2008). As such ICTs could drive services-led growth while leaving the basic structure of the energy system in tact (Moe, 2010). Others, however, have argued for a more pervasive impact of ICTs on the energy system, exemplified by the smart grid concept of system management based on two-way flows of both information and power.

Clustering is particularly evident in the mutual dependencies between energy conversion technologies and energy supply infrastructure and networks. Each of the major energy transitions in the United Kingdom since the 1300s were characterized by a change in energy source (e.g. horse to steam power, sail to steam ship transportation, candles to kerosene lighting); but each energy transition also involved major changes in the energy supply network, as well as the energy service provided (Fouquet, 2010).

Clustering and spillover effects mean it is difficult to dislodge a dominant technological regime with its component technological systems, high sunk

investment costs, and the associated institutions, patterns of social organization, and behavioral routines and practices that support a technological regime (Sovacool, 2009). This is referred to in the technology literature as “lock-in” (e.g. Unruh, 2000) and is described dynamically by the characteristics of “path dependency” (Arthur, 1989). Path dependency helps explain the persistent differences in development trajectories between countries, controlling for the effects of income. Path dependency in energy systems arises from differences in initial conditions (e.g. resource availability and other geographic, climatic, economic, social, and institutional factors) that in turn are perpetuated by differences in policy and tax structures, leading to differences in spatial structures, infrastructures, and consumption patterns (Grubler, 2008). These in turn exert an influence on the levels and types of technologies used by end-users and within the energy supply.

The time constants of technological change are long, decades not years

The turnover of capital stock in the energy system ranges from many decades to well over a century (Grubler et al., 1999). It took steam power in the UK close to 100 years (to the 1860s) to gain a 50 percent market share in total installed horsepower, gradually displacing wind and waterpower (Crafts, 2004). It took some 40 years (to the 1920s) for electric drives to account for 50 percent of all prime movers in US industry (Ausubel and Marchetti, 1996). Substantial capital and labor productivity effects arose only after that threshold was passed (Devine, 1983). In a range of UK energy transitions since the Industrial Revolution, the average time period from first commercialization to market dominance was around fifty years (Fouquet, 2010). Including the period from invention to first commercialization extends this time constant to around 100 years. Energy transition dynamics at the global scale are significantly slower: ranging from 80 to 130 years for new energy technology clusters to achieve market dominance and about twice as long when considering the entire technology life cycle from first introduction to market maturity. These slow rates of change are explained by spillover and clustering effects and the capital intensiveness and longevity of many energy-related plants and infrastructures from end-use applications (e.g. buildings) to conversion technologies (e.g. refineries, power plants) and distribution systems (e.g. railway networks, electricity grids) (Smekens et al., 2003; Worrell and Biermans, 2005).

More generally, the process of technological change, from innovation to widespread diffusion, takes considerable time. Figure 3.1 summarizes the two

Figure 3.1 Two grand transitions in global energy systems (1850–2008)

Source: Grubler (2008) updated using BP (2010); IEA (2010). Data prior to 1950 are estimates. Dotted lines show fitted logistic substitution models.

major energy technology transitions globally in the period 1850–1975: coal/steam replacing traditional biomass, and then modern energy technologies and carriers (oil, gas, and primary electricity from hydropower and nuclear) replacing coal/steam. The y-axis shows market shares as a percentage of total primary energy use for traditional fuels (brown), coal (grey), and modern energy carriers (red). Evident from Figure 3.1 are the long periods of slow and gradual market penetration of end-use and supply technologies alongside the observed substitution of energy sources (Marchetti and Nakicenovic, 1979). The turnover, or displacement times (Δt), of traditional fuels and then coal is around 130 years and 80 years, respectively, at the global level. The significant slowdown and near flatlining of these transition dynamics since 1975 are clearly evident, due largely to the continuing role of coal for electricity generation.

Experimentation and learning precede up-scaling and widespread diffusion

Widespread adoption of a technology follows an often extended period of experimentation during which the technology is tested, refined, and adapted to market conditions. This has been termed the “formative phase” of the

technology's life cycle (Jacobsson and Lauber, 2006) and characterizes the early stages of commercial diffusion. The life cycle of some energy technologies—from invention and innovation through to widespread market adoption and eventual saturation—is further characterized by a process of “up-scaling,” an increase in the capacity of an individual technological unit to convert energy into a useful service. Up-scaling is often associated with economies of scale, reductions in average unit costs as the size of individual units (“unit” scale economies) or the volume of total production (“manufacturing” scale economies) increases.

Figure 3.2 shows the “up-scaling” dynamic for a range of energy technologies that have diffused over the course of the twentieth century. Each line describes the changes over time of the average capacity in megawatts (MW) of newly installed “units”: steam turbine units in coal, gas, and nuclear power plants; wind turbines in wind farms; jet engines in passenger aircraft; internal combustion engines in cars; and compact fluorescent light bulbs in lighting systems.

Historically, the formative and up-scaling phases of energy technologies have tended to progress sequentially. Figure 3.3 shows more detailed data for coal power. The left-hand graph shows the number of steam turbine units built each year, along with their average and maximum unit capacities. These describe growth dynamics at the technological unit level. The right-hand graph shows the total capacity added each year as well as the steady growth over time of cumulative total capacity. These describe growth dynamics at the industry level.

Figure 3.2 Up-scaling of selected energy technologies since 1900

Notes: Lines show average capacity in MW of new units each year on log-scale y-axis.

Source: See graph legend and Wilson (2012); Bento (2013) for details.

Figure 3.3 Growth in coal power capacity globally since 1900

Notes: Left-hand graph shows unit capacities and numbers; right-hand graph shows capacity additions and cumulative total capacity.

Source: Platts (2005); see Wilson (2012) for details.

Figure 3.3 shows a clear overall sequence:

- i. a *formative phase* of many smaller-scale units with only small increases in unit capacity;
- ii. an *up-scaling phase* of large increases in unit capacities, particularly at the scale frontier, concurrent with an increase in numbers of units;
- iii. a *growth phase* of large numbers of units at larger unit capacities.

For the first fifty years, slow growth in cumulative total capacity is driven by increasing numbers of units. Unit capacities remain low, with maximum unit capacities typically in the 10–50 MW range. During the next twenty years, continued growth in cumulative total capacity is increasingly driven by a concentrated period of up-scaling, which is preceded by a dramatic jump in the numbers of units. Maximum unit capacities increase to around 1,000 MW; average unit capacities to around 250 MW. Over the course of the next thirty years, unit capacities vary somewhat around these saturation levels, but sustained growth in cumulative total capacity is driven again by increasing numbers of units.

The sequence of formative, up-scaling, and growth phases observed in the expansion of coal power capacity is broadly consistent across many different energy technologies and in all regions as well as globally (Wilson, 2012). However, the timing and rate of up-scaling varies. In general:

- i. Up-scaling occurs more rapidly (and over a shorter timeframe) for technologies with strong unit scale economies: for example, coal power, nuclear power.
- ii. Up-scaling occurs less rapidly (and over a longer timeframe) for technologies servicing heterogeneous or dispersed markets: for example, natural gas power, jet aircraft.

The potential tension between these two drivers is clear in the case of natural gas power whose scale independence in terms of technical efficiency has meant applications spanning distributed units in the kW range up to centralized combined cycle configurations in the 100s of MW or even GW range (Lee, 1987). The demand context for each technology thus determines the appropriateness of different unit scales. In general, market niches are more heterogeneous for distributed end-use technologies than for centralized supply-side technologies. End-use technologies (e.g. aircraft, light bulbs) supply a particular energy service (e.g. mobility, illumination) in a wide variety of contexts. As an example, the diversity of lighting services requires bulbs ranging in capacity from several watts (LEDs) to over 10kW for specialized exterior lighting (metal halide lamps) (IEA, 2006).

By comparison, energy supply and conversion technologies (e.g. refineries, power plants) produce one or a small number of homogeneous energy carriers (e.g. liquid transportation fuels, electricity). These are subsequently distributed to the point of use. With transmission networks and reasonable proximity to concentrated demand centers, electricity generation has historically been characterized by strong unit scale economies and rapid up-scaling of unit capacities (see Figure 3.2). In the case of US refineries, up-scaling was concentrated during the decades following the Second World War, concurrent with the growth phase of the industry. Increases in unit capacities largely saturated by the 1970s; industry capacity expansion similarly plateaued following the oil shocks. As the largest capacity end-use technology, jet aircraft also exhibited rapid and early up-scaling. First introduced commercially in 1958, up-scaling potential was largely saturated in 1969 with the Boeing 747 (see Figure 3.2).

Experimentation and learning are concentrated during the formative phase

The formative phase of a technology's life cycle describes the critical period between the early development of an innovation and widespread commercial diffusion sustained by positive feedbacks or "cumulative causation" (Jacobsson and Bergek, 2004). During the formative phase, technologies are repeatedly and iteratively tested, modified, improved, reduced in cost, and adapted to market demands. This often takes place in market niches that offer some protection from competitive pressures (Kemp et al., 1998). Well-functioning innovation systems are characterized by entrepreneurialism to conduct "*risky experiments necessary to cope with the large uncertainties that follow from new combinations of technological knowledge, applications and markets*" (Hekkert et al., 2007, p. 422). Dosi (1988) includes experimentation as one of five integral characteristics of innovation, the other four being uncertainty, scientific knowledge, complexity, and accumulation.

Experimentation with many small-scale units through the formative phase contributes to a process of "learning-by-numbers"—or building many before building big. This is illustrated further by Table 3.1, which summarizes data for five energy supply technologies in their initial markets (which vary geographically and in size). The right-hand column shows the length and number of units built during a formative phase, which runs from first commercial application to the point at which new units reach 10 percent of the eventual scale frontier. This formative phase lasts decades and sees the build out of hundreds of units. Nuclear

Table 3.1 Formative phases of energy supply technologies

Technology	Initial Market	First Commercial Capacity Installed	10% of Unit Capacity Frontier Reached	Formative Phase: Number of Years & Number of Units
Natural Gas Power	OECD	1900s	1948	50 years, >400 units
Coal Power	OECD	1900s	1950	50 years, >775 units
Nuclear Power	OECD	1950s	1963	10 years, 25 units
Wind Power	Denmark	1970s (1880s*)	1987	15–100 years, >1,400 units
Refineries**	US	1860s–1870s	(1948–average capacity only)	(80–90 years, >100 units?**))

Note: * First wind power generators date to 1880s, but from 1970s in their modern form.

** Refineries data are indicative only. Saturation capacity measured in terms of average rather than maximum capacities; number of units are rough estimate.

Source: Wilson (2012).

power is the outlier with a relatively short formative phase and relatively few numbers of units built prior to up-scaling. But in fact, this exception supports the generalizable rule. The unit scale frontier of nuclear power increased fivefold in the decade that followed commissioning of the first 50 MW commercial reactor in 1956. Ultimately, these rapid increases in unit size were a contributing factor to the rising complexity that created diseconomies of scale and constrained further growth of the industry in the late 1970s (Lovins et al., 2003; Grubler, 2010).

The knowledge generated and experience accumulated in the formative phase is neither automatic nor autonomous. In many cases, learning is facilitated by relationships between industry actors (supported by public investments in, for example, testing infrastructure) to ensure experiences feed back into subsequent designs (Garud and Karnoe, 2003). When this policy-supported process of collective learning is absent, the development of viable domestic technological capability and industry can fail (Neij and Andersen, 2014).

The magnitude and rate of expansions in energy conversion capacity are inversely related

Intuitively, the more pervasive the diffusion of technology, the slower the process (Grubler, 1996). The relationship between the extent and duration of capacity

expansion is a useful descriptive measure of the overall growth dynamic of energy technologies.

Figure 3.4 shows a strong positive relationship observed historically between the extent and duration of diffusion for a range of energy technologies. Both axes of Figure 3.4 show parameters from logistic functions fitted to historical time series data of cumulative total capacity in MW. The x-axis is a measure of the *duration* of diffusion. Δt is the period a technology takes to grow from 10 percent to 90 percent of its final saturation level. This saturation level is shown on the y-axis as a measure of the *extent* of diffusion, normalized to account for differences in the overall size of the energy system (i.e. analogous to market share). For details of the methodology and data, see Wilson et al. (2012a) and Bento (2013).

The consistency of the relationships in Figure 3.4 between the extent and duration of diffusion is surprising as the end-use and energy supply technologies analyzed are of markedly different characteristics (Wilson et al., 2012a). The technology life cycles of refineries, power plants, jet aircraft, cars, and light bulbs are characterized by distinctive cost and efficiency profiles, capital intensiveness, turnover rates, market niches, regulatory contexts, manufacturing bases, and so on. Why should the observed extent–duration relationships be so consistent across technologies? First, this may simply describe the dynamics of demand growth. How rapidly and how extensively demand changes is both driven and

Figure 3.4 Relationship between extent and duration of capacity growth historically

constrained by the adaptability of end-user needs and wants. These in turn are embedded in practices, routines, social networks, organizational structures, and so on. The inherent inertia to change in technological systems is similarly found in social systems: indeed, the two are inseparably entwined. Second, consistent extent–duration relationships may signal limits in the capacity of mechanisms shaping innovation to accelerate the time to mass market (Grubler, 1998). Such mechanisms include knowledge generation through R&D, learning and scale effects, knowledge spillovers (and knowledge depreciation), entrepreneurialism, demonstration activities, niche market applications, and so on (Grubler et al., 2012).

In sum, the simple relationship between diffusion extents and durations in Figure 3.4 describes the inherent inertia of a large, complex, interrelated system of technologies, institutions, and end-user needs.

Diffusion in late adopter regions is faster than in initial innovator regions but saturates at a lesser extent

A generalizable *temporal* pattern of technological diffusion sees a slow beginning as technologies are introduced that then—if successful—accelerates into a rapid growth phase before slowing and eventually saturating (Grubler et al., 1999). There is also a generalizable *spatial* pattern to diffusion. In the initial markets or regions where a technology is first commercialized, a technology's growth tends to be slower but more pervasive (Grubler, 1996). In subsequent markets, growth tends to be more rapid but saturates at a lesser extent (i.e. is less pervasive). Mobile phone densities are 1.2–1.3 per capita in the Scandinavian innovator countries (Finland, Sweden) but only around 0.85 in the United States and Japan (OECD, 2009). The spatial diffusion of cars is another example, albeit a more complex one given the interdependencies of infrastructure, urban form, and petroleum. In the United States as the initial market, car ownership per capita grew from the early 1900s throughout the twentieth century; in Japan, growth began in earnest in the 1950s and was compressed into several decades. But by the 1990s, ownership per capita in Japan was only slightly larger than that of the United States in the 1930s (Grubler, 1990, p. 151; Schipper et al., 1992). Less pervasive diffusion in later adopting markets reflects the long time constants of change in the interrelated systems of technologies, infrastructures, and institutions (including patterns of end-use services and end-user behavior).

More rapid diffusion in later adopting markets signals the “spillover” or transfer of knowledge from the formative phase of technologies in their initial

markets (Grubler, 1998). Knowledge spillover can shorten, but not preclude entirely the need for local development of the conditions and institutions that support diffusion and that are gained through cumulative experimentation and learning (Dahlman et al., 1987; Gallagher, 2006).

Figure 3.6 provides further evidence for faster rates of growth in later adopting regions for a range of energy technologies. The bars show the duration of each technology's growth in terms of cumulative total capacity as it diffuses spatially out of its initial "core" region through subsequent "rim" regions and ultimately into "periphery" regions. The measure of duration is the Δt in years derived from logistic functions fitted to the data. This measure of duration is inversely related to the rate of diffusion, so the longer the bars in Figure 3.5, the

Figure 3.5 Spatial diffusion of energy technologies historically

Notes: Bars show durations of diffusion in cumulative total capacity measured as the δt in years (or turnover time). "Core" regions are typically within the OECD; "rim" regions are typically Asian countries; "periphery" regions are typically Africa or Latin American countries. See Wilson (2012) and Bento (2013) for details and data.

more prolonged and the slower the rate of capacity expansion. The duration of diffusion consistently decreases from core to rim to periphery.

Scenario representations of future technological change

The role of technological change in future energy scenarios and in climate change mitigation has been reviewed comprehensively in the IPCC's Fourth Assessment Report (Fisher et al., 2007; Halsnæs et al., 2007). Here we summarize the levers of technological change for transitioning toward more sustainable energy systems. Growth dynamics in future scenarios are also contrasted with the historical perspective outlined previously.

Path dependency in future technological change

Figure 3.6 shows scenarios of industrial CO₂ emissions in the “high growth,” or A1 scenario, family of the IPCC Special Report on Emissions Scenarios (“SRES”), grouped into A1FI (high emissions), A1B (medium emissions), and A1T (low emissions) (Nakicenovic et al., 2000). None of these scenarios explicitly includes the effect of climate policies, yet the vast differences in terms of emission outcomes is striking.

Comparison of the fossil fuel intensive A1FI scenarios, the low-carbon technology A1T scenarios, and the “balanced” A1B scenarios, illustrate how the dynamics of technological change give rise to consistent and stable technological combinations that crowd out competing alternatives through increasing returns to adoption and consequent creation of path dependency on the dominant technology. Because of the long lifetimes of power plants, refineries, buildings, and other energy infrastructure, these contrasting technology strategies result in emissions diverging only gradually, after several decades or more (Grubler, 2004). But the seeds of subsequent divergence will have been widely sown by then, based on research and development efforts, intervening investments, and technology diffusion strategies (Nakicenovic et al., 1998). These translate into different environmental outcomes only as new technologies gradually replace older technology vintages. As a result, near-term technology and policy decisions are critically important for leveraging long-term change.

While systemic change is strongly path dependent, the growth paths of individual technologies can vary widely. In the scenario projections for solar photovoltaics (“PV”), there is a clear bifurcation of outcomes depending on

Figure 3.6 Industrial CO₂ emissions in the IPCC's SRES A1 "high growth" scenario family

Source: Nakicenovic et al. (2000).

assumed technology characteristics and investment costs as well as future market deployment environments including the existence and stringency of CO₂ emission constraints. But the temporal dimensions of this technological differentiation in energy systems are extremely long. In the medium-term (2030), only modest, niche-market inroads of solar PV into the global energy system are expected. Only by 2100 have scenarios clustered either around relatively small solar PV markets (0–80 EJ), assuming no or low CO₂ emission constraints and high investment costs, or around relatively large solar PV markets (100–180 EJ), under stringent CO₂ emission constraints and low investment costs. To put these numbers into perspective: current global energy demand amounts to some 530 EJ, and electricity generation to some 60 EJ. The highest growth scenarios suggest that by the end of the twenty-first-century solar PV could generate as much as three times more electricity than is generated at present for all sources and technologies combined.

Marked differences in long-term technology outcomes are the result of complementary (or absent) "market pull" and "technology push" innovation and technology policies. Underlying the alternative projections of solar PV

investment costs (which in turn reflect other technology characteristics such as conversion efficiency) are R&D efforts, improved designs, and “debugging” through niche market application and feedbacks. These processes “push” the technology through ever-wider diffusion as CO₂ emission constraints change the relative prices of energy sources and so “pull” solar PV and other low-carbon technologies into the market.

The supply-side emphasis of future energy transitions

Future scenarios tend not to explicitly portray alternative pathways of technological change in energy end-use. This reflects the current state-of-art of modeling technological change in scenarios of energy transitions and climate stabilization rather than any disavowal of end-use technologies on the part of researchers and scenario modeling teams. Even technologically explicit “bottom-up” models contain little detail at the level of energy end-use, instead using aggregate indicators such as sectoral energy intensity (GWh / \$ of GDP) (Hanaoka et al., 2009) or exogenously specified indices of efficiency improvements (Azar and Dowlatabadi, 1999; Magne et al., 2010). End-use technology investments are represented endogenously only indirectly through aggregate relationships between demand, energy price, and other factor inputs (capital, labor) (van Vuuren et al., 2009). In other words, unspecified technological change is assumed to occur and is represented in models only in terms of its impact on energy demand; these impacts are then interpreted *ex post* in terms of technological and/or behavioral changes. The energy transitions shown in Figure 3.7 predominantly concern the energy supply. This is in stark contrast to the driving role of changing and novel energy end-use services seen historically.

There are various reasons for the relatively poor model representations of future technological change in end-use technologies. First, there is an extreme paucity of end-use data as end-use technologies are classified under different industrial and consumer goods markets (Nakicenovic and Rogner, 1996). A related, practical data challenge is the increased granularity of end-use technologies: compared to energy supply technologies, they are smaller scale, more decentralized, more heterogeneous, and many more in number.

Second, it is extremely challenging to derive plausible and consistent scenario assumptions on the evolution of a large number of energy end-use applications—from new transport and communication technologies to manufacturing innovations and consumer appliances. This has important implications as it

causes scenarios to diverge from historical experience by downplaying the driving role of changing patterns of end-use services and technologies. A major intermodel comparison of stringent climate stabilization targets found that “all models pay considerably less attention to end-use energy efficiency technologies than to supply side technologies, which could create a bias towards favoring [carbon intensity] improvement” (Edenhofer et al., 2010, p. 28). Of the five models compared, the one with the most detailed representation of end-use technologies found “energy efficiency and end-use technologies constitute first rank options to cope with severe climate constraints” (Kitous et al., 2010, p. 58). This includes rapid penetration by mid-century of electric vehicles and low-energy buildings, with the diffusion dynamics of both end-use technologies modeled endogenously.

Implications for clean energy technology and innovation policy

Here we conclude by drawing broad policy implications from the dynamics of technological change observed historically and in future scenarios. The policy-induced technological change in climate change mitigation scenarios is a major point of departure from historical energy transitions. Consequently, past transitions offer insufficient guidance on whether regulation, externality pricing (carbon taxes), and other supporting policies to drive low-carbon technology diffusion will be adequate, and how it will affect rates and extents of growth. The future represented in the scenarios describe a world with more globally integrated markets, pervasive diffusion of information, and communication technologies, stronger regional growth in Asia, and so on. Together with the driving role of policy, these differences in future context imply the potential for more rapid technological change and faster spatial diffusion.

Portfolio diversification helps manage uncertainties

Innovation outcomes are irreducibly uncertain. This helps explain the cautionary wisdom around public policies trying to pick technological winners *ex ante*. Policies have to support a wide range of technologies. However seductive they may seem, silver bullets do not exist. Innovation policies should use a portfolio approach under a risk hedging or “insurance policy” decision-making strategy. Portfolios recognize that innovation is inherently risky. Failures vastly

outnumber successes. Experimentation, often for prolonged periods, is critical to generate the applied knowledge necessary to support the widespread diffusion of innovations and up-scaling to capture available scale economies. History cautions against overly exuberant efforts to compress formation and learning cycles. The diseconomies of scale ultimately revealed in the history of nuclear power were discussed earlier (see also Grubler, 2010). Another salutary example is the US synfuel program, which targeted a ramp-up in production through the 1980s from almost zero to a targeted 2 million barrels a day (some 25% of all US oil imports). The program was cancelled after five years, having spent almost \$5 billion (1980) to reach only 10,000 barrels a day (Anadon and Nemet, 2014).

A number of basic criteria define the design of technology portfolios. The whole energy system should be represented, not only particular groups or types of technology. The entire suite of innovation processes should be included, not particular stages or individual mechanisms. Less capital intensive, smaller-scale, that is, *granular* technologies or projects are a lower drain on scarce resources, and failure has lower consequences. Risk aversion and the resulting risk premia or extents to which decision makers are willing to pay to hedge against unexpected outcomes are important influences on optimal technology portfolio design. Unexpected outcomes or risk include anything from cost overruns and delayed market readiness to outright failure or infeasibility. Deterministic models suggest optimal investment should focus on those technologies forecast to have the least cost in the future and ignore the attractiveness of higher cost alternatives in terms of reduced risk. Portfolio theory can be used to capture the benefits from diversification for different degrees of risk aversion. In general terms, risk aversion means higher short-to-medium term investments in advanced, noncommercial technologies and deeper CO₂ emission reductions (Krey and Riahi, 2009).

Diversity in publicly funded portfolios should also help keep potential options open in the face of economic pressures to standardize and up-scale technological “solutions” that offer initial promise. Incumbents naturally favor current technologies, yet a characteristic of leading innovator countries in historical energy transitions has been a political appetite to overcome vested interests (Moe, 2010). In so doing, technology policy should also seek to avoid all innovation risks of novel concepts being transferred wholly onto the public sector.

An important, related challenge is to manage the risk of prematurely locking-in to technologies or clusters that may ultimately prove suboptimal (van den Bergh et al., 2007). This creates tension between short- and long-term policy

targets if the former rewards deployment of market-ready technologies at the expense of developing technologies with greater transformative potential (Sandén and Azar, 2005). This is illustrated well by “technology-neutral” market pull policies for renewable electricity such as the United Kingdom’s Renewable Obligation during the 2000s, which strongly favored the most commercially viable alternative (utility-scale wind farms). These contrast with “technology-banded” policies, which set differential support for technologies depending on their market readiness (e.g. Germany’s feed-in tariffs).

Scenario analysis helps identify technological “needs”

Scenarios are an important response to the uncertainty of technological change. Large-scale energy modeling studies described compare the most influential technological and market uncertainties across a set of scenarios (Nakicenovic et al., 1998; Nakicenovic et al., 2000). Scenario analysis can also be used to explore how optimal energy technology portfolios change under different socioeconomic, technological, and climate outcome assumptions. A related question is whether certain portfolios are more robust to these uncertainties than others.

Riahi et al. (2007) explored how portfolios of energy technologies changed as a function of how salient uncertainties were represented. Across twenty-two scenarios, they compared energy demand, resource constraints, the availability and cost of technologies, and also the stringency of greenhouse gas emission constraints. Grubler and Riahi (2010) developed this analysis further by testing the relative contribution of different types of technology across the scenarios, and so the robustness of different technology options. Figure 3.7 illustrates these contributions in GtC per year in the case of a high emissions baseline scenario (A2r) and an emissions constraint resulting in 550 ppmv CO₂-equivalent concentration by 2100. The top two “mitigation wedges” show the annual GtC contributions of carbon intensity (energy supply) and energy intensity improvements (end-use) in the baseline relative to a “frozen” state of technological development in 2000. The remaining wedges show the annual GtC contributions to emission reduction targets of different energy technologies and resource options.

The mean GtC contribution of different technology options to emission reductions are summarized in Table 3.2 in rank order. The ranking of these different “mitigation wedges” is quite robust across the scenarios explored, with energy efficiency and conservation the single most important option contributing over 50 percent to cumulative emission reductions over the twenty-first century.

Figure 3.7 Climate change mitigation wedges

Table 3.2 Comparing technology options: Emission reduction contributions versus R&D expenditures

	Cumulative Emission Reductions (GtC-Eq., 2000–2100) across All Scenarios Describing Future Uncertainties				% Cumulative Public R&D in IEA Countries (1974–2008, in 2008\$)
	Minimum	Mean	Maximum	Mean %	
Energy Efficiency	666	1,695	3,008	59	9
Renewables	64	520	917	18	9
Nuclear	64	243	425	9	54
Other	72	229	361	8	16
Fossil Fuels	19	177	415	6	13
Total	885	2,864	5,126	100	100

Source: Grubler and Riahi (2010); R&D data from IEA (2009).

This robustness is captured by the dispersion between the minima and maxima for each technology option as proposed by Riahi et al. (2007).

Innovations in end-use technologies are important and underemphasized

While the largest efficiency improvement potentials lie in energy end-use sectors (Grubler and Riahi, 2010), the allocation of public resources is mismatched. On the one hand, public R&D investments are heavily weighted toward supply-side technologies; of an estimated \$50 billion global annual investment (in

2005), less than \$10 billion were allocated to end-use technologies and energy efficiency. Of the \$417 billion spent on R&D in International Energy Agency (IEA) countries cumulatively in the period 1974–2008, less than \$40 billion were allocated to energy efficiency (compared to some \$56 billion allocated to the commercially unproven technology concept of nuclear fusion). On the other hand, market or diffusion investments are heavily weighted toward end-use technologies (Grubler et al., 2012). IEA estimates of annual investments in supply-side plant and infrastructure are roughly \$0.8 trillion (in 2005). A bottom-up estimate of the total annual costs of end-use technologies puts a conservative total somewhere between \$1–4 trillion (Wilson and Grubler, 2014). These asymmetries in R&D and market investments in favor of energy supply technologies are found throughout the energy innovation system (Wilson et al., 2012b).

The need for investment to support the widespread diffusion of efficient end-use technologies is also clearly shown in the scenario analysis of climate change mitigation summarized in Table 3.2. This allows a comparison of each technology's contribution to emission reductions with its relative position in public R&D portfolios, at least in the IEA countries for which R&D data are available. The two right-hand columns of Table 3.2 show a clear mismatch between the scenario analysis of robust contributions to future emission reductions and the balance of R&D investments to date. Energy efficiency is greatly underrepresented in R&D portfolios while the reverse is true for nuclear, which has dominated public R&D portfolios. Public innovation expenditure should be rebalanced to include smaller-scale end-use technologies (Wilson et al., 2012b). Support for such technologies in the past has proven both cost-effective and successful, generating high social returns on investment (Fri, 2003).

Policy can support performance advantages of innovations in niche markets

In historical transitions, cost-insensitive end-users in specific market niches have played a key role in the commercial testing, demonstration, and improvement of energy technology innovations. But in future transitions, there are few evident niches in which end-users may be willing to pay over the odds for environmental public goods. The specific niches that do exist for energy supply technologies are the result of other performance characteristics: no fuel inputs (e.g. solar PV in satellites or remote off-grid applications), quiet operation (e.g. nuclear power in submarines), and storage capacity (e.g. fuel cells for grid back-up). Efficient

end-use technologies may offer operational cost savings but may face either design trade-offs against more desirable performance attributes from the end-user's perspective such as size, power and acceleration in vehicles (e.g. Reynolds and Kandlikar, 2007; Nemet, 2014) or carry higher upfront capital requirements as in green buildings (e.g. WBCSD, 2009).

Policies to create and protect market niches are therefore important (Schot and Geels, 2008). Military and space applications are an obvious example of niche creation through direct procurement. By definition or by design, remoteness and reliability can support decentralized energy systems. Switzerland, for example, has mandated 100 percent reliability in the backup systems for its communication networks, creating a price insensitive niche market for off-grid supply. The US\$12,000 per kW (in 2003\$) of steam engines when first introduced are in the same ballpark as the current costs of fuel cells, which are often classified as prohibitively expensive. Niches shield new technologies from full commercial competition while experience builds, learning improves performance and reduces cost, economies of scale are captured, complementary infrastructure is expanded, and efficiency increases.

These market niche approaches sit in contrast to more conventional "market pull" efforts, which support the widespread diffusion of innovations into densely occupied and cost-competitive market segments. This alternative route for driving down units costs as a function of cumulative experience by subsidizing production ("buying down the learning curve") or underwriting sales with risk or price guarantees, sidelines the evidence from history. Even success stories like that of Brazilian ethanol suggests this route may take many decades rather than years (Meyer et al., 2014).

Innovation policy needs to be stable, credible, aligned, and well-timed

Technological change is described by long-term constants of change and the leverage of near-term decisions over path-dependent futures. Consequently, 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 too often been characterized by volatility, changes in emphasis, and a lack of clarity. The debilitating consequences on innovation outcomes of stop-go policies is illustrated well by the wind and solar water heater programs in the United States through the

1980s, as well as the large-scale US efforts to develop alternative liquid fuels (Grubler et al., 2012). In future scenarios, a lack of credibility in international climate policy imposes significant costs on climate stabilization as investment decisions in energy plant and infrastructure become increasingly myopic (Bosetti and Victor, 2011). Managing expectations among the many innovation system actors is important. Ill-timed policies or stop-start policies if short-term objectives are not being met can undermine long-term innovation investments.

Alongside stability and credibility, innovation policy needs to be aligned. Policies to support innovations through early research and development can be undermined by an absence of support for their demonstration to potential investors and their subsequent deployment in potential markets. Thus technology policies need to adopt an integrated approach, stimulating both the development as well as the adoption of energy technologies. R&D initiatives without simultaneously incentivizing users to adopt the outcomes of innovation efforts (e.g. promoting energy efficient building designs without strengthened building codes, or CCS development without a price on carbon) risk not only being ineffective but also preclude the market feedbacks and learning that are critical for continued improvements in the technologies. Incentives can also be perverse. Static innovation incentives can undermine continual improvement. By comparison, dynamic technology standards can spur a continuous innovation “recharge,” as illustrated by the Japanese “Top Runner Program” for energy efficient appliances (Kimura 2014).

Aligned policies are also systemic policies. The innovation system comprises not just technologies and infrastructures but also actors, networks, and institutions. The creation of a viable and successful Brazilian ethanol industry through consistent policy support over several decades ranging from agricultural R&D, guaranteed ethanol purchase prices, fuel distribution infrastructures, as well as vehicle manufacturing (initially ethanol only and more recently multi-fuel “flex fuel” vehicles) is a good example of a stable, aligned, and systemic technology framework (Meyer et al., 2014).

Technology policies supporting market deployment can support a build out of numbers of units, or an up-scaling of unit capacity, or both. Policies to support growth in numbers of units might diversify market niches, promote modularity, or advance flexibility and adaptability to different contexts. Policies to support up-scaling might cofund demonstration projects and field trials, streamline the licensing process for retrofits (or support leasing business models for process technologies), or provide testing infrastructure. Timing, however, is important.

The importance historically of a formative phase of building out large numbers of units over an often extended period strikes a cautionary note for policies acting too early in a technology's commercial life cycle to support up-scaling.

Conclusions

Table 3.3 illustrates how different policy mechanisms may generate innovation and diffusion outcomes over different timescales. The potential suggested by Table 3.3 for inducing a low-carbon technological future needs tempering by the lessons of historical transitions. The current dominance of fossil fuels relates to their relative cost and performance advantages over low-carbon technologies (Smil, 2003). Initially, performance advantages dominated in historical energy transitions. End-users in specific market niches were willing to pay handsomely for flexibility, convenience, safety, versatility, substitutability, or cleanliness (at the point of use). Other than in some specific contexts, there are no such obvious performance advantages for low-carbon technologies, and in terms of power density and intermittency, renewable energy technologies are unattractive (Smil, 2008). Neither do low-carbon technologies offer cost advantages under current institutional arrangements. Here, fossil fuel resource constraints may work alongside externality pricing to make renewables more cost-competitive, yet resource availability (competing land uses) may also act as constraints for the deployment of renewables at scale.

The fossil fuel present arrived through a centennial process of incrementally innovating and—borrowing from Newton—“standing on the shoulders of giants” (Acemoglu et al., 2009). The magnitude of decarbonization required in the future affords no such gradualism. Moreover, a transition away from the energy infrastructures and institutions that have coevolved with fossil fuels over the last century carries its own costs and inertias (Unruh, 2000). Policy-induced up-scaling and deployment without lengthy formative periods of experimentation and testing implies additional risks (Wilson, 2012).

Political efforts to overcome vested interests will be important together with strong public investment in infrastructure development. Government regulation with civil society support to create and protect niche markets will be critical (Schot and Geels, 2008). But it is otherwise unclear whether a *policy-driven* rather than *policy-enabled* energy transition in the coming decades will be institutionally similar to the historical transitions driven by better, and then cheaper, energy services (Fouquet, 2010).

Table 3.3 Illustrative technology innovation and diffusion policy approaches matched to realistic timescales of outcomes

Timescale of Policy Outcome	Examples of Policy Approaches
Short-term (e.g. to 2020) capital stock additions (some)	<ul style="list-style-type: none"> • create, stimulate, and protect market niches around performance advantages of new technologies • deploy market-ready clean technologies through credible and stable incentive mechanisms • develop long-term technology innovation and market deployment strategies in a consultative process, creating “joint expectations” • reduce/eliminate direct or indirect subsidies for technologies not aligned to long-term technology strategy and portfolios • use “sunset” clauses for planned retirement of depreciated inefficient or polluting capital vintages
Medium-term (e.g. to 2050) capital stock additions (all), capital stock turnover (some)	<ul style="list-style-type: none"> • expand public and private R&D investments stably in diversified portfolios designed to manage risks and corresponding with end-use needs • underwrite many, granular and multifarious technology demonstration and learning cycles • support disclosure, interaction, and feedback between innovation system actors • engage in multiple international collaborative projects to further knowledge dissemination and technology spillovers • align innovation and market deployment incentives (e.g. recycling externality pricing revenues back to R&D and market deployment incentives)
Long-term (e.g. to 2100) capital stock additions (all), capital stock turnover (all)	<ul style="list-style-type: none"> • set long-term targets with appropriate monitoring and enforcement mechanisms to sustain shared technology expectations • maintain portfolio diversity to prevent premature lock-in or standardization • set technology standards for the gradual phase out of “bridging” technologies
Throughout (present–2100)	<ul style="list-style-type: none"> • create and nurture formal and informal institutional settings for technology assessment, evaluation, portfolio design, and knowledge sharing

Notes

- 1 Tyndall Centre for Climate Change Research, University of East Anglia (Norwich, UK).
- 2 International Institute for Applied Systems Analysis (Laxenburg, Austria); School of Forestry, Yale University (New Haven, Connecticut, United States).
- 3 The joule is a derived unit of energy in the International System of Units. The gigajoule (GJ) is equivalent to 1 billion (10^9) joules and the potential energy generated by 160 liters of oil when burned is estimated at 6 GJ.

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