International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 342
Fax: +43 2236 71313
E-mail: publications@iiasa.ac.at
Web: www.iiasa.ac.at

Interim Report **IR-11-001**

Lessons from the history of technology and global change for the emerging clean technology cluster

Charlie Wilson (charliewilson.academic@gmail.com)
Arnulf Grubler (gruebler@iiasa.ac.at)

Approved by

Detlof von Winterfeldt
Director

January 2011

Contents

Abstract

This paper provides a synthesis review of current knowledge on patterns, drivers, and rates of change in historical energy technology transitions. Next to a historical review, also a synthesis of the corresponding futures scenario literature is given.

The paper concludes with a discussion of the implications for the possible emergence of a clean-technology cluster and for technology innovation policy.

Acknowledgments

This paper was written as input to the forthcoming UN World Economic and Social Survey (WESS) 2011.

We thank Rob Vos and Manuel Montes from United Nations Department of Economic and Social Affairs (UNDESA) for inviting this contribution.

Special thanks go to Alexander Roehrl and David Le Blanc for most useful and constructive feedback and comments.

About the Authors

Charlie Wilson is a Lecturer in Energy and Climate Change in the Tyndall Centre at the University of East Anglia (UK). His research interests lie at the intersection of technology, policy, behavior and decision making. After completing his PhD at the University of British Columbia (Canada) on the social and behavioral determinants of energy use, Dr. Wilson has held teaching and/or research positions at the London School of Economics (UK), Chalmers University (Sweden), and IIASA. Prior to his academic career, Dr. Wilson worked for a number of years in the private sector on renewable energy finance and climate change policy.

Arnulf Grubler first joined IIASA in 1976 to work with the Energy Systems Program; between 1979 and 1984 he was affiliated with the Resources and Environment Area. He returned to the Institute in 1986 and currently works as a Senior Research Scholar and Acting Leader of the Transitions to New Technologies Program on a part-time basis. He also holds a part-time appointment as Professor in the Field of Energy and Technology at the School of Forestry and Environmental Studies at Yale University, New Haven.

Lessons from the history of technology and global change for the emerging clean technology cluster

Charlie Wilson & Arnulf Grubler

1. Introduction

Technological change is widely recognized as the main driver of long-run economic growth (Solow 1957) and of development in general (Freeman & 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 paper is that these dichotomies cloud complex inter-dependencies. Technologies and their institutional and social settings co-evolve. Change in these different arenas is mutually dependent, mutually enhancing, mutually dampening. Regardless of these particular perspectives, all 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 the challenges ahead which include: mitigating climate change; providing universal access to modern forms of energy; ensuring secure markets and supply chains; reducing air pollution and human health impacts (GEA 2011). Meeting these challenges will require wholesale transformation for which innovation and technological change are integral. Clean technology innovations range from incremental improvements to radical breakthroughs and from technologies and infrastructure to social institutions and individual behaviors. The innovation process involves many stages from research and development ('R&D'), through incubation, demonstration, and (niche) market creation, to ultimate widespread diffusion. Feedbacks between these stages influence progress and likely success; innovation outcomes are inescapably uncertain. Innovations do not happen in isolation; inter-dependence and complexity are the rule not the exception. A narrow emphasis on particular technologies or parts of the energy system (e.g., a renewable energy supply) or technology policies that emphasize only particular innovation stages or processes (e.g., a 'Manhattan project' of energy R&D) is inappropriate. An approach to innovation is needed which is systemic and integrated. In the context of the energy system, this means supply and demand, laboratory and market, input and output, business and policy.

This paper reviews historical evidence on the dynamics and characteristics of technological change and diffusion, focusing on the energy system (Section 2). Alongside this historical emphasis is an analysis of how technological change is represented in future scenarios (Section 3). Both sources of evidence will be 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 (Section 4).

2. Historical dynamics of technology & global change

2.1. Historical energy transitions in industrialized and developing countries

Global energy use has grown by a factor of 25 over the past 200 years. This increase, far in excess of the roughly 7-fold increase in population over the same period, constitutes the first major energy transition, a 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. Both quantitative and qualitative transitions have been driven to a large extent by technological change. And both are far from complete. Some two billion people continue to rely on traditional patterns of energy use: non-commercial biomass as the principal source of energy; no access to electricity; and levels of energy use characteristic of pre-industrial societies (some 20-50 GJ primary energy/capita that delivers only some 2-5 GJ/capita in terms of useful energy services due to the inefficiency of traditional biomass use).

Figure 1 illustrates the historical energy transition in terms of energy use quantities for industrialized and developing countries - the minimum degree of representation of spatial heterogeneity. Over the entire 20th century, energy use in industrialized countries has been persistently *above* the levels seen in developing countries despite accounting (currently) for only around 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 (276 EJ of a global total 530 EJ in 2009). Representative scenarios suggest that by 2100, developing countries could account for between two thirds to three quarters of total global energy use, anywhere from 300 to 2000 EJ.

Although energy use has increased in both industrialized and developing countries over the past 200 years, the underlying driving forces have been radically different as shown in Figure 2. Historically, increasing energy use has been only 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 at least - only a linear increase in energy use. Only since 1975 (and especially since 2000) has the increasing *per capita* energy use characteristic of industrialized countries added significantly to the impact of population growth on total energy demand in developing countries. These historical differences are explained by the nature of the industrialization process and the defining characteristic of industrialized countries—income growth, fuelled by technological change, leading to affluence and high levels of material (and energy) consumption. Indeed, disparities in the growth of energy use between industrialized and developing countries roughly mirror disparities in the growth of income as the two variables are linked. The historical record suggests that many developing countries are now at the beginning of a long, decadal development path during which – setbacks notwithstanding – levels of energy use will increase as incomes rise. Conversely, in many (post-)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 as a lasting impact of the 'energy crises' in the 1970s.

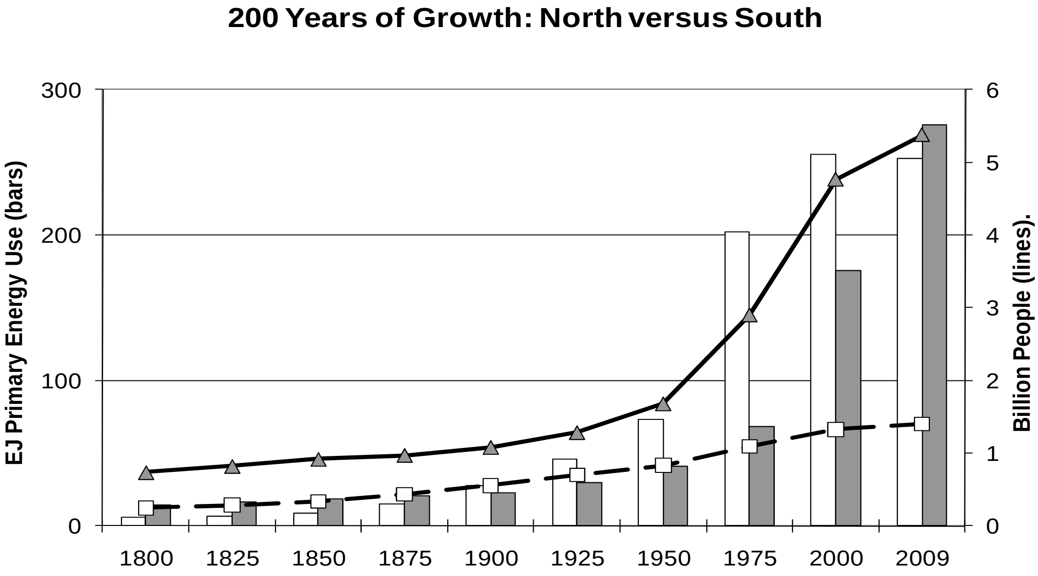


Figure 1. Growth in Energy Use and Population (1800-2009).
Notes: Primary energy use in EJ including non-commercial sources (columns, left-hand axis) and population in billions (lines, right-hand axis) for industrialised countries (white columns & markers) and developing countries (grey columns & markers) following UNFCCC distinctions between Annex 1 (industrialised) and non-Annex 1 (developing) countries. Data from: (Grubler 2008) updated using (BP 2010; IEA 2010). Data prior to 1950 are estimates.

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. The growth experiences of one country cannot necessarily be used to infer those of another. 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' helps to explain these differences in energy use patterns among countries and regions even at comparable levels of income. Path dependency is discussed further in Section 2.5. As an illustrative example, initial differences in resource endowments or social configurations may become perpetuated and magnified over time by differences in economic activity, technology adoption rates, consumption patterns and infrastructure. These shape and constrain the nature and direction of technological change, further reinforcing the influence of past on future, and so the observed divergence between countries.

What is clear, however, is that the challenges of a sustainable energy transition will have to be addressed across all regions, and 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 major challenge for developing countries is how to move from this historical sequence to an integrated, concurrent approach dictated by the sheer magnitude of numbers as well as 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 for a sustainable energy transition are substantial (GEA 2011). Technology and technology policy will be a key element, much as technological change has played a critical role in historical energy transitions.

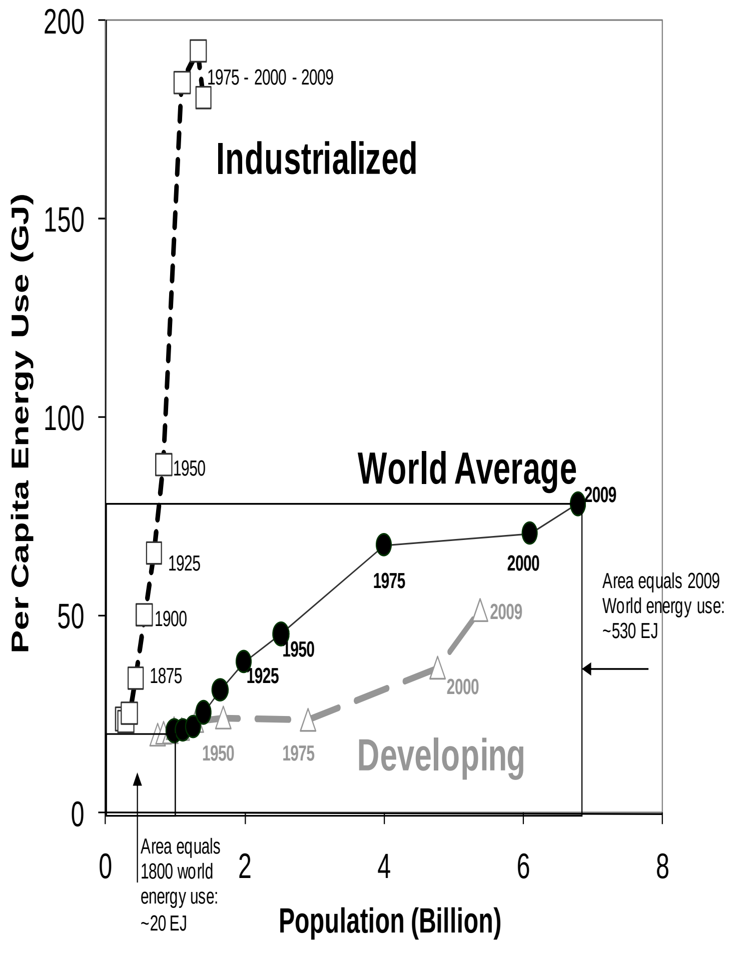


Figure 2. Growth in Per Capita Energy Use and Population (1800-2009).
Notes: Population in billions (x-axis) vs. per capita energy use in GJ including non-commercial sources (y-axis) in trajectories of 25 year intervals from 1800-2000 and updated to 2009 for industrialised countries (squares) and developing countries (triangles). Areas of squares connecting x-axis and y-axis coordinates (illustrated for 1800 & 2009) are proportional to total energy use. Data from: (Grubler 2008) updated using (BP 2010; IEA 2010). Data prior to 1950 are estimates.

2.2. Historical energy technology transitions

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 pre-industrial 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 fully: between the late 18th century until the 1920s when coal-based steam power constituted well 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). As noted earlier, 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 (GEA 2011).

Both these historical energy technology transitions are characterized by various ‘grand’ patterns of technological change, each of which is discussed in depth 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.

2.3. End-use applications drive supply-side transformations

The history of past energy transitions highlights the critical importance of end-use technologies, consumers and the demand for energy services such as heating, lighting, mobility and power. Historically, energy supply has followed energy demand in technology applications, and end-use markets have been the most important outlets for new energy technologies. 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, 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.

Stationary steam engines in industry and agriculture, and mobile steam engines on ships and locomotives, were by far the dominant markets for this new technology. Small by comparison were the coal mines, and coking and town gas plants, that represented the emerging cluster of a coal supply technology cluster based on complex chemistry and associated conversion technologies. In the case of electricity, it is no coincidence that 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 also dwarf their supply-side counterparts. Table 1 summarizes the evolution of energy technologies in the US since 1850. US data are used simply because of more reliable historical records than elsewhere. Although energy technologies are many and diverse, using a simple common metric such as installed power capacity data (here expressed in GW or 10^9 Watts) allows like for like comparisons. Table 1 differentiates between stationary and mobile end-use applications, as well as the supply-side energy sector applications, and further distinguishes three broad energy conversion categories: thermal (boilers, furnaces), mechanical (prime movers like steam engines or electric turbine-generators), and electrical (appliances, lights, and other specific, non-substitutable electricity uses like radios, TVs and computers).

Table 1. Installed Capacity of Energy Technologies in the US (1850-2000).
Data from: (US_DoC 1975; US_DoC 2007) apart from italicised numbers which are author's first order estimates. For details, see (Grubler et al. 2011).

Application	**Energy Conversion Category**	**Installed Capacity (GW)**			
		1850	**1900**	**1950**	**2000**
stationary end-use	thermal (furnaces/boilers)	*300*	*900*	*1,900*	*2,700*
	mechanical (prime movers)	1	10	70	300
	electrical (drives, appliances)	*0*	*20*	*200*	*2,200*
mobile end-use	animals/ships/trains/aircraft	5	30	120	260
	Automobiles	0	0	3,300	25,000
stationary supply	boilers (power plants)	*0*	*10*	*260*	*2,600*
	mechanical (prime movers)	<1	3	70	800
TOTAL	(numbers rounded)	300	1,000	6,000	34,000

Table 1 makes clear the overwhelming and persistent dominance of end-use applications in the total installed capacity base of energy technologies. 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 US. A hundred years later, this total had grown to some 34,000 GW or 120 kW per capita, 10 times the level of 1850. This spectacular expansion has been marked by the electrification of homes and industry, and the striking 1000-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 US, exceeding the thermal capacity of electric power plants by a factor of around 10 (giving rise to bold proposals for decentralized electricity generation by fuel cell powered road vehicles when parked).

2.4. 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 particular 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 substantively 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 1 percent only, 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 (from Newcomen's atmospheric engine, to Watt's low pressure engine, to the high pressure engines that finally made railroads possible). It took another century again to reach the current steam turbine efficiency of 40 percent. The initial costs of steam engines in the mid 18th century amounted to a phenomenal US$12,000 per kW (in 2003$) (Crafts 2004). Compared to today, the economy was also a factor of 130 smaller with per capita incomes a factor of 13 smaller, 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 (which, additionally, was often not available where needed). After an extended period of experimentation and development, costs of steam engines started to come down during the mid-19th century, 100 years after their introduction. By the beginning of the 20th century, costs had fallen to below US$3,000 per KW (in 2003$).

A similar pattern of new energy technologies being adopted despite initially extremely high costs 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 14 different 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." (p6591-2, Fouquet 2010).*

The 20th century trend in private mobility seen earlier in the US capacity data exemplifies a more generic pattern. 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. In turn, this sees a dramatic increase in the quantity of the service demanded (Fouquet & Pearson 2007; Fouquet 2010). A related characteristic of energy transitions is that efficiency gains are overwhelmed by this increase in service demand and a corresponding expansion in the volume and pervasiveness of end-use technologies (Haas et al. 2008).

2.5. 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 inter-related technologies; and "spillovers" or applications outside the configuration, use or sector 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 these synergies of technologies being deployed in a variety of applications and so further 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 18th 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 & Fernald 2008), although unlike steam power and electricity they do not concern the energy supply. 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 'informated' or 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 UK 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 and high sunk investment costs, but also a “congealed culture” of institutions, patterns of social organization, and behavioral routines and practices (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, from the energy intensive US to the energy efficient Japan. 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, both by end-users and within the energy supply.

2.6. 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% of all prime movers in US industry (Ausubel & 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 50 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.

So the process of technological change, from innovation to widespread diffusion, takes considerable time. But as rates of change become slower, the larger the energy system (components) affected and the more disruptive the consequences (Grubler 1996). Figure 3 summarizes the two major energy technology transitions globally: 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 percent of total primary energy use for traditional fuels (brown), coal (grey), and modern energy carriers (red). The dashed lines show coupled logistic equations describing the period 1850-1975. Evident from Figure 3 are the long periods of slow and gradual market penetration of end-use and supply technologies alongside the observed substitution of energy sources (Marchetti & Nakicenovic 1979). The turnover or displacement times first of tradition fuels and then of coal are around 130 years and 80 years respectively at the global level. Turnover times are measured here by the duration parameters of logistic diffusion and market substitution curves (the lines in Figure 3). A characteristic measure is the Δt (delta t) which is the time taken to grow from 1% to 50% or from 10% to 90% market share. The entire technology life cycle from 1% to 99% of the full market potential is therefore 2Δt.

Also visible in Figure 3 is the significant slow-down of transition dynamics since 1975 (with the model estimates for the second, post 1975 period shown as solid lines). This is largely due to the continuing role of coal for electricity generation. Although coal has a 26% share of primary energy, it directly meets only 9% of final energy use (BP 2010; IEA 2010). The vast majority of this is in the heavy metallurgical industry - the last technological testimony to the 19th century coal/steam age. This significant slow-down in the rates of structural change in energy technology systems since the mid-1970s sits uneasily with the need for an accelerated technological transition in a climate constrained world.

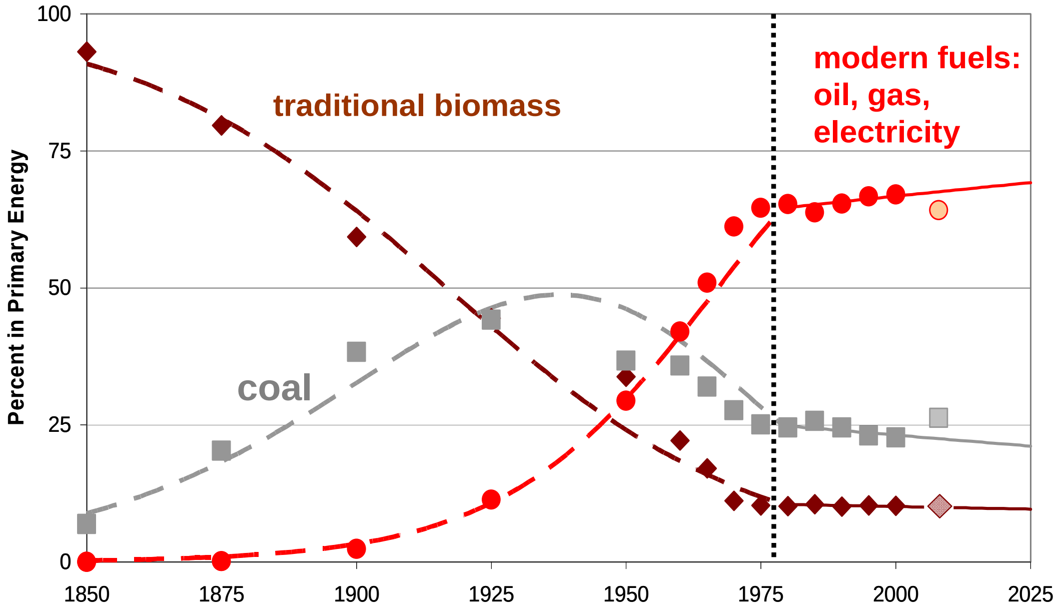


Figure 3. Two Grand Transitions in Global Energy Systems (1850-2008).
Data from: (Grubler 2008) updated for 2008 (light shaded symobls) using (BP 2010; IEA 2010). Data prior to 1950 are estimates.

The observed rates of transition in the energy system are influenced by various phenomena which, *ceteris paribus*, imply slower rates of change. These include:

i. <u>*Capital intensiveness*</u>. Investments in energy technologies are among the most capital intensive across industries, characterized by high upfront costs, a high degree of specificity of infrastructure, long payback periods, and strong exposure to financial risk (IEA 2003).

ii. <u>*Long capital stock lifetimes*</u>. Long-lived 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 high compared to other industrial equipment or consumer products (Smekens et al. 2003; Worrell & Biermans 2005). Lifetimes span several decades to a century, reducing the rate of capital turnover, and thus slowing the diffusion of new technologies particularly in developed countries where capital stock expansion is slower.

iii. *Formative periods*. Initial imperfections and high costs of new technologies imply an extended period of experimentation, learning and technology development through the cycle of innovation, specialized niche market application, and finally - if successful - pervasive adoption across many sectors, markets and countries.

iv. *Spillover effects*. Considerable time is needed for technology clustering and spillover effects to emerge, not just in inter-related technologies, but also in the organizational, institutional and social changes needed for technologies to realize their full productive potential. Using the electric dynamo as an example, David (1990) shows how the inter-relatedness between technologies, institutions and infrastructures creates lengthy 'diffusion lags' between first commercialization and pervasive adoption.

2.7. 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 iteratively tested, refined and adapted to market conditions. This has been termed the 'formative phase' of the technology's lifecycle (Jacobsson & Lauber 2006) and characterizes the early stages of commercial diffusion. The lifecycle 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'. The term 'up-scaling' is used here to mean 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. In general terms, economies of scale describe reductions in average unit costs as the size of individual units ('unit' scale economies) or the volume of total production ('manufacturing' scale economies) increase over the long run, i.e., assuming all production inputs are variable.

Figure 4 shows the 'up-scaling' dynamic for a range of energy technologies that have diffused over the course of the 20th century. Each line describes the changes over time of the average capacity in 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 5 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 in terms of technological units. 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 in terms of the whole industry.

Figure 5 shows a clear overall sequence. For the first 50 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 20 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 1000 MW; average unit capacities to around 250 MW. Over the course of the next 30 years, unit capacities vary somewhat around these saturation levels, but sustained growth in cumulative total capacity is driven again by increasing numbers of units.

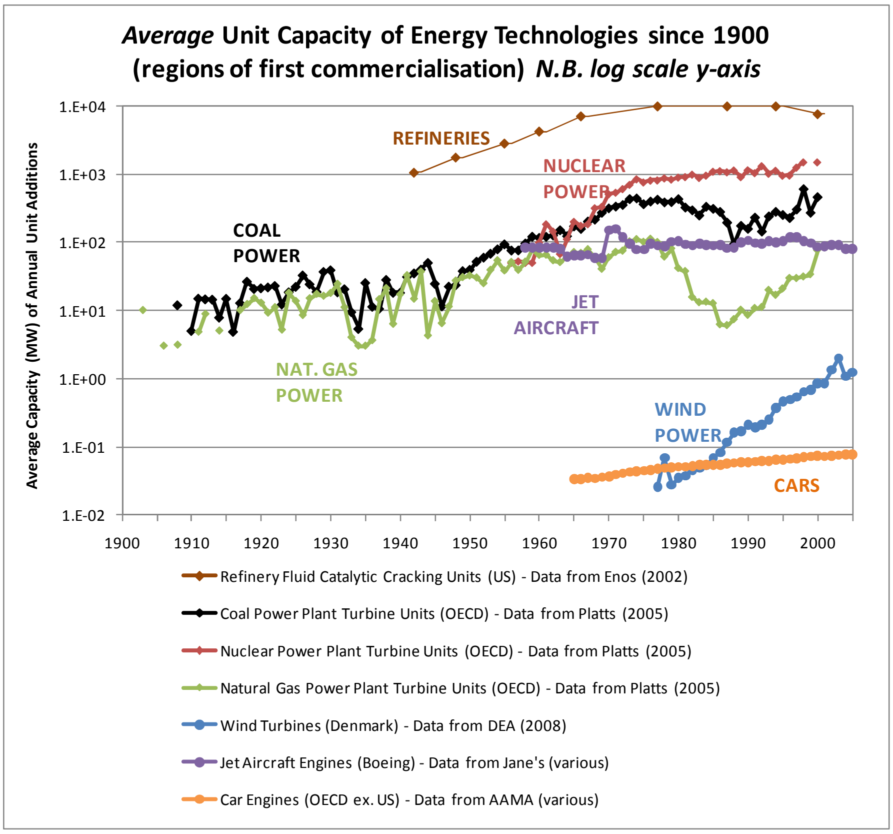


Figure 4. Up-scaling in Selected Energy Technologies Since 1900.
Notes: Lines show average capacity of new units in MW on log-scale y-axis. Data from: See graph legend and (Wilson forthcoming) for more details.

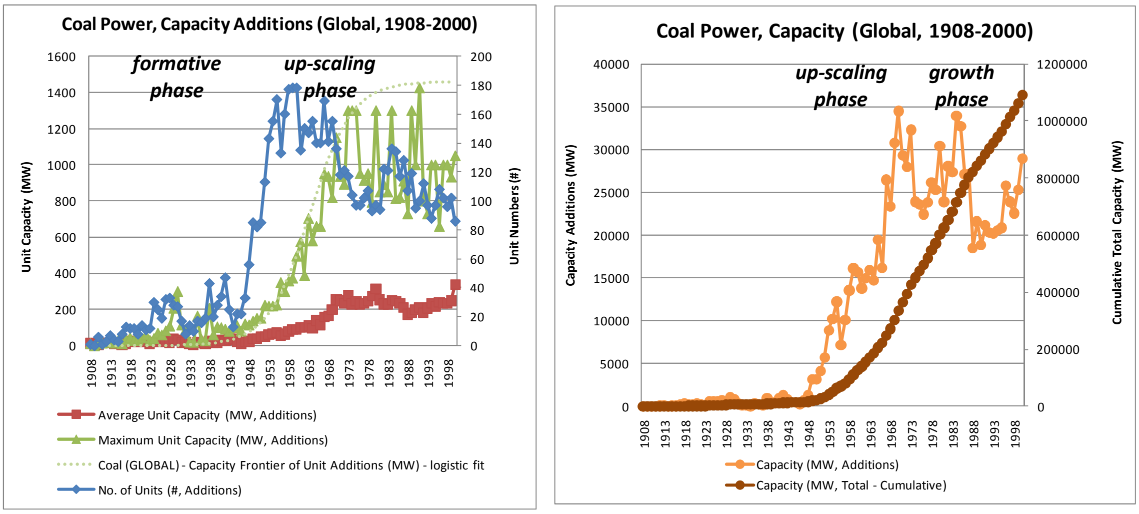


Figure 5. Growth in Coal Power Capacity Globally Since 1900.
Notes: Left-hand graph shows unit capacities & numbers; right-hand graph shows capacity additions & cumulative total capacity. Data from: (Platts 2005)**;** see (Wilson forthcoming-b) for details.

The sequence observed in the expansion of coal power capacity is broadly consistent across all the eight energy technologies analyzed (see Figure 4) and in all regions as well as globally. This sequence in the growth dynamic of energy technologies is summarized as:

i. a '<u>formative phase</u>' of many smaller-scale units with only small increases in unit capacity;

ii. an '<u>up-scaling phase</u>' of large increases in unit capacities, particularly at the scale frontier, concurrent with an increase in numbers of units;

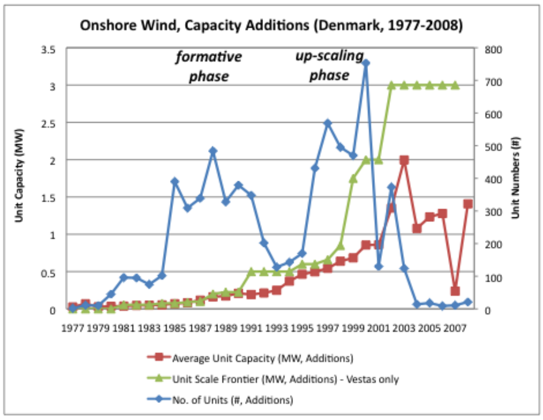
iii. a '<u>growth phase</u>' of large numbers of units at larger unit capacities.

2.7.1. The formative phase and the role of experimentation

The formative phase of a technology's lifecycle describes the critical period between the early development of an innovation, and widespread commercial diffusion sustained by positive feedbacks or 'cumulative causation' (Jacobsson & Bergek 2004). During the formative phase, technologies are repeatedly and iteratively tested, modified, improved, reduced in cost, and adapted to market demands. As noted earlier, this often takes place in market niches which offer some protection from competitive pressures (Kemp et al. 1998). Dosi (1988) includes experimentation as one of five integral characteristics of innovation along with uncertainty, scientific knowledge, complexity, and accumulation. Simply put, experimentation is "*an iterative process of understanding what doesn't work and what does*", encompassing both success and failure (p2, Thomke 2003). Experimentation allows technologies to be "*debugged*" through a process of "*designing-by-experience*" (Ruttan 2001). This is particularly important for radical technologies introducing into the market non-incremental changes in design or service provision

(Utterback 1994; Suarez 2004). Entrepreneurialism to conduct "*risky experiments necessary to cope with the large uncertainties that follow from new combinations of technological knowledge, applications and markets*" is one of the key functions of innovation systems (p422, Hekkert et al. 2007). In this vein, experimentation is a means of "articulating" the designs, markets, policies, and end-user demands of a technology (Kemp et al. 1998).

Figure 6 compares the growth dynamics of wind power in the same way as for coal power in Figure 5. The data are for onshore wind plants in Denmark, the pioneer market for widespread wind power commercialization. Complete time series data on maximum unit capacities are not available, but the commercial history of new turbine models developed by Vestas, the leading Danish (and global) manufacturer, is an approximation of the unit scale frontier. The resulting up-scaling of turbines is still far from saturation, particularly in the offshore segment for which 5MW and larger unit capacities are envisaged (GWEC 2008).



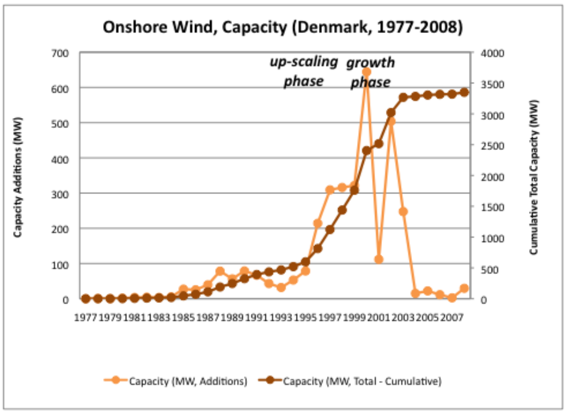


Figure 6. Growth in Onshore Wind Capacity in Denmark Since 1977.
Data from: (Danish_Energy_Agency 2008); see (Wilson forthcoming-b) for details.

Wind power is an interesting example in this context because, like coal power, the availability of unit scale economies level might be expected to drive rapid up-scaling. Specifically, larger turbines allow longer blades with more than proportional increases in power output, and the further benefit of stronger, more laminar winds at higher hub heights. Despite, this economic incentive for up-scaling, Figure 6 is notable for the formative phase from the late 1970s to the early 1990s characterized by the build out of many units of a relatively small and fairly constant unit size (though the first power generating wind turbines date back as far as the 19th century). This formative phase preceded the up-scaling of unit capacities through the late 1990s and early 2000s. In contrast, countries like Germany, Sweden, and Netherlands placed early emphasis on rapidly increasing turbine capacities to capture unit scale economies. In Sweden, for example, early government R&D emphasized up-scaling turbines to the 2 – 3 MW range in a context of uncertain market demand (Astrand & Neij 2006). This premature move to the up-scaling phase failed to build an enduring industry (relative to the Danish case) (Meyer 2007). As Heymann (1998) puts it: "*The problems in wind technology development [in Germany and the US] demonstrate that the testing, design* *improvement, and maturation of complex technologies require much practical experimentation and at least as much time, money, and effort as do the initial design and construction"* (p667). This is also consistent with the finding that up-scaling occurs only once the fundamental design issues and trade-offs for a technology are settled (Sahal 1985; Frenken & Leydesdorff 2000). In this way, up-scaling is part of the process by which the 'dominant design' of a technology is incrementally adapted to service different market demands as part of its widespread commercial diffusion.

Experimentation with many small-scale units contributes to a process of 'learning-by-numbers' – or building many before building big. This is illustrated further by Table 2 which compiles available data on 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% of the eventual scale frontier. This formative phase lasts decades, and sees the build out of hundreds of units. Nuclear 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 five-fold 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).

Table 2. Formative Phases of Energy Supply Technologies.
Source: (Wilson forthcoming-b).

Technology	Initial Market	First Commercial Capacity Installed	10% of Saturation Capacity 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 (1940s*)	1963	10 years, 25 units
Wind Power	Denmark	1970s (1880s*)	1987	15-100 years, >1400 units
*Refineries***	*US*	*1860s-1870s*	*(1948 - average capacity only)*	*(80-90 years, >500 units?**)*

* First nuclear installations on submarines date to 1940s; 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.

Finally, it is important to note that the knowledge generated and experience accumulated in the formative phase is neither automatic nor autonomous. In the Danish case, learning was facilitated by efforts to ensure experiences fed back into subsequent designs through relationships between industry actors supported by public investments in, for example, testing infrastructure (Garud & Karnoe 2003). This policy-supported process of collective learning was absent in other countries which subsequently failed to develop a viable domestic technological capability and industry (Neij & Andersen forthcoming).

2.7.2. The up-scaling phase and the importance of market niches

Although the basic sequence from formative phase to up-scaling phase to industry growth phase is generalizable, growth dynamics at the unit scale vary (see Figure 4). Two characteristics help explain differences in observed rates of up-scaling: unit scale economies, and heterogeneous markets. In general:

i. Up-scaling occurs more rapidly (and over a shorter timeframe) for technologies with strong unit scale economies: e.g., coal power, nuclear power.

ii. Up-scaling occurs less rapidly (and over a longer timeframe) for technologies servicing heterogeneous or dispersed markets: e.g., natural gas power, jet aircraft.

The potential tension between these two drivers are played out in the case of wind power as discussed above in the Danish context, but more clearly with 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 over 5 orders of magnitude, from several watts (LEDs) to over 10kW for specialized exterior lighting (metal halide lamps) (IEA 2006). By comparison, the successful commercialization of modular end-use technologies (e.g., cars, light bulbs) in the 20th century has been associated with mass production and manufacturing scale economies (at least since the model T Ford).

Conversely, 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 4). In the case of nuclear power, the unique issues associated with managing nuclear fuel cycles coupled with the need to reduce capital costs drove rapid up-scaling at the unit level from the mid-1960s to mid-1970s following a relative short formative phase (see Table 2). The build out of large capacity units continued until the late 1980s after which growth saturated. In refineries, up-scaling is concentrated during the several decades following World War II which is concurrent with the growth phase of the industry in total capacity terms (though data at the unit level are only available for the US in terms of average capacity, and only from 1940 onwards). Increases in unit capacities largely saturated by the 1970s; industry capacity expansion similarly plateaus 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 with the Boeing 707-100, up-scaling was largely completed by the introduction of the Boeing 747-100 in 1969 (see Figure 4, right-hand graph). This took place during the first 10 years of a 50 year period of continual growth in numbers of units. The recent introduction of the larger Airbus A380 has only marginally pushed up the unit scale frontier.

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

Intuitively, a technology should take longer to diffuse to a greater extent; or, as noted earlier, the more pervasive the diffusion, the slower the process (Grubler 1996). So the extent and duration of growth should be positively correlated, notwithstanding the many factors that affect growth dynamics (Grübler et al. 1999). The relationship between the extent and duration of capacity expansion is a useful descriptive measure of the overall growth dynamic of energy technologies.

Figure 7 confirms the basic intuition of the positive relationship observed historically between the extent and duration of growth for 8 different energy technologies, each in their respective initial markets. Both axes of Figure 7 show parameters from logistic functions fitted to historical time series data of cumulative total capacity in MW. The x-axis shows the turnover time which is a measure of the *duration* of growth (and inversely proportional to the rate parameter in the logistic function). The turnover time or Δt is the period a technology takes to grow from 10% to 90%, or alternatively 1% to 50%, of its final saturation level. This saturation level is shown on the y-axis as a measure of the *extent* of growth (the asymptote parameter in the logistic function). This is normalized to take into account differences in the overall size of the energy system into which different technologies diffused (so is analogous to a market share metric).

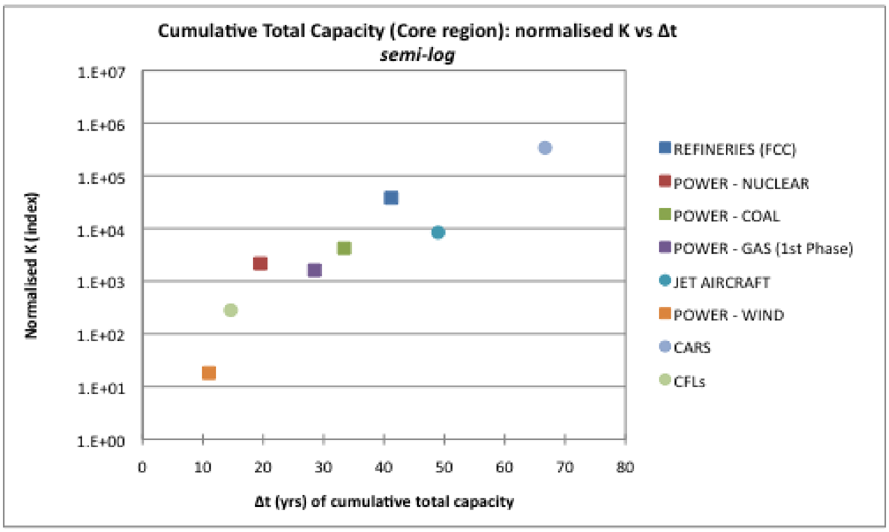


Figure 7. Relationship Between Extent and Duration of Capacity Growth Historically.

The consistency of the extent - duration relationship in Figure 7 is surprising as the end-use and supply-side technologies analyzed are of markedly different characteristics and vintage. This consistency also broadly holds across different regions as well as globally (Wilson forthcoming-a). The technology lifecycles 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 functions within the energy system. But as noted earlier, the energy system is driven by demand for useful services. The observed extent – duration relationship may simply describe the dynamics of demand growth. How rapidly and how extensively demand changes is both driven and constrained by the adaptability of end-user needs and wants, which 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.

Moreover, there are a common set of underlying mechanisms that shape innovation and the early deployment of technologies (Grubler 1998). These include knowledge generation through R&D, learning and scale effects, knowledge spillovers (and knowledge depreciation), entrepreneurialism, networks of innovation actors, demonstration activities, niche market applications, and so on (Grubler et al. 2011). A consistent extent – duration relationship for different technologies may signal limitations in the capability of these underlying mechanisms to speed up technologies through the earlier life cycle phases into the mass market. Thereafter, growth rates differ according to a technology's relative advantage, inter-dependencies with other technologies and infrastructures, the size and growth potential of niche markets (Grubler et al. 1999).

But the observed consistency in the extent – duration relationship suggests a trade-off between *how much* and *how fast* energy conversion capacity can accumulate in the energy system over time. A strongly supportive regulatory context for a technology may successfully increase a technology's growth rate but in so doing may reduce the potential extent of growth during a compressed time frame. Conversely, demand for a technology which is dispersed and only increasing gradually may imply slow growth rates, but an associated potential for growth to be more pervasive. This simple relationship between extent and duration describes the inherent inertia of a large, complex, inter-related system of technologies, institutions and end-user needs.

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

As seen earlier, there is a generalizable *temporal* pattern of technological diffusion, beginning slowly as technologies are introduced as new commercial applications which - if successful – then accelerates into a rapid growth phase before slowing and eventually saturating (Grübler et al. 1999). But 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 US & Japan (OECD 2009). The spatial diffusion of cars is another example, albeit a more complex one given the inter-dependencies of infrastructure, urban form and petroleum.

In the US as the initial market, car ownership per capita grew from the early 1900s throughout the 20th 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 US in the 1930s (p151, Grubler 1990; Schipper et al. 1992).

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). Less pervasive diffusion in later adopting markets reflects the long time constants of change in the inter-related systems of technologies, infrastructures and institutions (including patterns of end-use services and end-user behavior).

Figure 8 provides further evidence for faster rates of growth in late adopting regions for the eight energy technologies whose up-scaling dynamics were shown in Figure 4. 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 (see Section 2.6 for further details). This measure of duration is inversely related to the rate of diffusion: so, the longer the bars in Figure 8, the more prolonged, and the slower the rate of capacity expansion. In all cases for which data were available, the duration of growth decreases from initial to subsequent regions (or from core to rim to periphery). The only anomaly is the periphery region for coal power which is explained by South Africa's early exploitation of domestic coal due to restricted access to foreign energy resources in the apartheid era.

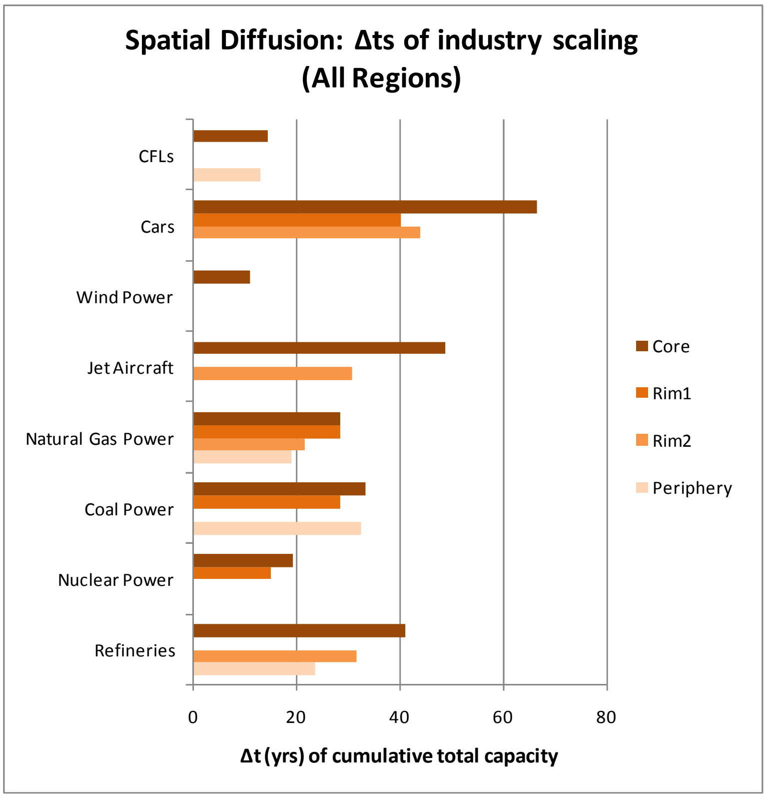


Figure 8. Spatial Diffusion of Energy Technologies Historically.
Notes: Bars show durations of growth in cumulative total capacity for eight energy technologies in 'Core', 'Rim1', 'Rim2' and 'Periphery' regions measured as the Δt in years (or turnover time) from fitted logistic functions. Regions are defined for each technology according to the corresponding spatial sequence of diffusion. 'Core' regions are typically within the OECD; 'Rim1' regions are typically former Soviet Union countries; 'Rim2' are typically Asian countries; 'Periphery' regions are typically Africa or Latin American countries. See (Wilson forthcoming-b) for further details.

3. 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 simple illustrations are provided to show the levers of technological change in transitioning towards more sustainable energy systems. Growth dynamics in future scenarios are also contrasted with the historical perspective outlined previously.

3.1. Path dependency in future technological change

The scenario taxonomy developed in the IPCC Special Report on Emissions Scenarios ('SRES') became the progenitor of a wide range of derived scenarios (Nakicenovic et al. 2000). The role of technological change is best shown by comparing scenarios within a particular SRES scenario 'family'. This holds all other salient variables constant (including population and economic growth) while varying assumptions on the direction and speed of innovation across a range of individual energy technologies. Figure 9 shows scenarios in the 'high growth' or A1 scenario family of SRES, grouped into A1FI (high emissions), A1B (medium emissions), and A1T (low emissions). Bold lines denote the 'marker' scenarios; other lines illustrate modeling uncertainties in the representation of technological change under a common set of scenario assumptions. Although none of these scenarios explicitly includes the effect of climate policies, the vast differences in terms of emission outcomes is striking. The A1FI scenario is fossil fuel intensive; the A1T scenario dominated by low carbon technologies. In both cases, as in the historical record, the long-term dynamic of change in the energy system is strongly path dependent. As a more 'balanced' scenario, A1B suggests lock-in at a differentiated regional level, for example 'clean' coal in China, but renewables in Latin America.

Comparison of the three scenarios illustrates how the dynamics of technological change give rise to consistent and stable technological combinations which crowd out competing alternatives through increasing returns to adoption. The transitions depicted in Figure 9 thus proceed along mutually exclusive, alternative technology pathways. This is not uncommon in the scenario literature. But consistent with historical experience, these contrasting technology strategies result in emissions diverging only gradually, after several decades or more. Because of the long lifetimes of power plants, refineries, buildings, and other energy infrastructure, there is insufficient capital stock turnover in the near future to allow scenarios to diverge significantly (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.

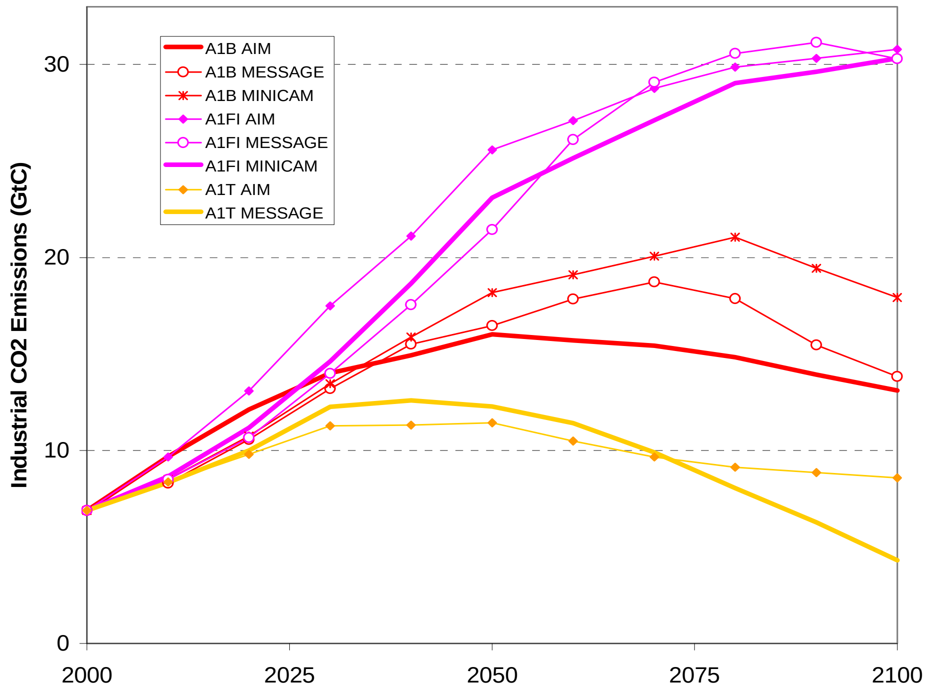


Figure 9. Industrial CO_2 Emissions in the IPCC's SRES A1 'High Growth' Scenario Family.
Source: (Nakicenovic et al. 2000).

3.2. Technology push and market pull drivers of future technological change

A survey of scenario projections for a wide range of energy supply technologies (electricity generation as well as synfuels) showed how the growth paths of individual technologies can bifurcate (Nakicenovic & Riahi 2002). As an example, Figure 10 shows scenario projections for solar photovoltaics ('PV') which distinguish over the long-term into groups of scenarios of either comparatively low or comparatively high market deployment (top panels for 2050 & 2100). This bifurcation is the result of differences in assumed technology characteristics, in particular investment costs (bottom panels for 2050 & 2100), as well as future market deployment environments including the existence and stringency of CO_2 emission constraints (colored blocks).

Figure 10 encapsulates two important findings of the scenario literature which are again borne out by historical evidence. First, the temporal dimensions of technological differentiation in energy systems are extremely long. Even the most ambitious scenarios depict no more than 60 EJ of solar PV electricity by 2050 (top left panel). Before then, and in the medium-term of 2020 or 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 CO_2 emission constraints and high investment costs, or around relatively large solar PV markets (100-180 EJ) under stringent CO_2 emission constraints and low investment cost projections (right-hand panels). To put these numbers into perspective: current global energy demand amounts to some 530 EJ, and electricity generation to some 60 EJ. So the highest growth scenarios suggest that by the end of the 21st century solar PV could generate as much as three times more electricity than is generated at present for all sources and technologies combined.

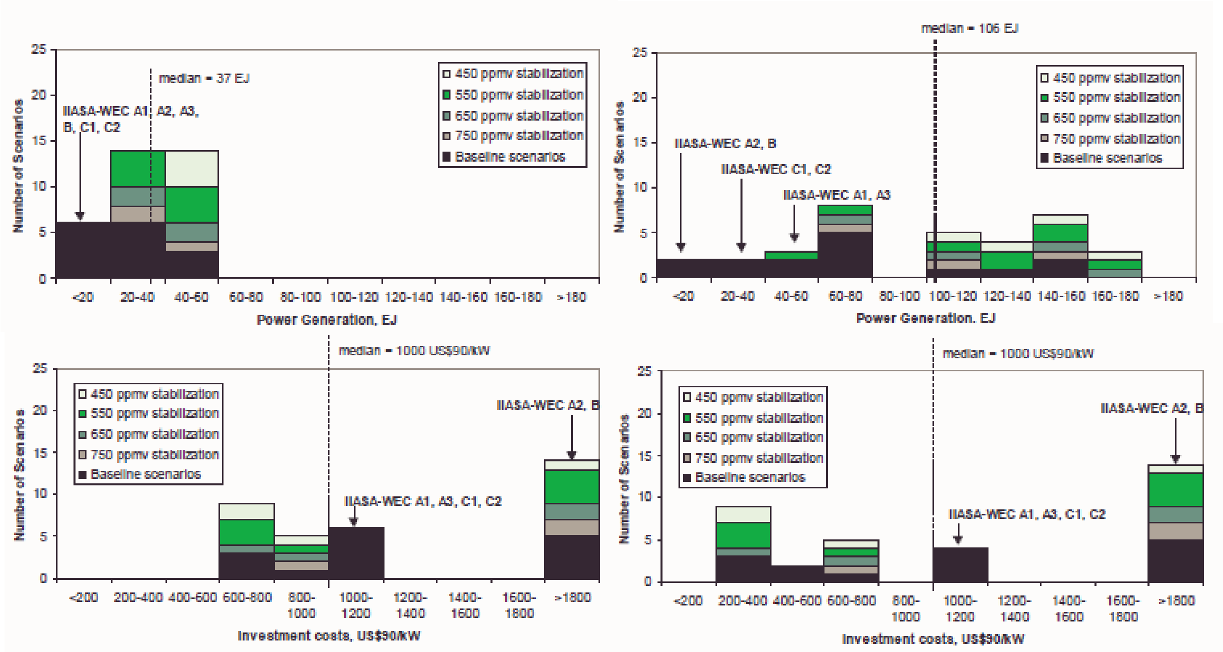


Figure 10. Scenarios of Solar PV Market Deployment As a Function of Investment Cost.

Notes: Left and right panels show 2050 & 2100 respectively. Top and bottom panels show market deployment in EJ and investment costs in \$/kW respectively. Colors show CO_2 emission constraints from 750 ppmv to 450 ppmv (shades of green) and also no constraints (in black). Source: (Nakicenovic & Riahi 2002).

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 technologies through ever-wider diffusion as CO_2 emission constraints change the relative prices of energy sources and 'pull' solar PV and other low carbon technologies into the market. The second key finding, therefore, is the necessity and complementarity of 'market pull' and 'supply push' policies to yield marked differences in long-term technology outcomes.

3.3. The supply-side emphasis of future energy transitions

The energy transitions shown in Figure 9 take place almost exclusively on the supply-side of the energy system. In stark contrast to the historical evidence, 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 & Dowlatabadi 1999; Magne et al. 2010). 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. Even in the rare efforts to model the diffusion of "general purpose" technologies, as in scenarios of a future hydrogen economy, the emphasis is on technological substitution leaving patterns of energy end-use unchanged (e.g., Barreto et al. 2003). In such scenarios, fuel cell vehicles substitute for internal combustion-based vehicles without substantive changes in the patterns of demand for private mobility by road. This is in stark contrast to the driving role of changing and novel energy end-use services seen historically (see Section 2.3).

A simple example of this asymmetrical treatment of supply- and demand-sides is provided by different modeling estimates of future investment requirements of the energy system under climate constraints. Table 3 compares the availability of investment estimates from 6 studies involving 13 major energy-economy modeling groups. As can be seen, *total* investments costs are modeled only on the supply-side. To the extent they are estimated, demand-side investment costs are expressed only in *incremental* terms (i.e., relative to a reference or baseline scenario). It is not possible, therefore, to make like-for-like comparisons of the investment implications of future technological change on both energy supply and end-use applications.

Table 3. Comparison of Supply- and Demand-side Investment Estimates.

Scenario Study	Energy system model	Supply-side investment estimates		Demand-side investment estimates	
		Total	Incremental	Total	Incremental
(Nakicenovic & Rogner 1996)	MESSAGE	yes	yes	no	no
(Hanson & Laitner 2006)	AMIGA	no	yes	no	yes
(IEA 2009b)	IEA World Energy	yes	yes	no	yes
(Luderer et al. 2009)***	IMACLIM, REMIND, WITCH	yes	yes	no	no
(van Vuuren et al. 2009)***	AIM, E3MG, ENV-Linkages, IMAGE, MESSAGE, WorldScan	no	yes	no	yes[b]
(Edenhofer et al. 2010)***	E3MG, IMAGE, MERGE, POLES, REMIND	no	no[b,c]	no	no[b,c]

(a) Inter-model comparison studies.
(b) Non-specific, or aggregated economy-wide estimates, rather than estimates disaggregated to specific technologies or sectors.
(c) Incremental costs expressed as % losses in GDP.

There are two main reasons for the relatively poor model representations of future technological change in end-use technologies: data, and dispersion. First, there is an extreme paucity of end-use specific data as energy statistics are framed through the lens of economic activities and sectors. Whereas supply-side technologies are manifestly part of 'the energy system', end-use technologies are classified under different industrial and consumer goods markets (Nakicenovic & Rogner 1996). And whereas energy provision or conversion tends to be the primary purpose of supply-side technologies, it tends to be – from the end-user's perspective - an incidental attribute of technologies whose primary purpose is to provide useful services such as heating, lighting and mobility. 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 in number. With respect to building technologies, for example, the IPCC authors note that: "*in the vast majority of countries detailed end-use data is poorly collected or reported publicly, making analyses and policy recommendations insufficiently robust ...* " (p437, Metz et al. 2007).

The second reason for the asymmetric treatment of demand-side technological change is that it is extremely challenging to derive plausible and consistent scenario assumptions on the evolution of an extremely large number of energy end-use applications - from new transport and communication technologies, to manufacturing innovations and consumer appliances. Moreover, the modeling tools available to quantitatively enrich the scenarios are less detailed on the demand-side (Hanaoka et al. 2009). 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).

This has important implications as it cause scenarios to diverge from historical experience by downplaying the driving role of changing patterns of end-use services and technologies. A comparative review of 'bottom-up' or technologically-explicit energy system models with 'top-down' macroeconomic models found that the former privileged supply-side decarbonization to a greater extent: *"A likely explanation is that energy system models are relatively rich in technologies included in energy supply and thus see considerable options to reduce emissions" (p5133, van Vuuren et al. 2009).*

This influence of model structure on model outcomes is similarly noted in a recent inter-model comparison of stringent climate stabilization targets, demonstrating that model outcomes are "*a function principally of each model's assumptions about the available technologies, learning rates, and resource prices*" (p26, Edenhofer et al. 2010). Explaining the dominance of reductions in carbon intensity over energy intensity (or supply-side change over demand-use change), the authors note 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)*" (p28). Of the five models compared, the one with the most detailed representation of end-use technologies (the POLES model) finds "*energy efficiency and end-use technologies constitute first rank options to cope with severe climate constraints*" (p58, Kitous et al. 2010). 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.

Another recent study of energy technology portfolios in a large ensemble of climate stabilization scenarios found energy efficiency improvements invariably accounted for at least 50% of all emission reductions on a cumulative basis (compared to hypothetical baselines that hold technological change constant) (Grubler & Riahi 2010). That end-use technologies and services constituted the single most important long-term emissions reduction option is in line with historical patterns but in stark contrast to the supply-side emphasis of public innovation investments. This is discussed further below in Section 4.3.

3.4. Comparing scenario technology projections with the historical record

Aside from this over-emphasis on supply-side technological change, are the technology growth dynamics in future scenarios consistent with historical experience? Or, more specifically, are the rates, durations and extents of growth in line with what has been observed in the energy system historically? One way to answer this question is to use the extent - duration relationship observed historically as described in Figure 7. The same two parameters representing the extent of growth and the duration of growth can be plotted for scenario projections of individual technologies. This is shown in Figure 11 (left-hand graph) for 6 energy technologies in 3 different growth scenarios (or scenario families) each described by a baseline and various increasingly stringent emission constraints (down to 480 ppmv CO_2-equivalent concentration by 2100). As with the historical data, the extent – duration relationships seen in Figure 11 (left-hand graph) are broadly consistent across the different technologies. The particular technology growth projections used were generated by the MESSAGE energy system model as part of an integrated assessment study of climate stabilization targets (Riahi et al. 2007). However, cumulative total capacity data were only available for certain electricity generation technologies. This limited the scenario analysis to: nuclear, natural gas, coal with carbon capture and storage (CCS), all fossil CCS, wind, and solar PV (centralized & decentralized). (See Section 3.3 for a discussion of why scenario models are less detailed in terms of end-use technologies).

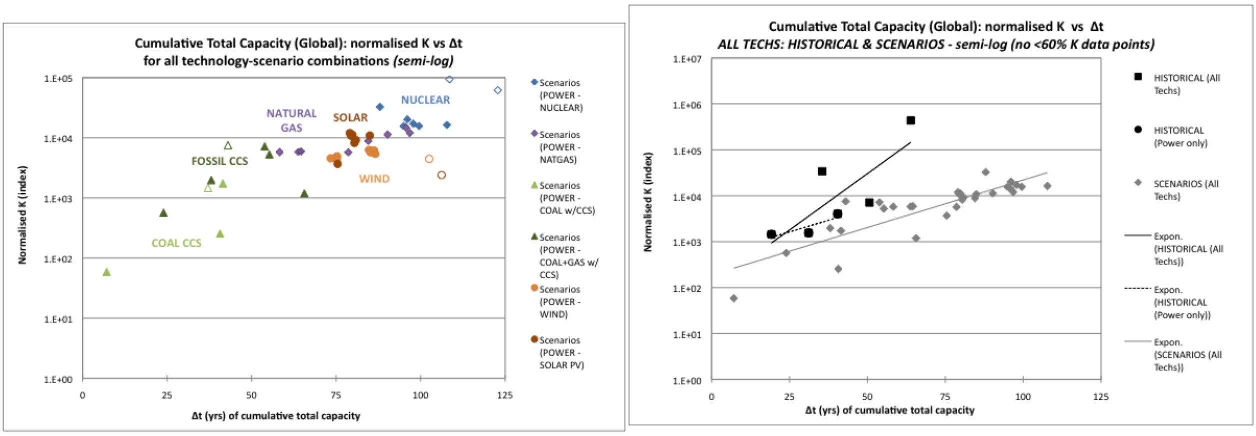


Figure 11. Relationship Between Extent and Duration of Capacity Growth in Scenarios.
Notes: Left-hand graph shows scenarios; right-hand graph compares scenarios to historical evidence.

The right-hand graph of Figure 11 shows the same scenario data points (grey diamonds) but alongside the historical data points (black squares) representing capacity growth in 8 different energy technologies (see Figure 7). Also included are exponential best fit lines for the two data series, and also for a sub-set of the historical data representing only power generation technologies (dotted black line). The implication of Figure 11 (right-hand graph) is that the scenario projections of energy technology growth appear generally more conservative than the historical record suggests possible. In other words, a longer duration of growth is required to reach a given extent of growth. With the exception of some of the low CCS data points, all the scenario data points lie below and to the right of the observed historical trend.

At first glance, it is relatively straightforward to explain this pattern: the durations of growth in the scenarios are much longer (data points further right in Figure 11). But then why is this growth not to a greater extent (data points further up)? There are various possibilities. One is that the observed differences are in fact an artifact of the analysis. The consistent historical relationship between extents and durations of growth is based on a small number of data points (solid black line). Moreover, comparing scenario data on *electricity generation* technologies with historical data on *energy* technologies more generally may be inappropriate. Using only historical electricity generation technologies as the comparator (the dotted black line) substantively reduces the apparent conservatism.

Although these explanations cannot be ruled out, another possibility is that the energy system models used to describe scenarios quantitatively are set up conservatively with respect to the potential for long-term technological change. As an example, models such as MESSAGE use market penetration constraints on technology deployment to prevent dramatic changes in model output as input parameters vary (Grubler & Messner 1996). Although these constraints are based on observed trends and realistic extrapolations, it is possible that over the centennial timescales of the scenarios they are overly conservative. This is discussed further in (Wilson forthcoming-a).

4. Implications for clean technology & innovation policy

In this concluding section, some broad policy implications are drawn from the dynamics of technological change observed historically and in future scenarios, and summarized as follows:

- The demand for better, different, and cheaper energy services and their associated end-use technologies have driven supply-side transformations. Falls in the effective costs of energy service provision lead to dramatic rises in the level of energy service demand. However, energy services and end-use technologies are relatively poorly represented in scenario studies of future technological change.
- Innovations attract end-users initially through their performance advantages not lower costs. These end-users constitute market niches which are protected from full cost competition and allow learning and other processes to improve, adapt and reduce the costs of technologies as a basis for widespread diffusion. Improved environmental performance is alone insufficient to support technologies through this process unless the pricing of environmental externalities affects the cost competitiveness of the energy services provided.
- Often extended formative phases see experimentation and commercial testing of many small-scale units as a precursor to up-scaling and the capturing of available unit scale economies. Up-scaling is less pronounced in technologies which service diverse market niches.

- Spillovers, clustering, inter-dependencies and infrastructures result in strongly path dependent technological change. Exacerbated by the longevity of much energy capital stock, this means that the time constants of change in the energy system are long, measured in decades not years.
- As a consequence of this path dependency, near-term choices define long-term outcomes though divergence emerges only gradually over the short-to-medium-term as existing capital stock is retired. Both ‘technology push’ drivers such as falling costs as a result of sustained R&D investments and ‘market pull’ drivers such as externality pricing are both necessary and complementary for supporting low carbon technological change.
- There is a trade-off between the rate and the extent of capital stock expansion: faster diffusion implies less pervasive diffusion. It is unclear from the historical record whether strongly policy-induced technological change will deviate from this pattern. It is also possible that models used to project technological growth in future scenarios are overly conservative with respect to the potential for energy system transformation over centennial timescales.

4.1. Discontinuities between historical and future transitions

From the outset, it is important to emphasize that the policy-induced technological change in climate change mitigation scenarios is a major point of departure from historical energy transitions. Consequently, past transitions offer inadequate guidance on whether relying on regulation, externality pricing, and other supporting policies to drive low carbon growth will be adequate, and how it will affect rates and extents of growth. Yet the future represented in the scenarios also tends to 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.

But 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 (see Section 4.4 below). Indeed, in terms of power density and intermittency, renewable energy technologies are relatively 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 or - to borrow from Newton - “standing on the shoulders of giants” (Acemoglu et al. 2009). The magnitude of decarbonization required in the future affords no such gradualism. But Moreover, a transition away from the energy infrastructures and institutions which have co-evolved with fossil fuels over the last century or more 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 forthcoming-b).

Political efforts to overcome vested interests will be important. Together with strong public investment in infrastructure development, this has been an institutional feature of historical energy transitions which has consistently set innovator countries apart from the (relative) laggards (Moe 2010). It also seems highly likely that government regulation with civil society support to create and protect niche markets will be critical (Schot & 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).

4.2. 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 - without the benefit of hindsight - 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 5 years, having spent almost $5 billion (1980$) to reach only 10,000 barrels a day, 2% of the interim production target (Anadon & Nemet forthcoming).

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, i.e., *granular* technologies or projects are a lower drain on scarce resources, and failure has lower consequences. Indeed, risk aversion and the resulting risk premiums 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, non-commercial technologies, and deeper CO_2 emission reductions (Krey & 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' which offer initial promise. Incumbents naturally favor the technologies currently in widespread use, yet a characteristic of leading innovator countries in historical energy transitions has been a political appetite to overcome vested interests (Moe 2010). Yet 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 sub-optimal (van den Bergh et al. 2007). This creates tension between short and long-term policy targets if the former reward deployment of market-ready technologies at the expense of developing technologies with greater transformative potential (Sandén & Azar 2005). This is illustrated well by 'technology-neutral' market pull policies for renewable electricity such as the UK's Renewable Obligation during the 2000s which strongly favor 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).

4.3. Scenario analysis helps manage uncertainties

Scenarios are an important response to the uncertainty of technological change. The large-scale, energy modeling studies described in Section 3 vary the most influential technological and market uncertainties across a set of scenarios (Nakicenovic et al. 1998; Nakicenovic et al. 2000). Effort has also been made to treat technological uncertainties endogenously within models, for example using stochastic energy prices and technology costs (Krey et al. 2007) or uncertain increasing returns to scale (Gritsevskyi & Nakicenovic 2000). But the energy system models used to enrich scenario descriptions remain largely deterministic. Technologies are selected on a least cost basis under a strict set of assumptions. Under slightly different assumptions, such selections can turn out to be considerably more expensive, for example, if the technologies do not develop at projected rates or with projected cost reductions. However, scenario analysis can still 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 22 scenarios, they varied energy demand, resource constraints, the availability and cost of technologies, and also the stringency of greenhouse gas emission constraints. Grubler & 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 to uncertainty. Figure 12 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 CO_2-equivalent concentration by 2100. The top two 'mitigation wedges' show the annual GtC contributions of (supply-side) carbon intensity and (demand-side) energy intensity improvements 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.

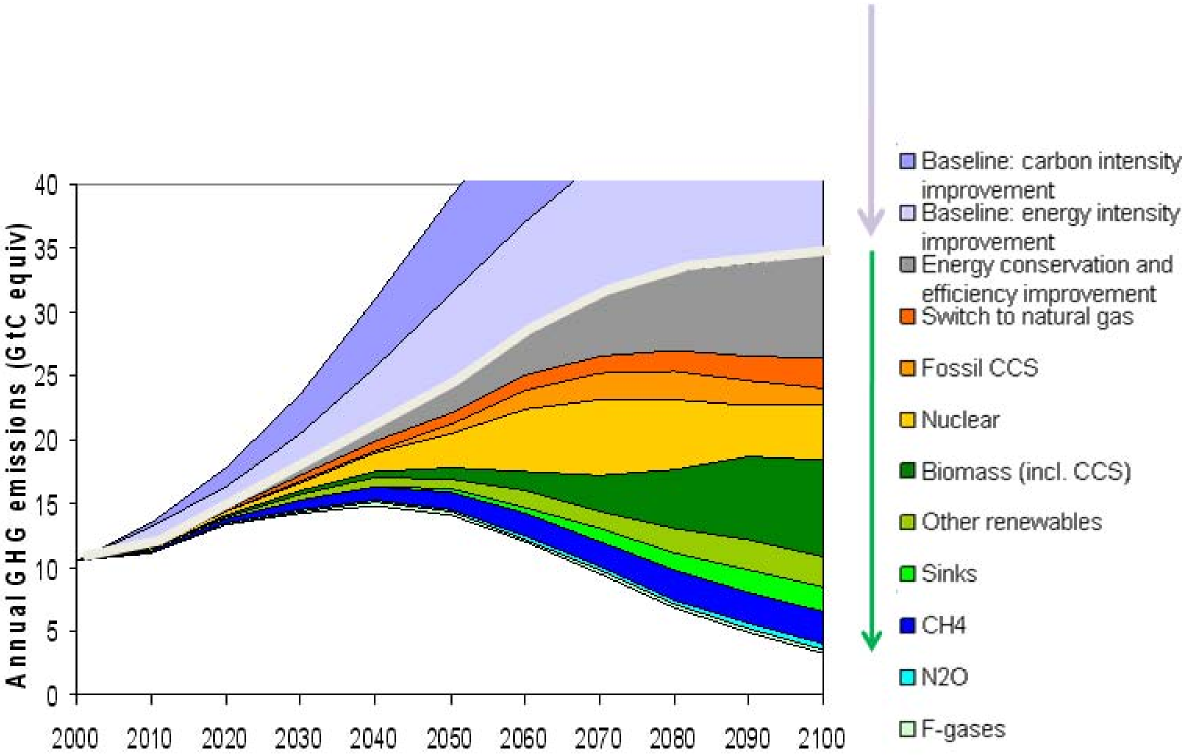


Figure 12. Climate Change Mitigation Wedges.

The mean GtC contribution of different technology options to emission reductions are summarized in Table 4 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% to cumulative emission reductions over the 21st century. This robustness is captured by the dispersion between the minima and maxima for each technology option as proposed by Riahi et al. (2007) and also shown in Table 4.

Table 4. Comparing Technology Options: Emission Reduction Contributions vs. R&D Expenditures.
Data from: (Grubler & Riahi 2010); R&D data from (IEA 2009a).

	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	**1695**	3008	**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	**2864**	5126	**100%**	*100%*

Table 4 also 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 4 show a clear mismatch between the scenario analysis of robust contributions to future emission reductions and the balance of R&D investments to-date. In particular, energy efficiency is greatly under-represented in R&D portfolios using the size of 'mitigation wedges' as a measure of future need; the reverse is true for nuclear (fission & fusion) which has dominated public R&D portfolios historically.

4.4. 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 (with modern energy supply infrastructure physically separating pollution impacts from the point of use). The specific niches which 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), storage capacity, non-polluting (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 & Kandlikar 2007; Nemet forthcoming) or carry higher upfront capital requirements as in green buildings (e.g., WBCSD 2009).

This re-emphasizes the importance of policies to create and protect substantive market niches (Schot & Geels 2008). Policy can certainly create, protect or incentivize such niches. Military and space applications are an obvious example of direct procurement. By definition or by design, remoteness and reliability respectively can support decentralized energy systems. Switzerland, for example, has mandated 100% reliability in the back-up systems for its communication networks, creating a price insensitive niche market for off-grid supply. It's interesting to note that 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 'buying down' the learning curve (driving down units costs as a function of cumulative experience) by subsidizing production 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. New technologies do not necessarily need subsidies if their decisive performance edge is attractive enough for users in specific niche markets.

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

Technological change is described by both long time 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 US through the 1980s, as well as the large-scale (but fickle) US efforts to develop alternative liquid fuels (Grubler et al. 2011). 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 & Victor 2011).

Alongside stability and credibility, innovation policy needs to be aligned. Policies to support innovations through early research and development can also be undermined by an absence of support for their demonstration to potential investors and their subsequent deployment in potential markets. Support for low carbon innovations is undermined by diffusion subsidies for carbon-intensive technologies. Static innovation incentives can undermine continual improvement. Conversely, dynamic technology standards can spur a continuous innovation ‘recharge’, as illustrated by the Japanese “Top Runner Program” for energy efficient appliances (Kimura forthcoming). 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.

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 (deSousa & Mytelka forthcoming).

Managing expectations among the many innovation system actors is also important. Stop-start policies if short-term objectives not being met can undermine long-term innovation investments. Table 5 illustrates how different policy mechanisms may generate outcomes over different timescales.

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 co-fund 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. As seen historically, the main phase of industry growth tends to follow a sequence of building out large numbers of units over an often extended period (the formative phase), then quite rapid up-scaling of unit capacities if economies of scale are available (the up-scaling phase), and finally a renewed emphasis on replicating large numbers of standardized units as the unit scale frontier is reached (the growth phase). This strikes a cautionary note for policies acting too early in a technology's commercial lifecycle to support up-scaling (as currently may be the case with carbon capture and storage demonstration projects at the scale frontier).

Table 5. Matching Policy Mechanisms to Realistic Timescales of Outcome.

Timescale of Policy Outcome	**Example of Current Policy Approach**
short-term (e.g., to 2015) capital stock additions (some)	• create, stimulate & protect market niches around performance advantages of new technologies • deploy market-ready technologies through credible and stable incentive mechanisms
medium-term (e.g., to 2030) capital stock additions (all), capital stock turnover (some)	• expand R&D investments in diversified portfolios designed to manage risk and correspond with end-use needs • underwrite many, granular and multifarious technology demonstration and learning cycles • support disclosure, interaction and feedback between innovation system actors
long-term (e.g., to 2100) capital stock additions (all), capital stock turnover (all)	• set long-term targets with appropriate monitoring and enforcement mechanisms to build and sustain shared expectations • maintain portfolio diversity to prevent premature lock-in or standardization

4.6. Innovations in end-use technologies are important and under-emphasized

Table 1 provides a powerful summary illustration of the importance of energy end-use technologies as market outlets for innovation and change, and explains also why the largest efficiency improvement potentials lie not with the energy supply but in energy end-use sectors (Grubler & Riahi 2010). Yet the allocation of public resources is mismatched to these resource needs. On the one hand, public R&D investments are heavily weighted towards 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 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, however, market or diffusion investments are weighted towards end-use technologies (Grubler et al. 2011). 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 (Grubler et al. 2011). 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 needs described above.

This points to a need to rebalance public innovation expenditure to include smaller-scale end-use technologies within technology portfolios. Support for such technologies in the past has proven both cost-effective and successful, generating high social returns on investment (Fri 2003). Technology policies need to adopt an integrated approach, stimulating both the *development* as well as the *adoption* of energy efficient end-use technologies and measures. R&D initiatives without simultaneously incentivizing consumers 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.

5. References

Acemoglu, D., P. Aghion, L. Bursztyn and D. Hemous (2009). The Environment and Directed Technical Change. Institute for International Economic Studies, Stockholm University, Stockholm, Sweden.

Anadon, L.D. and G.F. Nemet (forthcoming). The U.S. Synthetic Fuels Program: Policy consistency, flexibility, and the long term consequences of perceived failures. Energy Technology Innovation: Learning from Success and Failure. A. Grubler and C. Wilson. Cambridge, UK, CUP.

Arthur, B.W. (1989). "Competing Technologies, Increasing Returns, and Lock-In by Historical Events." The Economic Journal 99(394): 116-131.

Astrand, K. and L. Neij (2006). "An assessment of governmental wind power programmes in Sweden--using a systems approach." Energy Policy 34(3): 277-296.

Ausubel, J. and C. Marchetti (1996). "*Elektron*: Electrical Systems in Retrospect and Prospect." Daedalus 125(3): 139-169.

Ayres, R.U. (1989). Technological Transformations and Long Waves. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Azar, C. and H. Dowlatabadi (1999). "A Review of Technical Change in Assessment of Climate Policy." Annual Review of Energy and the Environment 24: 513-544.

Barreto, L., A. Makihira and K. Riahi (2003). "The hydrogen economy in the 21st century: A sustainable development scenario." International Journal of Hydrogen Energy 28(3): 267-284.

Basu, S. and J. Fernald (2008). "Information and communications technology as a general purpose technology: evidence from U.S. industry data." Economic Review: 1-15.

Bosetti, V. and D.G. Victor (2011). "Politics and Economics of Second-Best Regulation of Greenhouse Gases: The Importance of Regulatory Credibility " The Energy Journal 32(1).

BP (2010). Statistical Review of World Energy. BP, London, UK.

Crafts, N. (2004). "Steam as a general purpose technology: A growth accounting perspective." Economic Journal 114(495): 338-351.

Dahlman, C.J., B. Ross-Larson and L.E. Westphal (1987). "Managing technological development: Lessons from the newly industrializing countries." World Development 15(6): 759-775.

Danish_Energy_Agency (2008). Wind Turbine Master Data Register. Danish Energy Agency, Copenhagen, DK.

David, P.A. (1990). "The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox." The American Economic Review 80(2): 355-361.

deSousa, P.T. and L. Mytelka (forthcoming). Ethanol in Brazil. Energy Technology Innovation: Learning from Success and Failure. A. Grubler and C. Wilson. Cambridge, UK, CUP.

Devine, W.D. (1983). "From shafts to wires: Historical perspective on electrification." Journal of Economic History 43(2): 347-372.

Dosi, G. (1988). The nature of the innovative process. Technical Change and Economic Theory. G. Dosi, C. Freeman, R. Nelson, G. Silverberg and L. Soete. London, UK, Francis Pinter.

Edenhofer, O., B. Knopf, T. Barker, L. Baumstark, E. Bellevrat, B. Chateau, P. Criqui, M. Isaac, A. Kitous, S. Kypreos, M. Leimbach, K. Lessmann, B. Magné, S. Scrieciu, H. Turton and D. van Vuuren (2010). "The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs." The Energy Journal 31(Special Issue: The Economics of Low Stabilization): 11-48.

Fisher, B.S., N. Nakicenovic, K. Alfsen, J. Corfee Morlot, F. de la Chesnaye, J.-C. Hourcade, K. Jiang, M. Kainuma, E. La Rovere, A. Matysek, A. Rana, K. Riahi, R. Richels, S. Rose, D. van Vuuren and R. Warren (2007). Issues related to mitigation in the long term context. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change. B. Metz, O.R. Davidson, P.R. Bosch, R. Dave and L.A. Meyer. Cambridge, UK, Cambridge University Press.

Fouquet, R. (2010). "The slow search for solutions: Lessons from historical energy transitions by sector and service." Energy Policy 38: 6586-6596.

Fouquet, R. and P. Pearson (2007). "Seven Centuries of Energy Services: The Price and Use of Light in the United Kingdom (1300-2000)." The Energy Journal 27(1): 139-177.

Freeman, C. and C. Perez (1988). Structural crises of adjustment, business cycles and investment behavior. Technical Change and Economic Theory. G. Dosi, C. Freeman, R. Nelson, G. Silverberg and L. Soete. London, UK, Pinter: 38–66.

Frenken, K. and L. Leydesdorff (2000). "Scaling trajectories in civil aircraft (1913-1997)." Research Policy 29(3): 331-348.

Fri, R.W. (2003). "The Role of Knowledge: Technological Innovation in the Energy System." Energy Journal 24(4): 51-74.

Gallagher, K.S. (2006). "Limits to leapfrogging in energy technologies? Evidence from the Chinese automobile industry." Energy Policy 34(4): 383-394.

Garud, R. and P. Karnoe (2003). "Bricolage versus breakthrough: distributed and embedded agency in technology entrepreneurship." Research Policy 32(2): 277-300.

GEA (2011). The Global Energy Assessment. Cambridge, UK, Cambridge University Press.

Gritsevskyi, A. and N. Nakicenovic (2000). "Modeling uncertainty of induced technological change." Energy Policy 28: 907-921.

Grubler, A. (1990). The Rise and Fall of Infrastructures, Dynamics of Evolution and Technological Change in Transport. Heidelberg, Germany, Physica-Verlag.

Grubler, A. (1996). "Time for a Change: On the Patterns of Diffusion of Innovation." Daedalus 125(3): 19-42.

Grubler, A. (1998). Technology and Global Change. Cambridge, UK, Cambridge University Press.

Grubler, A. (2004). Transitions in Energy Use. Encyclopedia of Energy. Volume 6: 163-177.

Grubler, A. (2008). Energy Transitions. Encyclopedia of Earth. C.J. Cleveland. Washington, DC, Environmental Information Coalition, National Council for Science and the Environment.

Grubler, A. (2010). "The costs of the French nuclear scale-up: A case of negative learning by doing." Energy Policy 38(9): 5174-5188.

Grubler, A., P. Aguayo, M. Hekkert, F. Aguayo, K.S. Gallagher, M. Hekkert, K. Jiang, L. Mytelka, L. Neij, G. Nemet and C. Wilson (2011). The Energy Technology Innovation System. Global Energy Assessment. Cambridge, UK, Cambridge University Press.

Grubler, A. and S. Messner (1996). Technological Uncertainty. Climate Change: Integrating Science, Economics and Policy. N. Nakicenovic, W.D. Nordhaus, R. Richels and F. Toth. Laxenburg, Austria, IIASA.

Grubler, A., N. Nakicenovic and D.G. Victor (1999). "Dynamics of energy technologies and global change." Energy Policy 27(5): 247-280.

Grübler, A., N. Nakicenovic and D.G. Victor (1999). "Dynamics of energy technologies and global change." Energy Policy 27(5): 247-280.

Grubler, A. and K. Riahi (2010). "Do governments have the right mix in their energy R&D portfolios?" Carbon Management 1(1): 79-87.

GWEC (2008). Global Wind Energy Outlook. Global Wind Energy Council, Brussels, Belgium.

Haas, R., N. Nakicenovic, A. Ajanovic, T. Faber, L. Kranzl, A. M¸ller and G. Resch (2008). "Towards sustainability of energy systems: A primer on how to apply the concept of energy services to identify necessary trends and policies." Energy Policy 36(11): 4012-4021.

Halsnæs, K., P. Shukla, D. Ahuja, G. Akumu, R. Beale, J. Edmonds, C. Gollier, A. Grubler, M. Ha Duong, A. Markandya, M. McFarland, E. Nikitina, T. Sugiyama, A. Villavicencio and J. Zou (2007). Framing issues. Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. B. Metz, O. Davidson, P. Bosch, R. Dave and L. Meyer. Cambridge, UK, Cambridge University Press: 117-167.

Hanaoka, T., M. Kainuma and Y. Matsuoka (2009). "The role of energy intensity improvement in the AR4 GHG stabilization scenarios." Energy Efficiency 2(2): 95-108.

Hanson, D.A. and J.A.S. Laitner (2006). "Technology Policy and World Greenhouse Gas Emissions in the AMIGA Modeling System." Energy Journal 27(Special Issue: Multi-Greenhouse Gas and Climate Policy): 355-371.

Hekkert, M.P., R.A.A. Suurs, S.O. Negro, S. Kuhlmann and R.E.H.M. Smits (2007). "Functions of innovation systems: A new approach for analysing technological change." Technological Forecasting and Social Change 74(4): 413-432.

Heymann, M. (1998). "Signs of Hubris: The Shaping of Wind Technology Styles in Germany, Denmark, and the United States, 1940-1990." Technology and Culture 39(4): 641-670.

IEA (2003). World Energy Investment Outlook. International Energy Agency, Paris, France.

IEA (2006). Light's Labour's Lost: Policies for Energy Efficient Lighting. Paris, France, International Energy Agency.

IEA (2009a). IEA Energy Technology R&D, RDD Budgets Vol. 2009 release 01. International Energy Agency (IEA), Paris, France.

IEA (2009b). World Energy Outlook. Paris, France, International Energy Agency.

IEA (2010). Energy Balances of Non-OECD Countries. Paris, France, IEA Statistics.

Jacobsson, S. and A. Bergek (2004). "Transforming the energy sector: the evolution of technological systems in renewable energy technology." Industrial and Corporate Change 13(5): 815-849.

Jacobsson, S. and V. Lauber (2006). "The politics and policy of energy system transformation--explaining the German diffusion of renewable energy technology." Energy Policy 34(3): 256-276.

Kemp, R., J. Schot and R. Hoogma (1998). "Regime Shifts to Sustainability through Processes of Niche Formation: The Approach of Strategic Niche Management." Technology Analysis and Strategic Management 10(2): 175-195.

Kimura, O. (forthcoming). The Role of Standards in Japan's Top Runner Program. Energy Technology Innovation: Learning from Success and Failure. A. Grubler and C. Wilson. Cambridge, UK, CUP.

Kitous, A., P. Criqui, E. Bellevrat and B. Chateau (2010). "Transformation Patterns of the Worldwide Energy System – Scenarios for the Century with the POLES Model." The Energy Journal 31(Special Issue: The Economics of Low Stabilization): 49-82.

Krey, V., D. Martinsen and H.-J. Wagner (2007). "Effects of stochastic energy prices on long-term energy-economic scenarios." Energy 32: 2340-2349.

Krey, V. and K. Riahi (2009). Risk Hedging Strategies under Energy System and Climate Policy Uncertainties – A Stochastic Scenario Analysis using the SMS Modeling Framework. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Landes, D.S. (1969). The Unbound Prometheus: Technological Change and Industrial Development in Western Europe From 1750 to the Present. Cambridge, UK, Cambridge University Press.

Lee, T.H. (1987). Combined Cycle Systems: Technology and Implications. The Methane Age. T.H. Lee, H.R. Linden, D.A. Dreyfus and T. Vasko. Dordrecht, NE, Kluwer Academic Publishers: 131-146.

Lipsey, R.G., K.I. Carlaw and C.T. Bekar (2005). Economic Transformations: General Purpose Technologies and Long-term Economic Growth. Oxford, UK, Oxford University Press.

Lovins, A., E. Kyle Datta, T. Feiler, K.R. Rabago, J. Swisher, A. Lehmann and K. Wicker (2003). Small is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size. Snowmass, CO, Rocky Mountain Institute.

Luderer, G., V. Bosetti, J. Steckel, H. Waisman, N. Bauer, E. Decian, M. Leimbach, O. Sassi and M. Tavoni (2009). The Economics of Decarbonization – Results from the RECIPE model intercomparison: RECIPE Background Paper. Potsdam Institute, Potsdam, Germany.

Magne, B., S. Kypreos and H. Turton (2010). "Technology Options for Low Stabilization Pathways with MERGE." The Energy Journal 31(Special Issue: The Economics of Low Stabilization): 83-108.

Marchetti, C. and N. Nakicenovic (1979). The dynamics of energy systems and the logistic substitution model. IIASA, Laxenburg, Austria.

Metz, B., O.R. Davidson, P.R. Bosch, R. Dave and L.A. Meyer (2007). Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. Cambridge, UK, Cambridge University Press.

Meyer, N.I. (2007). "Learning from wind energy policy in the EU: lessons from Denmark, Sweden and Spain." European Environment 17(5): 347-362.

Moe, E. (2010). "Energy, industry and politics: Energy, vested interests, and long-term economic growth and development." Energy 35(4): 1730-1740.

Nakicenovic, N., J. Alcamo, G. Davis, H.J.M. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grubler, T.Y. Jung, T. Kram, E.L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Papper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor and Z. Dadi (2000). Special Report on Emissions Scenarios. Cambridge, UK, Cambridge University Press.

Nakicenovic, N., A. Grubler and A. McDonald (1998). Global Energy Perspectives. Cambridge, Cambridge University Press.

Nakicenovic, N. and K. Riahi (2002). An Analysis of Technological Change across Selected Energy Scenarios. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Nakicenovic, N. and H.H. Rogner (1996). "Financing Global Energy Perspectives to 2050." OPEC Review 20(1): 1-23.

Neij, L. and P.D. Andersen (forthcoming). "Comparative Assessment of Wind Turbine Innovation and Diffusion."

Nemet, G. (forthcoming). The Role of Standards: CAFE & Vehicle Efficiency in the US. Energy Technology Innovation: Learning from Success and Failure. A. Grubler and C. Wilson. Cambridge, UK, CUP.

OECD (2009). Communications Outlook. Organisation for Economic Cooperation and Development, Paris, France.

Platts (2005). World Power Plant Database. Platts, London, UK.
Reynolds, C. and M. Kandlikar (2007). "How hybrid vehicles are different from conventional vehicles: the effect of weight and power on fuel consumption." Environmental Research Letters 2: 1-8.
Riahi, K., A. Grubler and N. Nakicenovic (2007). "Scenarios of long-term socio-economic and environmental development under climate stabilization." Technological Forecasting and Social Change 74(7): 887-935.
Rosenberg, N. (1994). Exploring the black box: technology, economics, and history. Cambridge, Cambridge University Press.
Ruttan, V. (2001). Technology, Growth, and Development. Oxford, UK, Oxford University Press.
Sahal, D. (1985). "Technological guideposts and innovation avenues." Research Policy 14(2): 61-82.
Sandén, B.A. and C. Azar (2005). "Near-term technology policies for long-term climate targets: economy wide versus technology specific approaches." Energy Policy 33(12): 1557-1576.
Schipper, L., R. Steiner, P. Duerr, F. An and S. Strom (1992). "Energy use in passenger transport in OECD countries: Changes since 1970." Transportation 19(1): 25-42.
Schot, J. and F.W. Geels (2008). "Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy." Technology Analysis & Strategic Management 20(5): 537-554.
Smekens, K.E.L., P. Lako and A.J. Seebregts (2003). Technologies and technology learning: contributions to IEA's Energy Technology Perspectives. Energy Research Centre (ERC) of the Netherlands, Petten, The Netherlands.
Smil, V. (2000). "Energy in the Twentieth Century: Resources, Conversions, Costs, Uses, and Consequences." Annual Review of Energy & Environment 25: 21-51.
Smil, V. (2003). Energy at the Crossroads: Global Perspectives and Uncertainties. Cambridge, Mass., MIT Press.
Smil, V. (2008). Energy in Nature and Society: General Energetics of Complex Systems. Boston, MA, MIT Press.
Solow, R.M. (1957). "Technical change and the aggregate production function." Review of Economics and Statistics 39: 312–320.
Sovacool, B.K. (2009). "Rejecting renewables: The socio-technical impediments to renewable electricity in the United States." Energy Policy 37(11): 4500-4513.
Suarez, F. (2004). "Battles for technological dominance: an integrative framework." Research Policy 33: 271-286.
Thomke, S.H. (2003). Experimentation matters: unlocking the potential of new technologies for innovation. Cambridge, MA, Harvard Business School Press.
Unruh, G. (2000). "Understanding carbon lock-in." Energy Policy(28): 817-830.
US_DoC (1975). Historical Statistics of the United States: Colonial Times to 1970. U.S. Department of Commerce, Washington, DC.
US_DoC (2007). Statistical Abstract of the United States. U.S. Department of Commerce, Washington, DC.

US_NAE (2003). A Century of Innovation: 20 Engineering Achievements that Transformed our Lives. US National Academy of Engineering (NAE), Washington, DC.

Utterback, J.M. (1994). Mastering the Dynamics of Innovation. Boston, MA, Harvard Business School Press.

van den Bergh, J.C.J.M., A. Faber, A.M. Idenburg and F.H. Oosterhuis (2007). Evolutionary Economics and Environmental Policy: Survival of the Greenest. Cheltenham, UK and Northampton, MA, Edward Elgar Publications.

van Vuuren, D., M. Hoogwijk, T. Barker, K. Riahi, S. Boeters, J. Chateau, S. Scrieciu, J. van Vliet, T. Masui, K. Blok, E. Blomen and T. Krama (2009). "Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials." Energy Policy 37: 5125–5139.

WBCSD (2009). Energy Efficiency in Buildings: Business realities and opportunities. World Business Council on Sustainable Development, Geneva, Switzerland.

Wilson, C. (forthcoming-a). "Growth Dynamics of Energy Technologies: Using Historical Patterns to Validate Low Carbon Scenarios."

Wilson, C. (forthcoming-b). "Historical Scaling Dynamics of Energy Technologies: A Comparative Analysis."

Worrell, E. and G. Biermans (2005). "Move over! Stock turnover, retrofit and industrial energy efficiency." Energy Policy 33(7): 949-962.