Historical Case Studies of Energy Technology Innovation

CASE STUDY 1: ENERGY TRANSITIONS.

GRAND DESIGNS: HISTORICAL PATTERNS AND FUTURE SCENARIOS OF ENERGY TECHNOLOGICAL CHANGE

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AUTHORS' SUMMARY

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

If referencing this chapter, please cite:
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1 INTRODUCTION

Technological and congruent institutional and social change is widely recognized as the main driver of long-run economic growth ever since Solow (1957), and of development in general (Freeman and Perez, 1988). In terms of causality, technology and institutional/social settings *co-evolve*, mutually depending on, mutually cross-enhancing each other. Reality is a far cry away from simplistic, extreme notions of "technological determinism" (technology acting as main agent of change) or "social construction" perspectives (in which the technological landscape is perceived as mere outcome of the shaping of social forces or of class struggle). Energy technologies are no exception to this dichotomy of views, but no matter what the particular perspective, all scholars agree in the importance of technological change in past and future energy transitions (e.g., Grubler, 1998; Grubler, 2008; Halsnæs et al., 2007; Nakicenovic et al., 2000; Smil, 1994).

The following sections synthesize our current understanding of the linkages of technological change and the evolution of energy systems both from a historical as well as a futures (scenarios) perspective.

2 GRAND PATTERNS OF CHANGE

Four "grand" patterns characterize technological change and their corresponding energy transitions.

First, no individual technology, as important as it may be, is able to transform whole energy systems that are large and complex. The importance of technology arises in particular through *clustering* effects (combinations of interrelated individual technologies) and *spillover* effects (applications outside the initial sector/use for which a technology was initially devised). In other words, technologies operate more effectively as families or as "gangs" and not as individuals. Because of clustering and spillovers, it is very difficult to dislodge a dominant technological "regime", a fact referred to in the technology literature as "path dependency" or "technology lock-in" (e.g., Arthur, 1989).

Second, any new technology introduced is initially crude, imperfect, and very expensive (Rosenberg, 1994). Performance (the ability to perform a particular task of delivering a novel energy service) initially dominates economics as a driver of technological change and diffusion. Only after an extended period of experimentation, learning and improvements, and the establishment of a corresponding industrial base (in many cases profiting from standardization, mass production, and scale economies of a growing industry) new technologies start to be able to compete with existing ones on a pure cost basis. In other words: attractiveness beats cheap, at least initially.

Third, the history of past energy transitions highlights the critical importance of *end-use* (i.e. consumers, energy demand) that dominates technology applications. Historically energy supply has *followed* energy demand in technology applications, and energy end-use markets have been, and remain, the most important market outlets for new energy technologies. In other words: new energy technologies need to find consumers, and better many of them.

Finally, *fourth,* the process of technological change (from innovation to widespread diffusion) takes considerable time: as a rule many decades, and rates of change become slower, the larger the energy system (components) affected (Grubler, 1996). These slow rates of change of energy technologies arise from four phenomena:

- the extended time required for experimentation, learning and technology development from invention to innovation, to initial specialized niche market applications, and finally, in case of success, to pervasive adoption across many sectors, markets and countries;
- the considerable time required for technology clustering and spillover effects to emerge;
- the capital intensiveness of many new energy technologies that *ceteris paribus* slows technology diffusion;
- the longevity of the capital stock of energy systems in many end-use applications (buildings), conversion technologies (refineries, power plants), and above all infrastructures (railway networks, electricity grids), that spans several decades to a century, again slowing diffusion of new technologies.

Only in exceptional cases does the diffusion of new energy technologies proceed via the premature retiring of existing capital stock, as is the case in current cell phone markets or with information and telecommunication (ITC) technologies in general. In other words: if technological change in energy systems is on the policy agenda, one needs both a long breath and an early start.

2.1 Technology and Historical Energy Transitions

Two major transitions have shaped global energy systems 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 (limited availability of mechanical power, low energy density, lack of ubiquitous and cheap transport systems, cf. Landes, 1969). This first energy transition took well over a century to fully unfold: 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 transition is characterized by the displacement of the previously dominating coal-based steam technology cluster by electricity (drives, light) and petroleum-based technologies (automobiles, aircraft, petrochemicals). This second energy transition is far from completed: some two billion still lack access to modern energy services provided by electric appliances and end-use devices, as documented in the Global Energy Assessment.

These two historical energy transitions are both characterized by the four "grand" patterns of technological change in energy systems outlined above: clustering and spillovers, the dominance of performance over costs in the early phases of technology development, and of end-use applications over energy supply, as well as the long time constants of change.

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 (threshing) and also to mobile applications in form of railways and steam-ships. Technology researchers have introduced the concept of "general purpose" technologies (e.g., Lipsey et al., 2005) to describe these cross-enhancing effects that arise if a technology is deployed in a variety of applications furthering knowledge spillovers and market growth (and corresponding economies of scale). Steam and electricity, hailed as the "greatest engineering achievement of the 20th century" (NAE, 2003) are prominent examples of such general purpose technologies that assume their importance due to clustering and spillover effects. ITCs are a good current example.

Initial steam engines were by any standards inefficient and extremely expensive. The first atmospheric steam engines had thermal conversion efficiencies of only one percent (consuming some 45 pounds of

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coal per horsepower delivered, Ayres, 1989). It took a century to boost their thermal efficiency in a successive stream of innovations to some 20 percent (from Newcomen's atmospheric engine, to Watt's low pressure, to high pressure engines that finally made railroads possible), and another century to reach the current efficiency of steam turbines of 40 percent. Crafts (2004) provides estimates of the costs of steam engines in the 18th and 19th century. Initial costs (by 1760) amounted to a phenomenal 12,000 US$(2003) per kW, akin to current fuel cells (often classified as prohibitively expensive). Yet even their modest performance and high costs provided sufficient incentive for their deployment, as alternatives were either not available where needed (e.g., water power) or did not provide the performance required in terms of power output and density (e.g., horse power). After an extended period of experimentation, development costs started to come down after the mid-19th century (i.e., 100 years after the introduction of steam engines) and by the beginning of the 20th century costs had fallen to below 3000 $(2003)/kW. A similar story of new energy technologies being adopted despite initially extremely high costs can be told about the introduction of electricity and electric appliances for light and motive power (Devine, 1983; Smil, 2000).

Perhaps current concerns with the high costs of adopting climate friendly technologies arise from the fact that with a few exceptions (e.g., solar PV in remote off-grid applications) many current new energy technologies offer little comparative performance advantage in terms of services provided to consumers (apart from lower emissions whose benefits remain externalized). The conventional response to these concerns is subsidies, at least temporarily until costs can be “b(r)ought down”. But these subsidies may have to be sustained over many decades rather than years (as evidenced by the innovation history of Brazilian ethanol). Conversely, the historical precedent - developing and introducing technologies whose decisive performance edge does not necessarily require subsidies for early niche market adopters - seems to receive little attention. Evidently such performance-driven niche markets can be supported and stimulated by public policy. Consider the case where critical public and technological infrastructures like communication networks would be required to have 100 percent reliability back-up systems (as e.g., mandated in Switzerland) that could create a rather price insensitive niche market for off-grid, decentralized energy system solutions.

Another robust finding from historical energy transitions is the importance, even dominance of end-use applications and markets for the introduction and development of energy technologies. As discussed in the steam engine example above, stationary steam engines in industry and agriculture, and mobile steam engines on ships and locomotives were by far the dominant markets of these new technologies compared to the energy supply sector (coal mines, and coking and town gas plants that illustrate the emerging cluster of a complex coal-based 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: demand innovation (the electric light bulb) triggers supply-side innovations (electricity generation, transport and distribution).

Given the multitude of energy technologies and applications it is difficult to obtain a comprehensive picture of the entire energy technology landscape so one needs to rely on a simple common metric (installed power) and the example of a country, the US, where such data are available. Table 1 summarizes the evolution of energy technologies for the US since 1850 in terms of installed capacity (horsepower and Watts, converted to GW), differentiating between stationary and mobile end-use applications, as well as the energy (supply) sector applications and 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 such as communication via radios, TVs and computers).

Table 1 clearly shows the persistent dominance of end-use applications in the total installed energy technology base. Installed horsepower of prime movers in 2000 are based on 1992 values (US DOC, 2007), the most recent available. Thermal applications (boilers in end-use and power plants) have been inferred from final energy use statistics multiplied by representative load factors, or are derived from the rated thermal capacity of power plants. Electric applications are conservative estimates based on statistics of industrial electric drives of some 175 GW (US DOE, 1998) and residential electricity use statistics by application (EIA, 2001) multiplied by appliance specific load factors. The dominant estimated electric household technologies are small scale-motors in kitchen appliances and compressor pumps in residential air conditioning units.

TABLE 1. ENERGY TECHNOLOGIES IN THE US IN THE 19TH AND 20TH CENTURY BY GENERIC TYPE AND APPLICATION (IN GW, ROUNDED NUMBERS). NOTES: *ITALICS* INDICATE FIRST-ORDER ESTIMATES. SOURCES: DATA IN BOLD ARE DERIVED FROM US DOC (1975; 2007); FOR OTHER SOURCES, SEE TEXT.

	GW	**1850**	**1900**	**1950**	**2000**
stationary end-use	**thermal (furnaces/boilers)**	*300*	*900*	*1900*	*2700*
	mechanical (prime movers)	**1**	**10**	**70**	**300**
	electrical (drives, appliances)	*0*	*20*	*200*	*2200*
mobile end-use	**animals/ships/trains/aircraft**	**5**	**30**	**120**	**260**
	automobiles	**0**	**0**	**3300**	**25000**
stationary supply	**boilers (power plants)**	*0*	*10*	*260*	*2600*
	mechanical (prime movers)	**<1**	**3**	**70**	**800**
TOTAL	**(numbers rounded)**	**300**	**1000**	**6000**	**34000**

By the 1850s, the beginnings of the US steam age, the dominant energy technologies consisted of simple conversion devices to convert chemical energy (mostly fuelwood and some coal) into heat (ovens, boilers, furnaces). Horses constituted the dominant transport technology (conversion of chemical energy [feed] into mechanical energy) that surpassed the installed horsepower of first stationary steam engines five-fold. By 1900, close to the peak of the steam-coal energy technology cluster, thermal conversion in boilers and furnaces accounted for 90 percent of the one TW installed energy conversion technologies of the US. Non-thermal applications only constituted some 63 GW, with two thirds represented by steam engines and the remainder being accounted for by electricity applications (20 GW lights and motors in end-use and 3 GW generators in power plants). 100 years later, energy technologies in the US add up to some 34 TW (120 kW per capita, 10 times as large as in 1850) and the spectacular expansion of end-use technologies in electrified homes and industry as well as for private transportation with a more than 1000-fold increase since 1900 is particularly striking (see Table 1). Automobile (car and truck) engines comprise nearly three quarters of the total, roughly exceeding the thermal capacity of

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electric power plants by a factor of 10, illustrating the theoretical potential to entirely displace centralized generation (and utilities) by vehicle on-board electricity generation (e.g., via fuel cell vehicles, as first proposed by Lovins et al., 1996).

Table 1 provides a powerful summary illustration of the importance of energy end-use for energy technologies in terms of market outlets and explains also why the largest efficiency improvement potentials are in energy end-use sectors and not in energy supply.

A historical perspective also allows an appreciation of the considerable time required for a turnover of the energy technology capital stock that ranges from many decades to well over a century (for a review see, e.g., Grubler, 1996; IPCC, 2001; Grubler et al., 1999). Crafts (2004) summarizes the diffusion of steam power in the British economy: it took steam close to 100 years (until the 1860s) to gain a 50 percent market share in total installed horsepower, gradually displacing wind and waterpower. The electrification in US industry provides another example: it took some 40 years (to the 1920s) for electric drives to account for 50% of all prime movers in US industry (Ausubel and Marchetti, 1997), with substantial (capital and labor) productivity effects arising only after that threshold was passed (Devine, 1983). The factors explaining this slow rate of diffusion of new technologies include their initial imperfections and high costs, the lack of corresponding organizational/institutional changes to realize their full productivity potential, and finally also clustering and spillover effects that perpetuate the dominance of the old technology while taking considerable time to emerge with new technologies.

The dynamics of technological change of national and global energy systems have been increasingly well documented since the early studies by Marchetti and Nakicenovic (1979) and confirm typical energy systems turnover times of 70-120 years at the global level. Figure 1 summarizes the above discussed two "grand" energy transition (coal/steam replacing traditional renewables, and in turn modern energy technologies and carriers replacing steam/coal). Coal maintains its market share in primary energy of some 26% in 2008 primarily via coal based electricity generation (based on BP, 2009). In terms of final energy use, i.e. purchased energy forms that are compatible with the prevailing technologies in use by consumers, coal's share was less than 9 percent in 2007 (IEA, 2009), almost exclusively (some 80%) used by heavy, metallurgical industry that technologically is the last current testimony of the 19th century steam/coal age.

The turnover times of these two grand transitions have historically been remarkably consistent. (Turnover time is measured as the number of years to grow from 1 to 50%, or from 10 to 90% market share). Historical market dynamics are approximated in Figure 2 by a set a coupled logistic equations over the 1850 to 1975 period (dashed lines) indicating turnover times of 120 years (phase-out of traditional fuels and phase-in of coal) and 80 years (growth of modern fuels/technologies, decline of coal-based steam applications) respectively. Note in particular the long period of initial slow market penetration of new technologies.

Another, disconcerting trend since the mid 1970s is equally visible in Figure 1: a significant slowdown of historically observed (slow) energy market dynamics to a near-stagnation (model estimates shown as solid lines). In terms of turnover times, the post-1975 trends would suggest that it might take almost 1000 years to complete the historical energy "modernization" transition. Bad auspices indeed in view of the increasingly recognized need for accelerated energy technology transitions in a climate constrained world.

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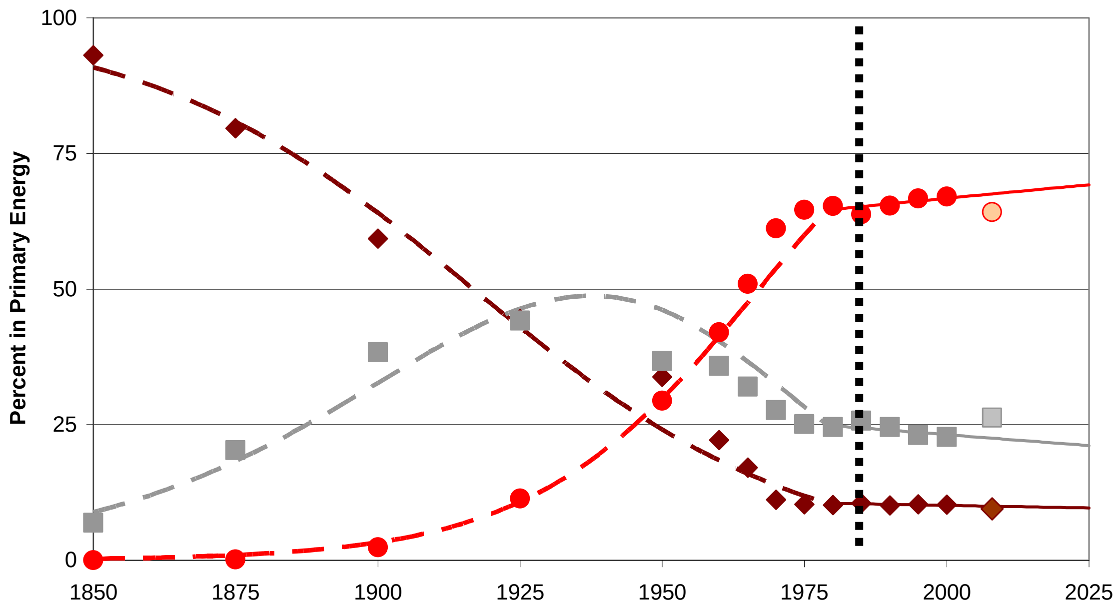

FIGURE 1. TWO GRAND TRANSITIONS IN GLOBAL ENERGY SYSTEMS MEASURING MARKET SHARES IN TOTAL PRIMARY ENERGY USE. NOTES: LINES SHOW TRADITIONAL FUELS (BROWN), COAL (GREY), AND MODERN ENERGY CARRIERS (OIL, GAS, HYDRO, NUCLEAR AND MODERN RENEWABLES, RED). HISTORICAL MARKET DYNAMICS ARE APPROXIMATED BY A SET A COUPLED LOGISTIC EQUATIONS OVER THE 1850 TO 1975 PERIOD (DASHED LINES). SOURCES: 1850 TO 2000 DATA BASED ON GRUBLER, 2008; 2008 DATA (DENOTED BY LIGHTED SHADED SYMBOLS) BASED ON BP, 2009, AND IEA, 2009.

2.2 Technological Change in Future Scenarios

The role of technological change in future energy scenarios and in climate mitigation has been reviewed comprehensively in the IPCC's Fourth Assessment Report (Fisher et al., 2007; Halsnæs et al., 2007) and is also addressed in the Global Energy Assessment. Here we focus briefly on contrasting future scenarios with the historical perspective outlined above, and also provide a simple illustration to show the levers of technological change in "bending the curve" in a transition to more sustainable energy systems. Such transitions often proceed along mutually exclusive, alternative technology pathways in the scenario literature and highlight the critical importance of near-term technology and policy decisions in structuring alternative long-term outcomes.

It is interesting to note that in contrast to the historical evidence, future scenarios portray almost exclusively technology transitions in energy supply systems, giving little detail on potentials and alternative pathways of technological change in energy end-use. This conclusion does not suggest that the importance of end-use technologies goes unacknowledged by researchers and scenario modeling teams, but it rather reflects the current state-of-art of modeling technological change in scenarios of energy transitions and climate stabilization. Even the most detailed 'bottom-up' models with detailed technological representations contain little detail at the level of energy end-use. Rather technological change is commonly represented via aggregate indicators of energy use, i.e., unspecified change is assumed to occur and represented only in terms of its energy demand outcomes in models. Reasons include both extreme paucity of technology-specific data as energy statistics are framed through the lens of economic activities and sectors rather than technologies, and the formidable challenge of deriving plausible and consistent scenario assumptions on the evolution of a potentially extremely large number of energy end-use applications (new transport and communication, manufacturing, and consumer applications) that would need to be modeled. To our knowledge, there has been no example in the scenario literature to-date describing the potential evolution of alternative scenarios of new "general purpose" technologies like steam or electricity that have historically been the main technology drivers of energy transitions. Even scenarios of the possible emergence of a "hydrogen economy" (e.g., Barreto et al., 2003) focus on technology substitutions of otherwise unchanged energy end-use service patterns. The best illustrations of the importance of technological change in future energy systems continue, therefore, to be those describing alternative transitions in energy supply systems.

Figure 2 gives an illustration from the IPCC Special Report on Emissions Scenarios (SRES, Nakicenovic et al., 2000) that became the ancestor of a wide range of derived scenarios following a similar scenario taxonomy. The SRES A1 "high growth" scenario family does not vary any salient scenario variables *except* technology. Yet the vast differences in terms of CO_2 emission outcomes are striking, and arise solely from differences in alternative technology development described in the A1FI and A1T scenario groups (and without any explicit climate policies).

This divergence in Figure 2 illustrates that technological change could cluster around alternative technological combinations, that remain consistent and stable respectively through increasing returns to adoption that crowd out other alternatives. (It might be argued therefore that the intermediary, "balanced" A1B scenario is more a modeling/scenario construct than a development pathway consistent with historical experience; yet it could also be taken to represent the global aggregate of differentiated "locked-in" regional technology developments such as clean coal technologies in China versus renewable energy in Latin America).

Another feature consistent with historical experience, is that despite the three scenario groups describing distinctively contrasting technology strategies and policies, emissions diverge only gradually (cf. the similar emission range across all scenarios by 2025). The seeds of long-term alternative outcomes have thus to be sown early on and translate in to different environmental outcomes only slowly as new technologies replace gradually older technology vintages. It is this long-term leverage (change) effect of near-term technology policies that are of current interest, particularly in the climate change domain.

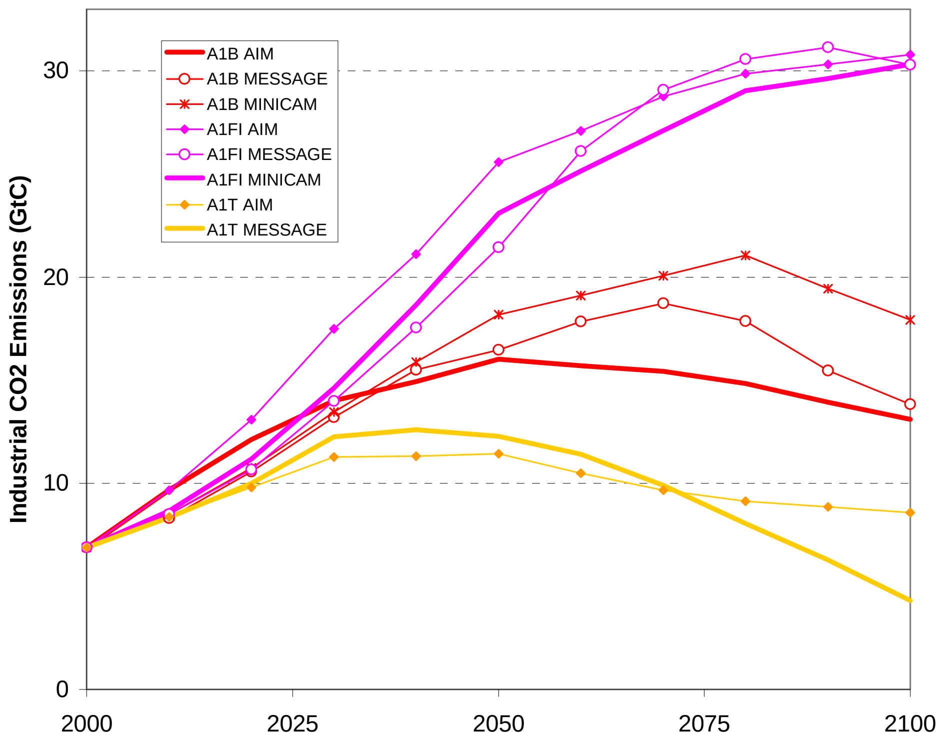

FIGURE 2. INDUSTRIAL CO_2 EMISSIONS (GTC) FOR THE IPCC SRES A1 "HIGH GROWTH" SCENARIO FAMILY. NOTES: SCENARIOS SHARE IDENTICAL ASSUMPTIONS OF THE FUTURE, EXCEPT TECHNOLOGY DEVELOPMENT THAT LEAD ALTERNATIVELY TO HIGH EMISSIONS, FOSSIL-FUEL INTENSIVE (A1FI) OR ALTERNATIVELY TO LOW EMISSIONS (A1T) SCENARIOS, WITH THE "BALANCED" A1B SCENARIOS TAKING AN INTERMEDIARY POSITION. BOLD LINES DENOTE SO-CALLED MARKER SCENARIOS, OTHER SCENARIOS ILLUSTRATE MODELING UNCERTAINTIES IN THE REPRESENTATION OF TECHNOLOGICAL CHANGE EVEN UNDER SHARED OVERALL ASSUMPTIONS OF TECHNOLOGY DEVELOPMENT TRENDS ACROSS MODELS. SOURCE: NAKICENOVIC ET AL., 2000.

It is also possible to draw on the scenario literature to illustrate technological bifurcations with respect to individual technologies. Nakicenovic and Riahi (2002) have performed a comprehensive survey of the scenario literature with respect to energy technology projections for a wide range of energy supply technologies (for electricity generation as well as synfuels). As an example, Figure 3 shows scenario projections for solar PV, that over the long-term bifurcate into groups of scenarios of either comparatively low, or alternatively high market deployment as a function of assumed technology characteristics, in particular investment costs, as well as future market deployment environments (absence vs. existence of CO_2 emission constraints and their magnitude). Note in particular the bifurcation in PV deployment scenarios for 2100 as a function of assumed carbon constraints (right top panel) as well as the bimodal distribution in projected investment costs (bottom right panel) that differ by a factor 10.

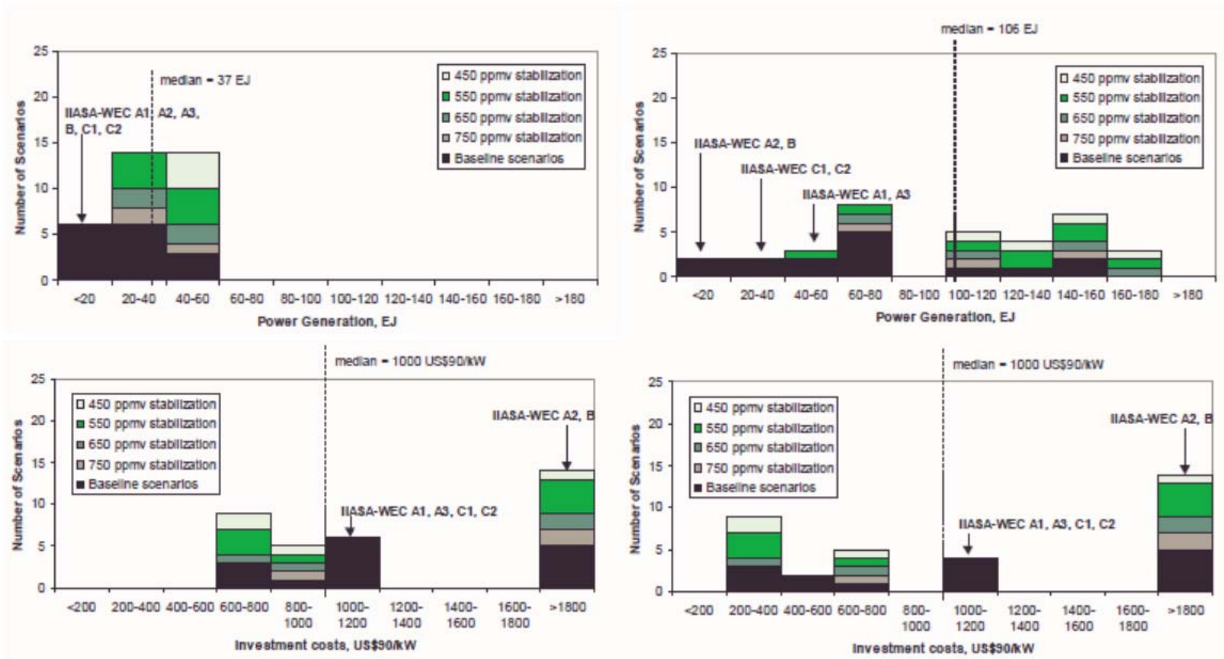

FIGURE 3. SYNTHESIS OF PV MARKET DEPLOYMENT SCENARIOS (TOP PANELS) IN THE SCENARIO LITERATURE AS A FUNCTION OF INVESTMENT COSTS (BOTTOM PANELS) AND CO_2 EMISSION CONSTRAINTS. NOTES: THE MARKET ENVIRONMENT IS REPRESENTED THROUGH THE ABSENCE (BASELINE SCENARIOS, BLACK) OR EXISTENCE OF VARIOUS CO_2 EMISSIONS CONSTRAINTS (PPM STABILIZATION TARGETS, SHADES OF GREEN). LEFT PANELS SUMMARIZE THE SCENARIO LITERATURE FOR 2050, RIGHT PANELS FOR THE YEAR 2100. SOURCE: NAKICENOVIC AND RIAHI, 2002.

Two important policy lessons are provided by the scenario literature. First, the temporal dimensions of technological bifurcations in energy systems are extremely long. Market deployment scenarios for 2020 (not shown) suggest only modest, niche market inroads into the global energy system, and even the most ambitious scenarios do not project more than 60 EJ PV electricity equivalent by 2050, with a technological bifurcation only expected well after that date. By 2100 scenarios cluster either around small (0-60 EJ) or large (100-180 EJ) solar PV markets and their respective scenarios can be clearly identified as either assuming no CO_2 constraints and high investment costs (low PV scenario cluster) or alternatively stringent CO_2 constraints combined with low investment cost projections (high PV scenario cluster).

Second, the scenarios illustrate well the needed leveraging of both “supply push” and “demand pull” policies in triggering such a policy-induced long-term technological bifurcation. R&D efforts and improved designs and “debugging” through niche market application feedbacks are underlying the alternative trends in projected PV technology characteristics (most notably costs that reflect other technology characteristics such as conversion efficiencies). Conversely, changes in relative prices in scenarios of CO_2 constraints constitute the necessary complementary “demand pull” policies that are needed to yield marked differences in long-term technology outcomes.

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3 CONCLUSIONS

In conclusion, certain generalisable patterns (with related policy implications) can be observed in the dynamics of energy transitions historically and in future scenarios.

First, 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.

Second, 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 experimentation, 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.

Third, 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.

4 FURTHER READING

For a more detailed version of this case study with additional empirical material, see Wilson and Grubler, 2011.

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If referencing this chapter, please cite:
Grubler, A. (2012). Grand Designs: Historical Patterns and Future Scenarios of Energy Technological Change. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

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