Apples, oranges, and consistent comparisons of the temporal dynamics of energy transitions

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Abstract

Benjamin Sovacool (2016) has provided interesting food for thought in asking “how long will it take?” for the unfolding of energy transitions. Historical evidence of “grand” or global energy system transitions taking decades to centuries to unfold contrasted with highly selective recent and rapid examples of mostly incremental technological change make for an engaging argument. But the observed contrasts are due to the apples-and-oranges comparison between transitions that are measured differently, defined differently, characterized by different processes, and explained differently.

Keywords

technology diffusion, energy transitions, adoption rates

Manuscript

1. Defining and measuring energy transitions should be done on a consistent basis

A transition is usefully defined as a change in the state of an energy system as opposed to a change in an individual energy technology or fuel source (Grubler, 1991). A prime example is the change from a pre-industrial system relying on traditional biomass and other renewable power sources (wind, water and muscle power) to an industrial one, characterized by pervasive mechanization (steam power) and the use of coal. Market shares reaching pre-specified thresholds are typically used to characterize the speed of transition (e.g. coal versus traditional biomass). Typical market share thresholds in the literature are 1%, 10% for the initial shares and 50%, 90% and 99% for outcome shares following a transition. A robust finding is that such state changes proceed non-linearly, in characteristic S-curves, widely used also in the diffusion and technological substitution literature (Grubler, 1996). The logistic function, a symmetrical S-curve, has the advantage that all important market share thresholds are related in a consistent fashion. The time it takes to move from 1% to 50% (and from 50% to 99%) is identical to the time required to grow from 10% to 90% market share. This has been termed the transition "turnover" time, or Δt (in years). If Δt is 10 years, it takes 10 years to move from the 10% to 90% market share (80% of the state change) and the logistic function implies it takes 2x Δt, or 20 years, to achieve 98% of the state change (from 1% to 99% market share).

By adopting an upper threshold of 25% for his definition of rapid changes, Sovacool *ex ante* has shortened the transition times of his examples by a factor of two compared to the evidence reviewed from the historical transition literature he cites which uses an upper threshold value of 50%.[1] The comparison is therefore not made on a like-for-like basis and so is misleading. (We return below to an analogous 'apples-and-oranges' problem with Sovacool's choice of starting threshold).

A second issue in energy transitions is how states of energy systems are measured. It matters whether energy system variables are described in terms of *stocks* or *flows*. Transition speed is affected by whether we analyze changes in the entire capital (technology and infrastructure) stock of an energy system (which changes slowly), or simply the rates at which this stock changes (its first derivative, or growth rate), which tends to be much faster. Whether stocks or

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[1] Comparable numbers of changeover times in the "rapid transition" cases can be derived simply by multiplying the original numbers by a factor 2. Thus the Δts in Sovacool's "rapid transition" sample (leaving out the incomparable Flexfuel [changes in sales instead of stock changes] and Kuwait examples [too small market size]) are in the range of 6 to 32 years compared to a range of between 47 to 69 years of the transition examples of western European economies in the 20th century shown in Table 2 of Sovacool (2016).

flows are used often depends on data availability rather than theoretical considerations, for which stock variables would be preferred[2].

In any comparison of transition speeds, however, one must not confuse these two fundamental concepts. Sovacool's example of rapid transitions in Flexfuel cars in Brazil is such an example of a misleading comparison based on flows rather than stocks. The Brazil examples shows a transition example in which the transition timing is determined by changes in annual sales volumes (Flexfuel versus other car sales, i.e. a flow variable), whereas a more appropriate measure would be to measure the share of Flexfuel cars in the total vehicle fleet (stock variable). The literature makes clear that using flows versus stocks affects transitions speeds. For example, Nakicenovic (1986) has shown that the regulated introduction of catalytic converters in cars yielded an almost instantaneous change in the share of new vehicle sales with catalytic converters (a flow variable). Within less than a year, all new cars sold were equipped with catalytic converters. Yet it took 10 years for catalytic converters to be installed in 80% of the US car fleet and 20 years to achieve a 98% substitution in the vehicle fleet (stock variable).[3] According to Sovacool's measure, the transition to purchases of new Flexfuel cars in Brazil was almost complete (at 90%) in 2009. Yet, by 2010 only 40 percent of registered cars in Brazil were Flexfuel (Du and Carriquiry, 2013) and their combined use of domestically produced ethanol accounted for only 18 percent of road transport energy use (IEA, 2015). This is hardly a situation one can consider a completed rapid energy transition.

Box: Definitions

Energy transition: change in the state of an energy <u>system</u>

"Grand" energy transition: pervasive changes in an energy system that affect multiple energy resources, carriers, sectors, and end-use applications, often associated with the diffusion of "general purpose" technologies (e.g. steam engines or electricity).

Substitution: displacement of one energy carrier or technology by another with little disruption of, or need for integration with, supporting infrastructures

Diffusion: adoption of a technology over time within a population and geography of potential adopters

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[2] Stocks and flows are evidently related. Stocks accrue from adding and withdrawing stock components (investment and retirement), i.e. by the accumulation of two flow variables: new investments and depreciation. Alternatively the size of a stock variable can often be approximated by an appropriate flow variable. For instance in the example of the rise and fall of the coal economy in Europe discussed by Sovacool, annual coal use (a flow variable) is used to describe the growth and demise of the coal-using capital stock of Europe's energy system (its coal using boilers, furnaces, fireplaces, steam locomotives and steam ships).

[3] Coincidentally, the average speed to the vehicle fleet turnover has not changed much compared to the beginnings of the 20th century: also the substitution of horses by early automobiles proceeded with a turnover rate Δt of 12 years (Nakicenovic, 1986).

2. Several well-understood factors explain differences in observed transition speeds

Sovacool's comparison of very different examples of transitions would have been more convincing if appropriate *ceteris paribus* conditions of what is being compared to what, and why, had been provided from the outset. He does start to recognize these conditions in the conclusion—and it largely invalidates the inferences he draws from the ten selective cases of rapid transitions. To ensure like-for-like comparisons, it is essential to embed these cases within available literature that explains differences in transition speeds, spanning fields such as technology systems theory, diffusion theory, industrial economics, and scaling analysis. Insights from these streams of literature can readily explain the superficially puzzling differences outlined by Sovacool.

We give a few selected examples focusing on explanations in three main areas:
a. Technological complexity;
b. Length of formative phases in technology development, spatial diffusion, and market size;
c. Type of adoption decisions, adoption effort and benefits, and supporting policies.

Our basic argument is that slow transition processes share common characteristics or conditions:

a. They involve changes in multiple technologies, infrastructures, and organizational and institutional settings—all of which have a high degree of technological complexity;

b. They involve the development and testing of novel concepts (during a long drawn out 'formative phase') that, when successful, diffuse pervasively across many applications and sectors on a global scale. These large market sizes take decades rather than years to develop;

c. They require investments in (expensive) large-scale technologies and infrastructures and so have a high adoption effort, often with only long-term benefits or non-market benefits (e.g. social or environmental improvements). That is, they have low immediate individual adoption benefits for consumers or firms, and involve complex coordination issues between centralized (e.g. regulatory) and decentralized decision making agents (households, companies).

The examples of rapid transitions given by Sovacool also share common conditions, and these tend to be at the opposite of those characterizing slow transition processes:

a. A new, well established technology simply substitutes for an older one (clean cookstoves, LPG, electronic ballasts, Flexfuel cars) with little disruption of, or need for integration with, supporting technological, organizational, and institutional infrastructures. These transitions therefore involve a low degree of technological complexity;

b. Substitute technologies have been previously used in other markets, benefitting from knowledge spillovers from early adopting markets and thus having shorter local formative phases which explains their rapid adoption. Further, the scale of transition is comparatively small, either in national markets (Kuwait, Netherlands, Denmark) or sub-national markets (Ontario);

c. Technologies offer high tangible benefits for adopters in terms of health (clean cookstoves, LPG), flexibility (Flexfuels), cost savings (energy efficient ballasts), convenience (natural gas in Netherlands, oil and electricity in Kuwait, air conditioners in the US), and benefit from well-coordinated public policies and institutions (nuclear in France, coal phase-out in the Netherlands, combined heat and power in Denmark[4]).

The innovation literature provides robust explanations about why these less complex, incremental technology transitions are easier and occur faster. They are not representative of the more pervasive energy system transitions that have been the focus of historical studies or of the climate and sustainability transition scenario literature. The cases of rapid transitions selected by Sovacool are thus qualitatively different and not directly comparable on a like-for-like basis with the global systems transitions needed to meet climate change, energy access, and energy security goals (GEA 2012). We address each of the reasons why in more detail (see a, b, c above for a summary).

3. Complexity in technological systems slows transitions

Technological complexity is a characteristic of both individual technological artifacts as well as of technological systems (combinations of artifacts). The latter technological complexity, operating at the systemic level, was first described and modeled by Marvin Frankel in 1955.[5] Technological complexity at the systemic level has two important implications. First it explains why the emergence of new complex technological combinations takes a long time. Second it explains why countries, industries, or consumer groups that have adopted previous technological combinations pervasively experience "lock in" (Arthur, 1989) and so make the transition later and more slowly, compared to adopters that adopted the previous system later or less pervasively.

The case discussed by Frankel was the rapid adoption in the 19th century of new textile technologies (the spinning mule) in the USA compared to the industrial leader, England, which was "locked in" to the previous technology and hence quickly lost its industrial leadership

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[4] The pre-existence of district heating grids originally supplied by oil-based heating plants is an additional explaining factor for the rapid substitution through combined heat and power plants in Denmark.

[5] For a contemporary reinterpretation using an agent-based model of the long-term evolution of technological complexity in energy systems see Ma et al. (2008).

position. The phase out of coal-fired steam and related systems in Europe provides an example from the 20th century (see Grubler (2012) which is summarized in Table 2 in Sovacool, 2016). The pioneering country, England phased out coal systems much later and at a slower pace, compared to Southern European countries that had adopted coal and steam much later and less pervasively.

In the language of technology systems theory, we might summarize: Change of individual technologies via substitution can happen quickly. Change of entire technology systems, i.e. the diffusion of complex sets of interrelated technologies, infrastructures, and institutions is inevitably a lengthy process. Data make clear that transition times increase with complexity. Table 1 shows a hierarchy of the duration of changes in technologies revealed by the striking similarity in the transition timing of transport infrastructures in the capitalistic USA, compared to centrally planned USSR.

Table 1. Hierarchy of transition processes and their timing arranged by technological complexity. Note: Examples illustrate the growth of transport technologies and infrastructures in the USA and USSR. These two countries had vastly different political, economic, and social adoption environments, yet show comparable transition speeds that increase with systems complexity. t_0 denotes the diffusion mid-point (50% market share). Δt denotes the time to grow from 1% to 50% (also from 10% to 90%) market share. Source: adapted from Grubler et al., 1999.

complexity & scale	**transition measure**	**USA**		**USSR**	
		t_0	**Δt**	**t_0**	**Δt**
systems of systems	Growth in total length of all transport infrastructures (km length)	1950	80	1980	80
individual system	Growth of railway network (km length) 1830-1930 1930-1989	 1858 decline	 54 decline	 1890 1949	 37 44
upgrading existing system	Railway network improvements (% of tracks) treated ties (USA) track electrification (USSR)	 1923 	 26 	 1965	 27
change in single technology using existing system	Replacement of railway steam locomotives (% of t-km transported)	1950	12	1960	13

Adoption of technologies using existing infrastructures happens fast (a decade), upgrading existing infrastructures takes longer (up to three decades), and building entire new infrastructures (technological systems) involves transition times of four to 5 decades. Lastly, “systems of systems”, the ensemble of what constitutes our modern transport infrastructures (our waterways, railways, roads, and airways and associated communication networks) takes yet longer: 8 decades in both the USA and USSR (Table 1 above).

Roger Fouquet in his contribution in this Issue also emphasizes the critical distinction (and difference in transition speeds) between technology and sector-specific transitions as opposed to pervasive systems transformations that involve many technologies and sectors, i.e. entail a much higher degree of systems complexity.

4. Lifecycle stage and spatial characteristics of diffusion influence transition speeds

Growth rates and changes in market shares describing transitions are highly sensitive to the stage of the diffusion lifecycle observed, to the market’s position in the spatial diffusion sequence from leading core (innovator) through rim (follower) to periphery (late adopter) regions, and to the size of the market. In comparing different transition speeds across time and space the following generalizations are useful:

a. Transitions are faster in specific markets, and when observed during the main growth phase of diffusion (i.e. omitting the slow initial formative phase of a technology's development).

b. Transitions are slower when measured across multiple markets, temporal or spatial scales. As no new technology is adopted instantaneously across all markets, diffusion proceeds via a leader-follower pattern in time and space (from core to rim to periphery). Global or multi-sector diffusion processes by definition take considerably more time than single market or single sector transitions.[6]

c. Diffusion in innovating core markets takes considerably longer than in later adopting markets that benefit from learning externalities ("spillovers" of knowledge) and improved, cheaper technologies developed and tested in core markets. As discussed above, the phase out of a technology in core markets also proceeds much slower than in later adopting markets which experience weaker technological “lock-in”.

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[6] Global growth rates and changes in market share, for example, are the sum of market-specific diffusion dynamics. Taking the current case of nuclear power as an example, global growth rates mask very different diffusion dynamics: at an early stage of diffusion in a late adopter market (China), at a stable market share in a large early adopting market (USA), and at a declining market share (Germany). Isolating any one market to demonstrate rapid transition speeds (e.g., rapid growth of nuclear in China) is highly misleading as this one market is interdependent on other markets at different lifecycle stages and with different geographies.

d. In initial markets or regions where a technology is first commercialized, a technology's growth tends to be more pervasive but slower (Grubler 1998). In subsequent markets, growth tends saturates at a lesser extent (i.e., is less pervasive) but is quicker. 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). 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 (Schipper et al. 1992).

Sovacool's selective examples fail to control for these important temporal and spatial characteristics of technology diffusion. We explain and evidence each in turn.

a. Change is slow during formative phases in early adopting markets.

The formative phase of a new technology is an extended period of experimentation during which the technology is tested, refined and adapted to market conditions (Jacobsson and Lauber 2006).[7] The formative phase corresponds roughly to the flat 'front tail' of the S-curve prior to market take-off.

Bento and Wilson (2016) develop a standardized set of indicators to measure the start and end points of formative phases. They argue that the formative phase begins with the first two years of sequential commercialization of a technology, and ends when 2.5% of potential end users have adopted the technology (in line with the definition by Rogers (2003) of the 'innovators' market segment). Their indicators are consistent with innovation system structures and functions that enable a technology's widespread diffusion.[8] Applying the indicators to a set of 16 energy technologies, Bento and Wilson (2016) find average formative phase durations

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[7] Wilson (2012) finds a common sequential pattern in a technology's diffusion from a lengthy, decadal formative phase (volatile low to high growth rates) through an expansion, takeoff or 'upscaling' phase (high growth rates) into a maturing, stable 'growth' phase (stabilizing medium to slow growth rates) that eventually slows and saturates (slow, declining growth rates and loss of market share).

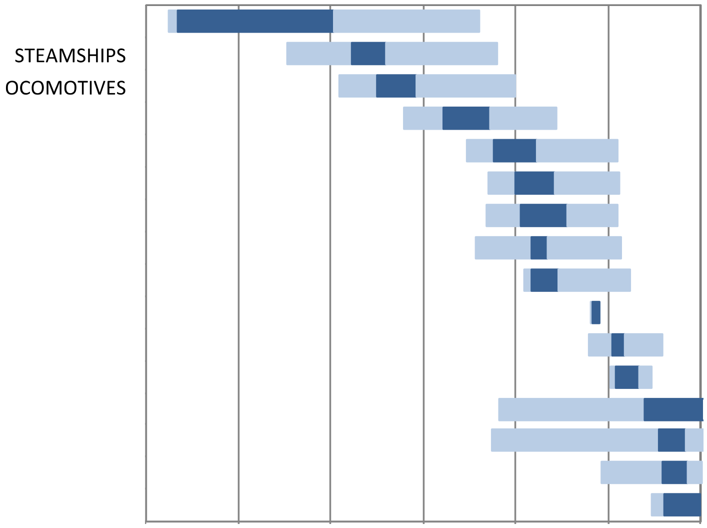
[8] During the formative phase, constitutive elements of a new innovation system are set up, and essential functions of the emerging innovation system begin influencing the technology's development (Hekkert et al. 2007, Bergek et al. 2008a). Four important dimensions to the innovation systems for energy technologies are knowledge, resources, actors and institutions, and adoption and use (Grubler and Wilson, 2014). Knowledge creation is particularly important during formative phases (Hekkert and Negro 2009). Knowledge creation refers to how knowledge is generated, combined, codified and shared to establish the necessary scientific and technological base for an innovation to progress (Jacobsson and Bergek 2011). However, the knowledge generated and experience accumulated in the formative phase is neither automatic nor autonomous. As an example, learning is facilitated by relationships between industry actors (supported by public investments in, for example, testing infrastructure) to ensure experiences feed back into subsequent designs (Garud and Karnoe 2003). When this policy-supported process of collective learning is absent, the development of viable technological capability can fail (Neij and Andersen 2014).

historically of 22 years (Figure 1). Roger Fouquet in his contribution in this Issue also confirms these findings: the fastest formative phase (referred to by Fouquet as the time between invention and begin of market uptake) of any example analyzed for the UK was 10 years (gas and kerosene lighting) with all other examples entailing formative phases of several decades.

In the Bento and Wilson sample, relatively rapid formative phases are observed for fluid catalytic cracking, nuclear power plants and jet aircraft. The emergence of all three technologies was linked to the unique institutional environment around World War II, including strong demand-pull, price insensitive military users, and sharing of intellectual property (Delina and Diesendorf 2013). This raises the possibility - as suggested by Sovacool - that formative phases can be compressed or accelerated in extreme demand environments with simultaneous market-pull and technology-push efforts, and low sensitivity to risk.

In general, however, formative phases are long because establishing a functioning innovation system to support a technology's diffusion takes time. In particular, formative phases are longer for non-ready substitute technologies that need new institutions and infrastructures, and that provide novel energy services (Grubler et al. 1999). Technologies that create new service demands and markets require not just an extended period of experimentation and knowledge development, but also an extensive institutional process of legitimation to overcome the "liability of newness" (Bergek et al. 2008b). Non-ready substitute technologies also have a more limited potential to share structural elements with other innovation systems.

Figure 1. Durations of formative phases for energy technologies are at a decadal scale (Bento and Wilson 2016). Note: Ranges refer to alternative definitions for the start and end points of formative phases, and so capture measurement uncertainties.



b. Formative phases are omitted in transitions observed during growth phases in later adopting markets.

Formative phases are most relevant for characterizing a technology's initial development in core markets and yet, they are often omitted in examples of seemingly “rapid” transitions that often analyze technology growth only after “take-off”, e.g. when having reached at least a 1% market share threshold as in Sovacool’s examples. These examples also mostly refer to late adopting markets, which benefit both from the experience gained in the formative phase of a new technology developed in innovating core markets as well as from significant improvements in terms of performance, costs, and other product attributes resulting from the diffusion in innovating core markets.More rapid diffusion in later adopting markets therefore signals the ‘spillover’ or transfer of knowledge from the formative phases of technology and its subsequent improvements in innovating core markets(Grubler 1998).[9]

This is an important and generalizable characteristic of the *temporal* dynamics of diffusion as diffusion proceeds *spatially*, and is long established in geographic studies of regional

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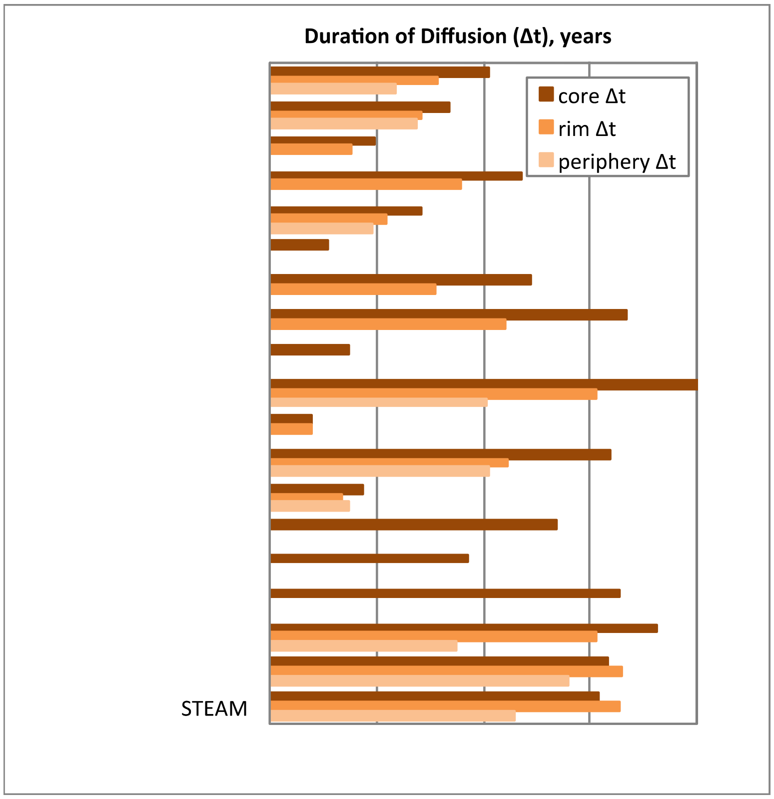
[9] Knowledge spillover can shorten, but not preclude entirely the need for local development of the innovation system elements necessary to support diffusion which are gained through cumulative experimentation and learning (Gallagher, 2006).

development (Hägerstrand, 1968). Figure 2 shows diffusion speeds for 13 different energy technologies observed historically in core, rim and periphery markets (subject to data availability, and the functional form of diffusion) (Wilson and Grubler 2014). The bars show the duration of each technology's growth in terms of cumulative total capacity as it diffuses spatially out of its core market into subsequent rim and then periphery markets. The measure of duration is the Δt in years derived from logistic functions fitted to the data. This measure of duration is inversely related to the rate of diffusion: so, the longer the bars in Figure 2, the more prolonged, and the slower the rate of capacity expansion. As Figure 2 shows, the duration of diffusion consistently decreases from core to rim to periphery.

Transition speeds observed in late adopting markets are therefore not directly applicable to new technologies beginning in early adopting markets which face lengthy formative phases. Sovacool mentions this spatial dimension but fails to control for it.

Figure 2. Diffusion speeds accelerate as technologies diffuse spatially. Notes: Bars show durations of diffusion measured by cumulative total capacity installed, with historical data fitted via a logistic growth curve and the diffusion duration expressed as Δt in years. 'Core' is typically within the OECD; 'Rim' is typically Asian countries; 'Periphery' is typically other world regions. For details and data, see: (Wilson 2012, Bento 2013).



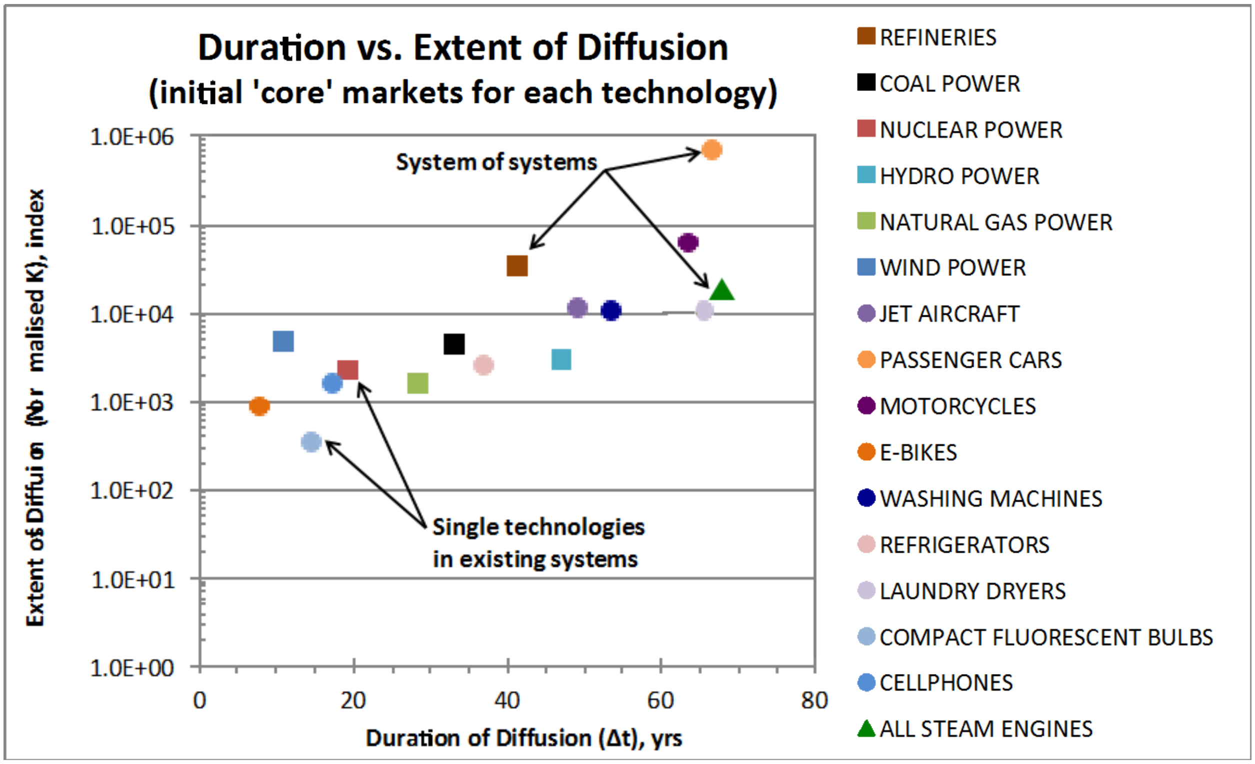
***c**. Market size and transition speeds are **inversely** correlated**: s**mall markets can change quickly, large markets only slowly.*

Generalizing rapid transition speeds in later adopting markets - as Sovacool seeks to do - is misleading for a second reason. Later adopting markets tend to see less pervasive diffusion (i.e., lower market shares, or saturation at lesser extents). As noted above, this reflects the long time constants of change in the inter-related systems of technologies, infrastructures, institutions, and end users.

Diffusion processes are slower when saturation levels are more pervasive (Grubler 1998). Empirically, the extent and duration of capacity expansion for energy technologies are strongly and positively related (Figure 3). Both axes of Figure 3 show parameters from logistic functions fitted to historical time series data of cumulative total capacity. The x-axis is a measure of the duration of diffusion. As explained earlier, Δt is the period a technology takes to grow from 10%

to 90% (or from 1% to 50%) of its final saturation level. This saturation level is shown on the y-axis as a measure of the extent of diffusion, normalized to account for differences in the overall size of the energy system (i.e., analogous to market share). For details of the methodology and data, see: (Wilson 2012, Bento 2013).

Figure 3. Diffusion durations scale with market size (Wilson and Grubler 2015). Notes: x-axis shows duration of diffusion (Δt) measured in time to grow from 10% to 90% of cumulative total capacity; y-axis shows extent of diffusion normalized for growth in system size. All data are for 'core' innovator markets. Round symbols denote end-use technologies; square technologies denote energy supply technologies; triangular symbol denotes general purpose technologies (steam engines). Arrows show illustrative examples of system of systems (refineries describing the rise of multiple oil uses across all sectors, cars describing the concurrent growth of passenger cars, roads, and suburbs, and steam engines are a proxy of the growth of all coal-related technologies in the 19th century). Arrows also highlight examples of single technologies diffusing into existing systems substituting existing technologies (nuclear power, compact fluorescent light bulbs).



The consistency of the relationships in Figure 3 between the extent and duration of diffusion is surprising as the end-use and energy supply technologies analyzed are of markedly different characteristics (Wilson et al. 2012). 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 so on. Why should the observed extent - duration relationships be so consistent across technologies? Or - of relevance for the question of rapid transitions - why does diffusion into larger markets always take longer?

Vaclav Smil in his contribution in this Issue argues that “scale matters”. The critical interdependence between systems size, complexity (discussed above), and related capital intensity of the global fossil-fuel infrastructure (highlighted by Smil) constitute powerful constraints for rapid change and explain the consistent relationship between scale and rapidity of change: small systems can change fast, large systems only slowly.

One additional reason is end-users. How rapidly and how extensively demand changes is both driven and constrained by the adaptability of end-user needs and wants. Larger markets include larger numbers of late adopters, characteristically resistant to change. Another reason is inter-dependent infrastructure and institutions. Larger markets require greater ancillary investments in infrastructure build-out and a greater reach of market or regulatory institutions which enable diffusion. Both these reasons are central elements in Unruh’s conceptualization of lock-in by ‘techno-institutional complexes’ (Unruh, 2000). Resulting inertia may be qualitatively similar in small and large markets, but - ceteris paribus - will take longer to overcome as markets increase in size.

A third reason why inertia to change may scale with market size relates to the drivers of technological change, particularly those which move innovations to mass market (Grubler 1998). These drivers include knowledge generation through R&D, learning and scale effects, knowledge spillovers (and knowledge depreciation), as well as entrepreneurialism, demonstration activities, niche market applications, and so on (Grubler et al. 2012). Larger markets typically involve larger numbers and diversities of innovation actors, more diverse end-user experiences feeding back into technology development, more heterogeneous innovation search activities (e.g., R,D&D), and so on. While it is hard to generalize the effect of large market size on the direction, effectiveness, or quality of technological lifecycles, it is intuitive that the drivers of technological change will play out over longer durations. This generalization is clearly not a rule, as larger markets may also be more centralized, concentrated, homogeneous. It is therefore important to take into account the different technology characteristics and factors in the adoption environment which explain differences in diffusion speeds (see below).

The importance of comparing like with like.

Sovacool's apples-and-oranges comparison between the slow dynamics of global system transitions and the seemingly rapid dynamics of national end-use and resource transitions fail to account for any of the important determinants outlined above. Sovacool's selective examples of rapid transitions are variously characterized by one or more factors associated with faster transition speeds. These include: (1) selective specific markets (2) omitted formative phases (3) already-constituted innovation systems (4) proven technologies (5) later adopting markets (6) relatively small market sizes. Comparing these rapid transitions to global aggregates or to the experiences of early adopter 'core' markets in which technologies were first developed is highly misleading. The temporal and spatial phase of the overall diffusion lifecycle of an innovation is critically important and needs to be considered in like-for-like comparisons.[10]

5. Adoption decisions, effort, and benefits explain differences in transition speeds.

Two related research fields offer particularly relevant insights into the factors that explain vastly different speeds of transition processes: diffusion research; and empirical studies within industrial economics on the adoption of industrial innovations that also use many fundamental concepts of diffusion research.

The iconic work summarizing and synthesizing the diffusion research field are Everett Rogers' *Diffusion of Innovations* whose five editions span the period from 1962 to 2003. Rogers (2003) summarizes the findings from a wide range of diffusion studies across many sectors and disciplines on the determinants of the diffusion rate (speed of adoption, or in the present context speed of transition). According to Rogers these determinants can be regrouped into two broad categories, those related to the adoption environment, and those related to the innovation characteristics.

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[10] Careful distinctions between new and proven technologies, and between early and late adopting markets, are important when comparing transition speeds due to the non-linearity in the expansion of a new technology or in the transition from one system state to another one. The well-established technology life cycle model (Porter, 1990) is equally applicable to the energy transitions field. The 'fundamental laws' for new energy technologies proposed by Kramer and Haigh (2009), broadly confirmed by Wilson's (2012) analysis of physical up-scaling, are reincarnations of the technology life cycle model. These laws describe how technologies grow for two decades at exponential rates (~26%/yr) until reaching 'materiality', defined as a ~1% share of the global energy system, after which growth rates slow linearly to an eventual equilibrium market share. Hook et al. (2012) similarly note a 'scaling behavior' of technologies as a consistent inverse proportionality between growth rates and energy output. Technologies with larger market shares have lower growth rates as the denominator of the growth rate increases. Immature technologies in their formative phases when the installed capacity base, and so the denominator for growth rates, are low are likely to show high growth rates but small, slow changes in market share. Mature technologies in their stable growth phases when the installed capacity base is already high are likely to show low growth rates but larger changes in market share. As a result, growth rates or changes in market share cannot be simply compiled and compared without carefully accounting for differences in diffusion/life-cycle stages.

Factors in the adoption environment that can explain differences in diffusion speed include: the type of adoption decision (individual, collective, authoritative), the type of communication channels involved (mass media vs. word-of-mouth, interpersonal communication), the nature of the social system (interconnectedness, sources of learning: internal vs. external), and lastly, the existence and efforts of change agents that promote diffusion among members of a social system. Often these determining factors of transition speeds are very context dependent. For instance, as Rogers (2003) discusses, authoritative decision making not necessarily leads to faster adoption or transitions if in conflict with other characteristics of the adoption environment or innovation characteristics, e.g. when the "mandated" new solution is perceived as being disadvantageous.

Factors related to the characteristics of an innovation that explain differences in adoption speed include according to Rogers, the perceived attributes of an innovation in particular its relative advantage (e.g. performance, costs) compared to existing products/technologies, the required adoption effort (e.g. upfront investment costs), and the compatibility, observability, and trialability of an innovation. With exception of the adoption effort, all factors are positively related to the diffusion speed, i.e. the higher the relative advantage of an innovation, the higher the observability (social visibility) of its adoption, or the higher its compatibility (with social norms and pre-existing practices and infrastructures), the faster diffusion is expected to happen. Conversely, adoption speed and effort are negatively correlated, i.e. the higher the adoption effort (e.g. upfront investment), the slower diffusion. While a quantitative meta-study the replicates the qualitative synthesis of Rogers remains outstanding, studies on the diffusion of industrial innovations provide quantitative results on the influence of different factors on diffusion speed. Two classical references are Mansfield (1968) and Davis (1979) which studied the determinants of diffusion speed of a sample of 12 and 22 industrial innovations respectively. In these two samples diffusion speeds vary enormously from rapid to slow: from a Δt of 2 years (adoption of the tin can in the US brewing industry studied by Mansfield, 1968) to 52 years (adoption of electric hygrometer weaving in the UK textile industry, Davis, 1979) and yet in both studies excellent explicative power of these vast differences was obtained for two variables: investment size (adoption effort) and expected profitability (both models also include a sector-specific dummy variable to capture sectorial heterogeneity). In other words, despite the enormous range in diffusion speeds, differences in the speed of adoption of industrial innovations can be explained[11] by three variables: upfront costs, profitability of adoption, and

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[11] Equally important, also "balancing" relationships are revealed. For instance, in Mansfield's (1968) sample, a doubling of upfront investment costs could be compensated by an increase in an innovation's profitability by a factor of 2.3 if one wanted to maintain identical rates (speed) of change. In other words, the responsiveness to alternative incentives (e.g. investment tax credits versus price changes via environmental taxes) seems to be asymmetrical, certainly a useful piece of information to policy makers pondering on leverages for accelerated transitions.

sector characteristics.

Roger Fouquet in his contribution in this Issue summarizes his work on historical transitions in energy service provisions in the UK, emphasizing the critical importance of novel energy services as well as prices and their impact on stimulating demand growth. In the language of the above discussed diffusion literature transitions can happen fast when a novel, valued service is provided (high degree of relative advantage), service provision costs fall rapidly due to improved efficiency and economy of scale and learning effects (adoption efforts decline rapidly), and as a result, market response is vigorous (high demand growth providing for rapid capital turnover and further positive feedbacks on efficiency, scale, and learning effects). Fouquet’s prototype example of a rapid transition is the case of electric lighting that offers a unique combination of above discussed diffusion determinants resulting in a rapid transition: within 25 years 80% of all lighting services in the US (measured by lumen-hours delivered) switched from kerosene and gas lighting to electric lights. This compares to transition times of between 75 and 126 years that characterize previous transitions to town gas lighting or whale oil lamps in the UK.

Using the rapid transition example of LPG as household cooking fuel in Indonesia discussed by Sovacool and the insights from diffusion research mentioned above the rapidity of transition comes as no surprise as combining high relative advantage (clean, convenient, and price subsidized LPG) with low adoption effort (LPG stoves distributed for free as part of the substitution campaign) and a policy-driven extension of the LPG bottle distribution infrastructure from urban centers to the countryside. Readers can use their imagination of how the case of electric vehicles in California compares with the favorable Indonesia example in terms of the upfront costs of a Tesla car and the lack of a wide network of charging infrastructures in California before deciding if indeed as Sovacool seems to suggest, there are no practical limits to the rapidity by which technological transition can happen.

Lastly, diffusion pioneer Everett Rogers provides yet for another cautionary observation: the pro-innovation bias of the literature, i.e. mostly successful diffusion or transition cases are studied and described, with failures remaining largely undocumented. Indeed household fuel choices in China and in Indonesia have changed rapidly as Sovacool points out. And yet, it should also be mentioned that despite numerous efforts and programs no comparable rapid transition has occurred in India to date (Mobarde et al., 2012). In contrast, taking a global technological systems view avoids this bias by including the sum of all diffusion processes: the fast, the slow, the successful and the failures. This may provide an additional reason why these process appear slow in comparison to speeds observed in selected case studies. Only when we

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can explain why transitions happen fast or slow, can we also start to address the question of how to address failed transitions (lack of diffusion), or carefully craft strategies of accelerated transitions, in case these are judged highly desirable from a social or environmental perspective.

Conclusion

The context of the current debate on the timing of technology transitions is that numerous such transitions are pending if indeed the political imperatives of the UN Sustainable Development Goals (SDGs) or the Paris climate agreement are to be translated into policy action, public and private sector investments, and changes in consumer choices and behavior. Simply pointing to selected cases of rapid transitions fails to convey to policy makers the urgency of action now in view of the required lengthy, decades-long overall transition required. There is also a risk of failing to communicate that faster transitions, while possible in theory, require a deep understanding of the determinants of the rates of change of complex social, economic, and technological systems that need to be translated into carefully designed policies, incentives, and communication strategies in order to achieve accelerated transitions. Degree of “political will” (as argued by Kern and Rogge in their contribution in this Issue) is a poor aggregate substitute for a deeper understanding of the multiple drivers that govern transition speeds.

The need for a “grand” transition towards sustainability is clear, be it for eradicating poverty worldwide, providing clean energy and water for all, ensuring universal health and sanitation, and all whilst respecting planetary boundaries like staying below a 2°C global mean temperature increase. Simply arguing that technological solutions (fixes) to respond to the climate challenge do exist as done by Bromley in his contribution in this Issue (but contradicted with useful words of caution and technology realism by Vaclav Smil) does not answer the question of how and how rapid these solutions can be brought to markets and diffuse pervasively and rapidly.

In our view, it is clear that an encompassing sustainability transition (that includes stabilizing climate change, but addresses many other pressing development goals as well) will require changes that are systemic, large scale (need to be implemented globally) and often have little immediate adoption benefits besides significant reductions in social and environmental externalities. Hence the required sustainability transition is highly likely to take many decades to implement fully.

In some locations (e.g. cities), in some sectors, for some consumer groups, or for some technologies, changes could happen fast. Sovacool provides some useful examples, and it is important that we learn more about the determinants of these success stories. But overall and at a global scale the complex hierarchies of technologies, practices, sectors, markets, and locations that all require coordinated changes provides for a daunting challenge for the highly ambitious time targets laid out in the SDGs or suggested by scenarios of deep decarbonization of our fossil fuel dominated energy systems. Nonetheless, it may be the most important contribution of Sovacool's thought-provoking piece: to move the discussion from "How long does it take?" to "What does it take?" to achieve rapid transitions. As the exchange in this Issue demonstrates, this critical conversation has begun.

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