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Short communication

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.

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 [13]. 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 [14]. 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 $2 \times \Delta t$, 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 flows are used often depends on data availability rather

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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 6–32 years compared to a range of between 47 and 69 years of the transition examples of western European economies in the 20th century shown in Table 2 of Sovacool [40].

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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 [32] 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% of registered cars in Brazil were Flexfuel [9] and their combined use of domestically produced ethanol accounted for only 18% of road transport energy use [24]. This is hardly a situation one can consider a completed rapid energy transition.

Box: Definitions Energy transition: change in the state of an energy system.
"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.

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).

[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 [32].

[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.