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Review

Rethinking innovation for decarbonizing energy systems

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ABSTRACT

While technological innovation is an implicit element of any plausible strategy for responding to climate change, the complexity of innovation processes has not been adequately accounted for in such strategies. Using many examples from different areas of technological innovation, we show that the inevitable unintended and unforeseeable consequences of innovation likely make it impossible to strategically steer the global energy system in desired directions. Given this conclusion, we then look at technological complexity in terms of a simple three-level schema of sociotechnical change. This perspective points towards innovation policies that focus on long-term, incremental advance at the level of individual technologies, and on public policies that use a public goods-public works rationale to justify government investments in the needed innovations.

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Technological innovation since the time of the first Industrial Revolution is the proximate cause of global warming. Further innovation in technical and social systems is the necessary route to mitigation. Always and everywhere, innovation is messy, complicated, and contingent. Major questions for mitigation of climate change begin with choice of policy tools for guiding the world energy system along desirable pathways. And while prospective technologies have been reasonably well mapped, policy choices—dependent on political coalitions that solidify and dissolve unpredictably—cannot be similarly mapped. For example, governments must find ways to reduce emissions of greenhouse gases (GHGs) while at the same time providing ample supplies oflow-cost energy for those who cannot afford high-cost energy, a difficult task in poor parts of the world and impoverished enclaves even in the wealthiest countries. They will have to devise political arrangements that foster innovation while dampening and diffusing opposition by interests that see their freedom of action and profits threatened.

With hindsight, the societal and technological aspects of innovation can be uncoupled; foresight necessarily remains conjectural because of system-level complexity. This essay explores the implications of such complexity for moving toward a low-carbon global energy system. Our argument unfolds in three parts. Sections 1–3 examine the complexity of technological change in the contexts

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of energy, innovation itself, and the social forces that condition innovation. Section 4 provides a three-level framework for helping to make sense of the complexities explored in preceding sections. Section 5 discusses aspects of energy technology innovation that make it different from other technological domains, and Section 6 discusses why these differences make the shift away from carbon-based energy especially challenging. In our concluding section we articulate what we believe to be the two main lessons of our overall analysis. First, given the complexity and contingency of energy systems, steering them in a desired direction—that is, toward a zero-carbon future—can best be achieved through a focus on accelerating innovation of specific energy technologies. Second, and following from the previous point, policies aimed at accelerating a transition to a zero-carbon future will be most successful over the long-term when they adopt a direct, public goods approach to technological change.

1. Introduction

The essence of the climate-change dilemma for policy and politics has commonly been viewed in terms of externalities and the conflict between energy prices (actual, or shadow prices intended to offset externalities, in part or in whole, as for instance through carbon taxes) and presumptive climate change mitigation costs [1]. While narrowly true, the issues run deeper. In wealthy countries, economic, political, and cultural forces have locked in place systems (for electric power, for transportation) based predominately on fossil fuels [2]. These represent complex and often opaque political and social arrangements and enormous sunk costs. At the same time, fossil fuels remain relatively abundant and relatively inexpensive. No one can know what level of energy prices might be necessary to drive to completion, within a few decades, the social and technical changes necessary to move away from fossil fuels. More to our point, no one can know what highly unpredictable consequences for society and the environment such price rises might create.

The reasons reflect standard views of uncertainty in technological and sociotechnical systems. Short-term forecasting of many technological and some sociotechnical trends is feasible, and useful. Past some (unknowable) point in time, predictions, even for “simple” technological components and systems become increasingly likely to go off the rails [3]. For non-simple, that is to say complex systems [4]—uncertainty mounts because of incomplete or imperfect understanding of interactions among system components [5]. The usefulness and reliability of predictions therefore depends on context: on what is known, in terms of mechanism and past history, of the system in question, as well as on the time frame of interest.

In some cases, of course, prediction is impossible, as for scientific/technological discoveries without precedent in either theoretical understanding or past empirical findings. High-temperature superconductivity, an example that surfaces briefly later in this essay, illustrates. Three decades after the initial discovery in 1986, advances such as new material combinations resulting in higher critical temperatures still cannot be anticipated. This is because the well-established mechanisms that explain superconductivity in elemental metals and their alloys fail for the new classes of complex intermetallics synthesized since the mid-1980s and no adequate theory for these new materials has yet appeared. Research, under these circumstances, continues to be guided by heuristics.

For existing technologies, or technological families, those for which an experience base exists to be queried—lithium-ion batteries for electrically-powered vehicles or flow batteries for grid storage—advances in performance (however performance might be measured) can be anticipated, within limits, through methods such as extrapolation of learning or experience curves. Absent a useful experience base, expert judgment easily goes astray. Zinc-air batteries, theoretically superior to lithium-ion cells, have been under development for decades; no one can say with confidence if or when rechargeable zinc-air batteries will become practical [6]. If they do, substantial changes in road vehicle technologies would likely follow, since zinc-air promises much greater range (because of much greater energy density) and much lower costs (since zinc is inexpensive) than lithium-ion systems. Given a few data points, learning curves for zinc-air systems and zinc-air-battery-powered electric vehicles would provide a basis for technological prediction.

Combining an innovation such as practical zinc-air battery systems with the socioeconomic dimensions of market acceptance, patterns of usage, and the ongoing evolution of transportation infrastructure and urban/regional development introduces complexity of the sort that defeats predictability. Indeed, even in hindsight explanations for outcomes involving social, political, and economic dynamics combined with technological development will sometimes remain contested more or less indefinitely, as for example in retrospective evaluations of choices made during the 1950s and 1960s among competing nuclear power reactor design concepts. Directions of technological change relevant to the climate-energy challenge may be powerfully influenced by unpredictable exogenous factors as diverse as political change (for example, US President Ronald Reagan's disinvestment in renewable energy in the 1980s), economic factors (for example, the decline in hydrocarbon fuel prices due to improvement in hydrofracking techniques), or even geological events (for example, the 2011 Tohoku earthquake and tsunami and its effects on social attitudes toward nuclear power). Indeed, a major goal of this essay is to explore in a different way what uncertainties in technological change imply for successful policies aimed at decarbonizing energy systems.

2. Innovation in context

Whatever pathways societies may follow in managing the consequences of GHG buildup, those pathways are today unpredictable, and as they unfold are likely to be highly diverse. To begin with, invention, commercialization of innovations, and diffusion proceed differently in different parts of the world, depending on “innovation systems” that reflect institutional structures, politics, and culture, as well as technological particulars [7]. Nicholas Bloom, an economist who has conducted extensive cross-national comparisons of firm-level performance, may overstate, or maybe not, in saying “If Sam Walton had been based in Italy or in India, he would have five stores by now, probably called ‘Sam Walton's Family Market.’ Each one would have been managed by one of his sons or sons-in-law” [8].

More broadly, the common feature of innovation, whether technological, political, or behavioral (individual and societal), is this: Whatever is considered new is not just an idea but a change of some sort that has diffused and found acceptance, with observable consequences. In the pioneering analyses of Joseph Schumpeter during the first half of the 20th century, which continue to underpin our understanding of innovation, business entrepreneurs devise and bring to market new products (automobiles, telephones), learn to produce familiar goods or services in new ways (catalog retailing in the 1920s, Internet retailing today), and introduce new forms of organization (joint stock corporations, lean production in manufacturing) [9]. All such efforts can also be understood as part of an ongoing process of social and technological co-evolution [10].

As Schumpeter understood, the immensely productive dynamism of economies such as that of the United States stems in large measure from the entry of new firms and the exit of old. New product concepts do not count as innovations until commercialization—marketplace introduction—after which some