Carbon Lock-In: Types, Causes, and Policy Implications

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Abstract

Existing technologies, institutions, and behavioral norms together act to constrain the rate and magnitude of carbon emissions reductions in the coming decades. The inertia of carbon emissions due to such mutually reinforcing physical, economic, and social constraints is referred to as carbon lock-in. Carbon lock-in is a special case of path dependency, which is common in the evolution of complex systems. However, carbon lock-in is particularly prone to entrenchment given the large capital costs, long infrastructure lifetimes, and interrelationships between the socioeconomic and technical systems involved. Further, the urgency of efforts to avoid dangerous climate change exacerbates the liability of even small lock-in risks. Although carbon lock-in has been recognized for years, efforts to characterize the types and causes of carbon lock-in, or to quantitatively assess and evaluate its policy implications, have been limited and scattered across a number of different disciplines. This systematic review of the literature synthesizes what is known about the types and causes of carbon lock-in, including the scale, magnitude, and longevity of the effects, and policy implications. We identify three main types of carbon lock-in and describe how they coevolve: (*a*) infrastructural and technological, (*b*) institutional, and (*c*) behavioral. Although each type of lock-in has its own set of processes, all three are tightly intertwined and contribute to the inertia of carbon emissions. We outline the conditions, opportunities, and strategies for fostering transitions toward less-carbon-intensive emissions trajectories. We conclude by proposing a carbon lock-in research agenda that can help bridge the gaps between science, knowledge, and policy-making.

Contents

1. INTRODUCTION TO CARBON LOCK-IN

Ambitious goals for climate change mitigation such as those adopted in the Paris Agreement will require rapid reduction of regional and global CO_2 emissions, on the order of 5–10% per year (1, 2), which in turn requires transformations of vast and entrenched networked systems of infrastructure, institutions, and human behaviors. The current global energy system is the largest network of infrastructure ever built, reflecting tens of trillions of dollars of assets and two centuries of technological evolution, and is supported by an equally extensive complex of coevolved institutions, policies, and consumer preferences (3–5). Roughly 80% of the energy delivered by this system worldwide now comes from burning fossil fuels (6), with attendant CO_2 emissions that are the primary cause of climate change (7).

However, the inertia of technologies, institutions, and behaviors individually and interactively limit the rate of such systemic transformations by a path-dependent process known as carbon lock-in, whereby initial conditions, increasing economic returns to scale, and social and individual dynamics act to inhibit innovation and competitiveness of low-carbon alternatives (4, 8, 9). In particular, inexpensive and reliable energy is central to the techno-institutional complex that underpins all historical industrialization and continues to support high levels of consumption in the most developed countries of the world, and for more than a century the dominant source of this energy has been fossil fuels. Society's desire for economic affluence and the related demand for energy will increase. For example, many of the Sustainable Development Goals (SDGs) recently passed by the United Nations (10) include improving the accessibility and quality of modern energy services (SDG-7), promoting economic development and industrialization (SDG-9), and supporting consumption (SDG-12). However, given all historical precedents, these goals are at odds with efforts to reduce the use of fossil fuels to combat climate change (SDG-13). Reconciling these goals thus requires rethinking and remaking a monolithic and change-resistant complex of technologies, institutions, and behaviors that have up until now been vital to the economic activities and growth that we are determined to sustain.

Path-dependent processes are those that develop inertial resistance to large-scale systematic shifts, with resistance to change driven by favorable initial social and economic conditions and the momentum of increasing returns to scale. There are many examples of path dependence that entrench technical, institutional, and behavioral systems with known technical and environmental disadvantages. Where these disadvantages include carbon emissions to the atmosphere, the path dependence is termed carbon lock-in. Carbon lock-in generally constrains technological, economic, political, and social efforts to reduce carbon emissions. Given the predicted magnitude and timeline of its worst impacts, an effective response to climate change will require large-scale and relatively rapid disruption to existing systems. Carbon lock-in poses significant challenges to making such changes on the necessary timetable, especially when the changes needed require undoing quite entrenched and reinforced patterns and institutions in multiple technological, economic, political, and social systems. Undoing or escaping carbon lock-in will require undertaking significant initiatives and investments in the near term while retaining flexibility to adapt, refine, and replace those initiatives and investments in the long term. Here, we review recent progress conceptualizing, evaluating, and quantifying carbon lock-in and its drivers; examining important examples, types, and causes; exploring the scale, magnitude, and longevity of the effects; and outlining possible policy implications.

We conceptualize three major types of carbon lock-in: (*a*) lock-in associated with the technologies and infrastructure that indirectly or directly emit CO_2 and shape the energy supply; (*b*) lock-in associated with governance, institutions, and decision-making that affect energy-related production and consumption, thereby shaping energy supply and demand; and (*c*) lock-in related to behaviors, habits, and norms associated with the demand for energy-related goods and services. Henceforth we refer to these as infrastructural and technological lock-in, institutional lock-in, and behavioral lock-in, respectively. We refer to the path dependence of these interacting technological, institutional, and behavioral systems as lock-in, with carbon lock-in referring to a specific negative type of lock-in related to systems that emit carbon. In contrast, lock-in favors the status quo but is normatively neutral: It can foster either positive or negative outcomes. Carbon lock-in is negative because it inhibits changes deemed desirable, such as a transition to a low-carbon society. An alternative lock-in taxonomy might differentiate lock-in related to energy supply (e.g., the infrastructure to generate and transmit electricity) from lock-in of energy demand (e.g., end-use technologies, habits, and behavior). The concept of carbon lock-in suggests that the three types of lock-in are mutually reinforcing and create collective inertia. Consequently, efforts to break from one type of lock-in result in hardening or compensating resistance to change in other types of lock-in.

2. INFRASTRUCTURAL AND TECHNOLOGICAL LOCK-IN

The long life of physical infrastructure may lock societies into carbon-intensive emissions pathways that are difficult or costly to change, emphasizing the importance of initial conditions and early decisions. They also involve long lead times, that is, investments in which costs occur now and payoffs occur later, and create substantial sunk costs (**Figure 1**).

There are two main strategies for reducing energy-related CO_2 emissions: decreasing the carbon intensity of energy used (i.e., the CO_2 emitted per unit of energy) and decreasing the energy intensity of the economy (i.e., the energy used per unit of economic production). The two strategies are sometimes related, for example, where a specific fossil fuel–burning device is involved.

Energy demand patterns are locked in through large incremental investments in long-lasting built infrastructure, such as street layouts, land use patterns, and buildings, with the ultimate effect of inhibiting efforts to reduce the energy intensity of an economy. Elements of the built environment determine energy demand for decades after their construction. In areas with high construction rates, these lock-in risks underscore the urgency of adopting state-of-the-art

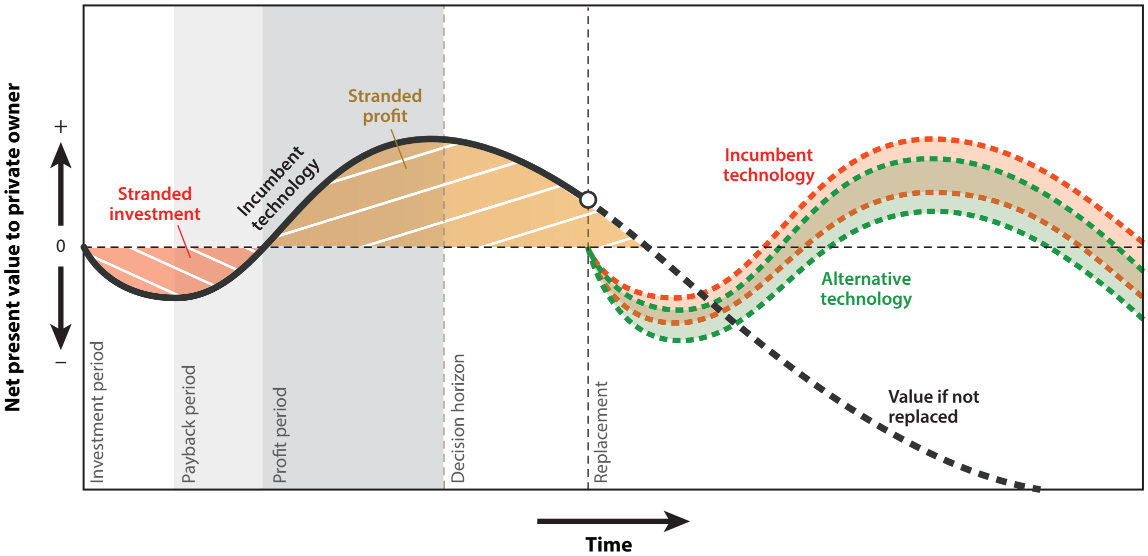

Figure 1

Schematic of the value of a hypothetical energy asset over its lifetime. The solid black curve depicts the net present value (NPV) of a capital asset such as a power plant to its private owner. During the investment period, capital costs exceed operating returns. When this ceases to be the case, NPV begins to increase, and the returns gradually pay back the initial capital investment. Afterwards, there is a profit period until the aging asset's operating and maintenance costs begin to encroach on returns. Depending on the time required to finance and permit the asset's replacement, a decision must be made about retrofit or replacement technologies in anticipation of future costs, risks and policies. If this expected economic life cycle is interrupted by early replacement of the asset, value will be lost. Depending on how early, the losses due to such early replacement will include "stranded investments" (i.e., unpaid capital costs) and/or "stranded profits" (i.e., anticipated operational profits). Furthermore, if technology costs and policies are changing quickly may also greatly increase risks. The black dashed line after the replacement suggests the NPV if the asset were not replaced and continued to be maintained at ever greater expense.

performance standards. Together, buildings and urban form lock-in transport mode choices, average distances traveled, housing choices, and behaviors (11).

Meanwhile, reductions in the carbon intensity of energy produced are constrained by long-lived fossil fuel–burning infrastructure, which are in turn dictated by operating conditions, fuel type/quality, and physical specifications, which typically change little over the lifetime of the infrastructure (barring a major upgrade or retrofit). Despite known environmental disadvantages, the fossil fuel energy generation and distribution system thus represents a barrier to the adoption of new and cleaner renewable energy technologies.

Less directly, fossil fuel–supporting infrastructures such as pipelines, refineries, and gasoline stations also contribute to locking in carbon intensity insofar as their value is dependent on the extraction and transport of fossil fuels. The lock-in contributed by these supporting infrastructures may be understood according to the concept of asset specificity (12), which describes inputs that cannot be readily used by other systems because the investments are unique to a particular task. Thus, owners of assets that do not directly burn fossil fuels may nonetheless have strong incentives to favor policies that maintain lock-in insofar as their assets are specific to the technologies favored by the existing form of lock-in. Such supporting infrastructure also suggests the self-reinforcing incentives to resist change. Indeed, lock-in is not suboptimal from the point of view of those entities that benefit from it. In this regard, lock-in is a commons dilemma: What benefits individuals may not benefit the whole of society.

2.1. Carbon-Emitting Infrastructure

Lock-in due to technologies that directly emit CO_2 has increasingly been the subject of quantitative research. Early modelers of socioeconomic inertia with respect to climate change explored the most cost-effective pathways to CO_2 abatement when different infrastructure lifetimes were assumed and found that abatement delays make climate mitigation much more costly (13). This conclusion conflicted with assertions from other scholars who argue that mitigation efforts should target more reversible—cheaper—capital stock (14). There is growing consensus, however, that delayed mitigation will be more costly (15, 16). In 2009, the World Bank made the point more explicitly, identifying the specific types of long-lived infrastructure that most contribute to socioeconomic inertia (17).

In 2010, this literature was extended by estimating global committed emissions, that is, future CO_2 emissions expected if all existing infrastructure were operated during its expected lifetime (18). By assessing the age distribution of power plants, on-road vehicles, and industrial and commercial infrastructure in different countries worldwide, it was found that these systems could be anticipated to emit cumulative future emissions of 496 Gt of CO_2, nearly half of which will come from power plants (18). If the historical buildup of power infrastructure is considered, then total committed emissions in the power sector are estimated to have increased globally at the rate of ~4% per year (19). Further, the results showed that 1 Gt of future CO_2 emissions is committed by roughly every 6 GW of new coal-fired generating capacity and every 12 GW of gas-fired generating capacity. However, these numbers are sensitive to the expected lifetime of power plants as well as their capacity factor (i.e., the fraction of time the plants are operating). For instance, it has been estimated that existing power plants worldwide would emit 307 Gt CO_2 in the future if a 40-year lifetime were assumed for each plant (19). However, assuming a 20-year lifetime decreased the total emissions to 98 Gt CO_2, whereas assuming a lifetime of 60 years increased the estimate to 578 Gt CO_2.

The sensitivity of committed emissions to infrastructure lifetime highlights a key uncertainty related to quantifications of technological lock-in: The decision to retire a device is usually based on an evaluation of economic competitiveness that incorporates mounting maintenance or looming retrofit costs, the costs of alternatives, and the current and anticipated social and policy context (e.g., **Figure 1**). Additionally, economic incentives can increase or reduce the extent of lock-in. For example, mobile phones and computers are replaced well before their technology becomes obsolete or economically noncompetitive because we are incentivized to upgrade the technology. At its simplest, the problem is that adoption of a low-carbon energy technology is not economically favorable until the capital and operating costs of the new technology are less (and probably substantially less) (e.g., 20) than the capital and operating costs of the incumbent fossil fuel–burning technology (21), which is unlikely to happen during the normal lifetime of the already-operating technology. This is especially true for power plants where the end-product is not functionally different after switching to a new, cleaner technology. However, sufficiently aggressive policies could shift the balance toward new low-carbon technologies. In this case, though, the policies will incur costs by "stranding" serviceable energy assets. Thus, another rapidly developing area of research is assessing the potential of different policies to create stranded power-generating assets (22–25). Related to this future-looking research, activists have begun tracking proposals to build new emitting infrastructure and opposing their construction on the grounds of the emissions that the new infrastructure would commit (26, 27).

A particularly ambitious and comprehensive assessment evaluated the costs of carbon lock-in from different technologies based on their expected lifetime, the carbon price required to make a low-carbon alternative competitive, the difference between deployment levels in business-as-usual and 2°C scenarios, and the market share of the technology in its industry sector (28). The results highlight the acute risks of coal-fired power plants, whose operating lifetime can be more than 50 years and can require a carbon tax of up to \$100 per ton of CO_2 (tCO_2) to induce replacement (**Figure 2**). The authors also noted the very high lock-in risk posed by internal combustion vehicles in the transport sector: Despite their shorter operating lifetimes, such vehicles command the vast majority of the large and growing personal transportation market and, once sold, would require a very high carbon price to displace (>\$1,000 per tCO_2).

In connection to lock-in research, some researchers have directly compared estimates of committed emissions to carbon budgets corresponding to different climate targets. For example, a

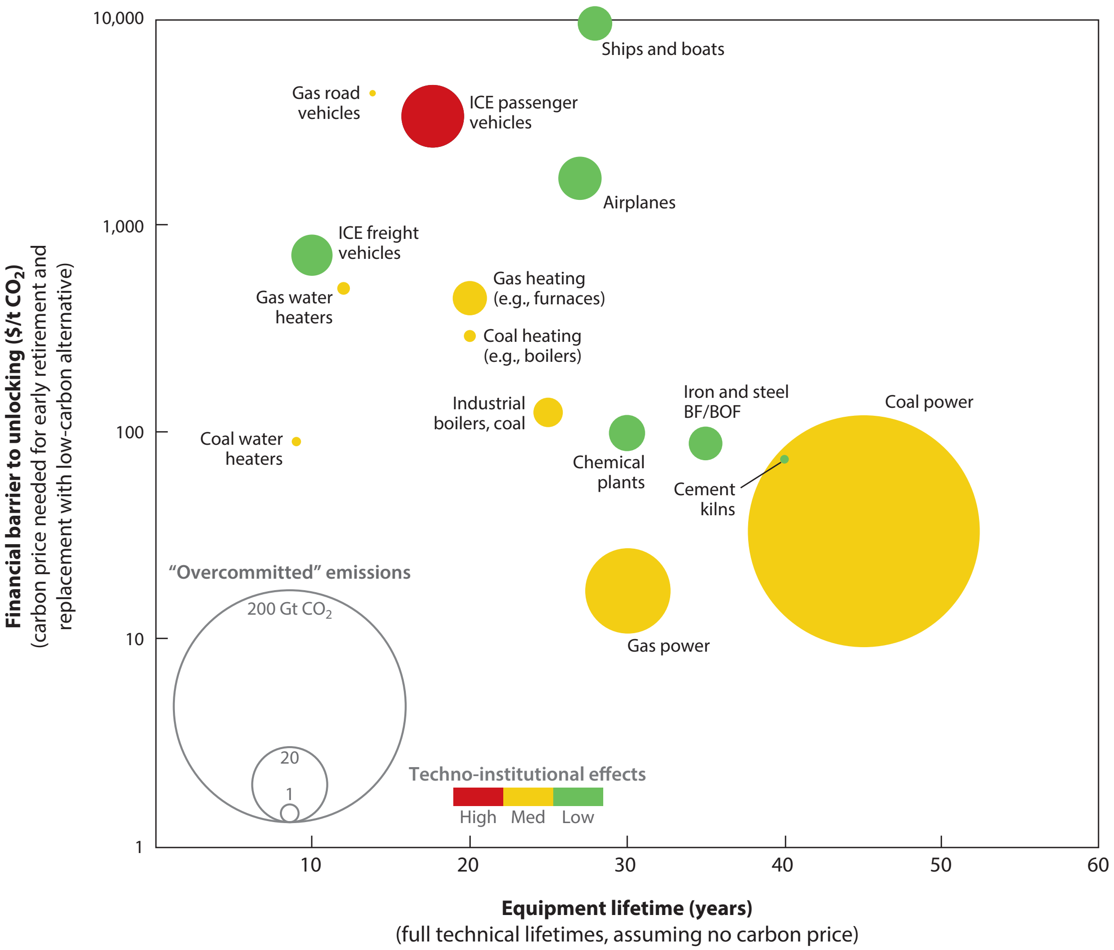

Figure 2

Assessments of lock-in related to different types of CO_2 emitting infrastructure. Different types of fossil fuel–burning infrastructure are plotted according to their historical lifetime (*x*-axis), the carbon price (\$ per ton of CO_2) that would be required to equalize the marginal cost of the existing infrastructure (mainly fuel) with the total levelized cost (i.e., including capital and operating expenses) of a low-carbon replacement (*y*-axis). The sizes of circles reflect the cumulative future emissions related to each type of infrastructure that are in excess of what that type of infrastructure can emit under a 2°C climate scenario, and the colors are a qualitative indicator of the techno-institutional resistance of that type of infrastructure to unlocking (e.g., stocks of very specific intellectual capital, established subsidies, entrenched social norms, large supporting infrastructures, political influence, etc.). For further details, see source (28). Adapted under CC BY License (**https://creativecommons.org/licenses/by/3.0/**).

recent study shows that global committed emissions in 2013 were half of the total CO_2 emissions associated with a 50% chance of avoiding 2°C of mean surface warming relative to preindustrial levels (1). Another study analyzes several thousand scenarios of infrastructure lifetimes, economic growth, and carbon budgets (reflecting uncertainty of both climate sensitivity and the availability of negative emissions) to estimate the carbon intensity of future economic growth (25). In half of the scenarios, a 2°C target required an intensity of economic growth between 33 and 73 gCO_2/\$—much lower than the current global average of 360 gCO_2/\$. Furthermore, each year of lifetime added to existing carbon-emitting infrastructure decreases the carbon intensity of future economic growth required to meet a 2°C carbon budget by 1.0–1.5 gCO_2/\$, and on the current emissions trajectory, each year of delaying the start of mitigation decreases the required intensity by 20–50 gCO_2/\$ (25).

Although nearly all analyses of carbon lock-in have focused on how incumbent fossil fuel technologies resist displacement by low-carbon alternatives, low-carbon alternatives may also be locked-out by earlier generations of low-carbon technologies. For example, perovskite is an emerging photovoltaically active material that holds the promise of greatly improving upon the efficiency and cost of current crystalline silicon solar cells. However, there is a large uncertainty on what the pace of production cost decline will be for perovskite, and the funding for research on perovskite technologies from US federal agencies is low compared to the funding levels for silicon solar cells that dominate today's rapidly growing solar market (29).

2.2. Carbon Emissions–Supporting Infrastructure

Most CO_2-emitting technologies depend upon networks of supporting, nonemitting infrastructure such as pipelines, refineries, and refueling stations, but the extent to which these latter technologies contribute to carbon lock-in has not been quantitatively estimated. Doing so would entail valuing the contribution of these technologies per unit of fuel burned (and CO_2 emitted), for example, by their cost of replacement. In specific cases, researchers have estimated future greenhouse gas emissions related to supporting infrastructure. For example, studies have estimated that the controversial Keystone XL oil pipeline would increase annual emissions by 0 to 110 Mt CO_2-equivalent (28). Similarly, others have sought to quantify the additional future emissions linked to U.S. coal exports, including terminals proposed for the Pacific Northwest (27, 30). These types of estimates typically depend upon models of supply and demand and counterfactual scenarios that are difficult to evaluate, especially given the historic unpredictability of energy markets.

Similarly, researchers have also begun to estimate resource assets that might be stranded by policy. One 2014 study, for instance, estimated the types and locations of fossil fuels that are unburnable under a 2°C target (31). Others have looked at the extent to which such stranded fossil fuel reserves might spur deployment of carbon capture and storage (CCS) technologies (32). Reversing the perspective, a recent commentary suggested that substantial investments related to fossil fuel exploration might reflect a commitment to extract and burn proven reserves, noting that between 1980 and 2013 total proven oil reserves grew at more than twice the rate of oil extraction (33). In the time since, analysts have begun working to develop methodologies for estimating and reporting emissions represented by fossil reserves (34), new investments in oil (35), and cumulative emissions (36).

2.3. Energy-Demanding Infrastructure

Some of the longest-lived infrastructures are not CO_2-emitting power plants—which last on the order of decades—but buildings, transportation infrastructure, and other spatial arrangements of urban settlements. The fundamental building blocks that make up the physical features of urban settlements, such as the layout of the street network and the size of the city blocks, can affect and lock in energy demand for long time periods (37, 38). Once in place, basic urban structures and patterns are not easily reversed. The long-lasting legacy of urban form is evident in cities around the world, with examples of spatial patterns dating back hundreds to thousands of years. The fact that cities usually develop incrementally limits the opportunities to adopt alternatives that could prompt and contribute to systemic change. There is significant interdependence among infrastructure, land use, transport and travel mode.

Only a handful of studies have examined locked-in energy demand from urban form. One 2011 study provided an estimate of greenhouse gas emissions related to future demand for energy in the transportation sector based on the location and density of existing infrastructure and assuming no change in the volume or modes of transport (39). According to their calculations, even with ambitious decarbonization of the transport sector, travel on existing roads between existing buildings represents a substantial additional commitment of future emissions from the transport sector.

Carbon emissions from activities in buildings result from a plethora of end-uses, some of them being flexible and fast to change, whereas others can be influenced over long time frames only. Heating and cooling energy use is strongly influenced by a combination of the physical characteristics of the building shell (e.g., the level of heat transmissivity of the walls, roofs, floors and windows; reflectivity of the insolated surfaces), the physical environment of the building (e.g., local climate, physical shading from insolation, barrier to winds, siting, and orientation), and the heating and cooling equipment (40).

These factors have different lifetimes. Some elements of the physical environment have long lifetimes, such as siting, building orientation, sources of shading, local heat islands, and heat sources and sinks. Others factors are less permanent, such as the elements of the building shell (e.g., basements, walls) and major heating-related infrastructure (e.g., district heating networks, availability of more efficiently burning heating fuels such as piped gas and electricity). Still, other factors are relatively short-lived, such as building insulation, doors, windows, roofs, building-integrated renewable energy generation sources such as photovoltaic cells. Very short-lived elements include heating and cooling equipment such as boilers and air conditioners.

Although it is difficult to attribute specific amounts of heating and cooling energy use to specific factors, building infrastructure is receiving increasing attention as a driver of emissions. While the literature on building energy use and its optimization has been dominated by a focus on equipment energy efficiency, recent research has also shed light on the importance of the building envelope in reducing building energy use. When the building shell is well designed, the building can have minimal or even no heating systems, even in the coldest climates.

Much of this also holds for cooling, although infrastructure has a more limited influence on cooling than heating for several reasons. First, a significant part of cooling energy use can be devoted towards air dehumidification, which does not apply for heating. Second, elements of the building infrastructure such as shading, thermal mass, and insulation can help limit cooling energy use only to a certain degree. Beyond certain levels of outdoor temperatures, even fully optimized building infrastructure cannot avoid the need for mechanical cooling. The key difference in this sense between heating and cooling is that there are many heat sources inside buildings (e.g., people, equipment) that could be effectively utilized for heating energy, whereas in the case of cooling, there are no sources of energy that could be utilized for this purpose.

Ventilation and lighting energy use are also influenced by the building's infrastructure. For the former, the air tightness of the building and ventilation infrastructure are the longer-living infrastructural elements determining ventilation energy use. For the latter, building surface to volume ratio, envelope and window structure, window surface areas, the internal wall, and furnishing design are all longer-lived infrastructural determinants of natural indoor illumination levels, and thus energy needs for artificial lighting. Daylighting infrastructures, some lighting system elements and fixtures, and wiring schemes, may also form part of the shorter- to mid-lifetime components of building infrastructures. In contrast, lamps and some light fixtures can be very short lived or low cost and are flexible to short-term replacements.

The expected lifetime of buildings varies considerably by geographic location, climate, culture, and affluence levels. Typical lifetimes for buildings and residences range from 20 to 30 years in places like China to more than 100 years in countries such as Australia and New Zealand (41, 42). Lifetimes are influenced by the durability and longevity of the materials used, the settlements, economic conditions, and cultural values (43). Some cultures favor long-lasting construction and place high values on old buildings, whereas others favor functionality and flexibility and turn over building stock more rapidly. Urbanization and other processes that facilitate or encourage migration also tend to shorten the lifetime of structurally usable buildings. The structure-related energy use of a building also strongly depends on the major retrofits performed on the building. Retrofit cycles are strongly determined by affluence as well as culture for similar building stock types. For instance, in the United States, buildings are regularly remodeled—involving changes in many parts of the building shell. In other regions, building shell–related infrastructure is mostly replaced only when needed. This can lead to highly variable cycles for major retrofits, from 20 years in the United States to 40 years in Europe.

3. INSTITUTIONAL LOCK-IN

Carbon lock-in arises when the infrastructural and technological lock-in (prior section) is reinforced by institutional lock-in (this section) and behavioral lock-in (next section). Political scientists, sociologists, and other social scientists have developed theories of institutional lock-in as part of broader theories of institutional stability and change, reflecting the view that institutional choices at one point in time significantly shape later choices (44).

Institutional lock-in differs from technological lock-in in important respects. First, lock-in is an intended feature of institutional design, not an unintended by-product of systemic forces. Because institutions are "distributional instruments laden with power implications," institutional lock-in rarely arises from "early chance events" but from conscious efforts by powerful economic, social, and political actors (45). These actors seek either to reinforce a status quo trajectory that favors their interests against impending change or to create and then stabilize a new, more favorable, status quo (46–48). These actors engage in intentional and coordinated efforts to structure institutional rules, norms, and constraints to promote their goals and interests in ways that would not arise otherwise. Second, this intentional nature of institutional lock-in means that it is beneficial for the winners in the "battle over the nature of institutions," even if it is suboptimal from an aggregate social welfare perspective (49). Third, differences between political processes and market forces make institutional lock-in likely to occur more often and with greater intensity than technological lock-in (48). Despite these differences, institutional lock-in parallels technological lock-in in that institutions end up in an inertial equilibrium state on a trajectory that proves quite resistant to change and that creates increasingly costly and challenging barriers to switching to any alternative trajectory.

3.1. Processes Leading to Institutional Lock-In

The extent to which institutions generate carbon lock-in reflects political conflict between actors who benefit from the existing set of economic, social, and cultural arrangements that favor a carbon-intensive trajectory and those who would benefit from an alternative trajectory. Both sides see institutions as a way to establish stable economic, social, and cultural systems that favor their interests. The short time horizons and status quo biases of politicians make it difficult to overturn governmental policies and institutions of any sort, including those that favor the use of fossil fuels (48). Institutions strengthen the interests of—and, hence, increase the resources available to—those powerful actors, such as oil and energy companies, that wield the most influence over their creation and modification (28, 48, 50, 51). Not surprisingly, the networks that arise among policy-makers, institutional bureaucracies, and powerful energy interests further reinforce and stabilize carbon-intensive systems. In an institutional feedback loop, those actors that most benefit from existing energy infrastructures push for institutional rules that further their interests, provide them with greater resources, reinforce their political and economic dominance, and allow them to deploy yet greater resources to shape institutions to their benefit. As in technological and behavioral carbon lock-in, such networks of relationships raise powerful barriers to efforts to get national political institutions to adopt policies that would foster a transition to a lower-carbon trajectory (44, 48).

Although institutional lock-in is a characteristic of institutions, it arises through the coevolution of multiple systems or spheres (8, 9, 52). Technological, economic, scientific, political, social, institutional, and environmental spheres coevolve, with changes in each being both responses to and causes of changes in other spheres (53). Coevolution involves iterative dynamics that strongly favor lock-in, with each sphere's norms, rules, actors, processes, and logic increasingly coming to favor reproductive over disruptive changes. Disruptive changes that do emerge in one sphere tend to be tamped down by status quo pressures from within that sphere and from other spheres. These dynamics generate a mutually reinforcing consistency, with each sphere and the system as a whole becoming increasingly resistant to change.

It is difficult to identify a single starting point for—or single cause of—lock-in. Light-water technology came to dominate nuclear power not because of its inherent technological or economic advantages but because of various governments' investments in research and development (R&D) and interventions in economic markets as well as intergovernmental cooperation that favored certain technologies and interests (54). Despite the obstacles to change presented by institutional lock-in, scholars have identified various pathways for institutional transitions (45, 55). Institutional change can occur through interactions between permissive conditions and prompting forces. Transitioning from lock-in is more likely if conditions have increased institutional plasticity, opening windows of opportunity during which policy entrepreneurs can promote carbon-reducing policies more successfully (28, 56–58). Many scholars have argued that such windows open up in response to exogenous shocks, as evident in France's shift toward nuclear power after the OPEC oil embargos of the 1970s and the shift away from nuclear power after the Three Mile Island, Chernobyl, and Fukushima accidents (52, 59, 60).

German experiences with renewables illustrate how iterative interactions between political institutions and the economic and technological spheres can undercut carbon lock-in. Efforts to promote renewables that began in the 1970s gained political support in response to the Chernobyl accident and early parliamentary reports on climate change (49). That momentum then was enhanced by a feed-in law that created incentives to invest in renewables, expanded markets, fostered learning networks, and increased the strength with which industry associations lobbied for renewables on economic grounds (49). These dynamics made lock-in of renewables sufficiently likely that traditional power sector actors lobbied to have these renewable policies overturned; in turn, the failure of those efforts reassured renewable energy investors, which promoted even faster growth (49). Similarly, intentional yet incremental policy changes help explain recent growth in renewables in various European countries (61, 62). Of course, these same processes can generate less optimistic outcomes as in decisions in some U.S. states (e.g., Nevada) to remove tax credit and/or subsidy policies for solar energy systems and electric cars in ways that lead companies and individuals to undo the carbon-reducing financial, technological, and infrastructural investments they have already made.

Whether exogenous shocks or intentional policy efforts foster an institutional transition depends on how relevant actors respond, which depends, in turn, on preexisting institutional, social, political, and economic landscapes. France responded to the OPEC embargo by investing aggressively in nuclear power, such that it grew from 25% to 75% of French electricity between 1980 and 2012; Britain responded quite differently and its nuclear share of electricity only grew from 12% to 19% during that period. Institutional lock-in is evident in the trajectory of French nuclear power, which appears to be wholly uninfluenced by domestic antinuclear protests or the Three Mile Island, Chernobyl, and Fukushima accidents. A given policy can produce different outcomes because different technological and political contexts provide firms and individuals different incentives that generate different economic and political responses and, hence, different outcomes. These feed back and create "different regulatory settings [that lead] to different patterns of adoption and implementation" (63). Disruptive policies initiate interactions among institutional, economic, political, and social spheres that can induce both positive and negative feedbacks: Newly favored firms gain economic resources they can deploy to demand further change, but their very success can prompt resistance from traditional firms. These comments highlight that efforts toward transition are more likely to fail than succeed and that success requires self-conscious and sustained promotion of protransition policies in the face of resistance by economically and politically powerful actors (49).

3.2. Transformative Theory: Escaping Institutional Lock-In

Like Hardin's "tragedy of the commons" (64), the compelling logic of institutional lock-in suggests a certain inevitability and pessimism with respect to avoiding institutional lock-in. Just as Ostrom's work showed that people can overcome a tragedy of the commons, scholars have shown that overcoming institutional lock-in is possible but requires propitious circumstances and exogenous shocks that galvanize stakeholder attention and create a window of opportunity (65). Insights into the way out stem both from empirical research showing "technological and institutional changes have occurred repeatedly in history" (9) and from theory that has identified various pathways for breaking out of institutional lock-in (45). The processes and conditions described above document that, over time, institutional lock-in becomes both more likely and more difficult to escape. A transformative theory of institutional change must identify both factors that create permissive conditions for such change to occur and self-conscious processes that promote institutional change given those conditions.

Breaking institutional lock-in to prompt a system-level transition to a decarbonizing trajectory requires efforts to plant, and foster the growth of, seeds of transition (49). At each level of governance and in every sphere, those with interests threatened by a transition will mobilize to maintain existing rules, institutions, and systems. But intentional efforts or propitious circumstances can create conditions of institutional plasticity, shifting the political and economic advantage toward actors who would benefit from such a transition.

Transitions can begin with organic responses to incentives in the status quo economic and political system, for example, encouraging innovations by corporate interests that coincidentally reduce carbon emissions. But governments can adopt more proactive strategies that directly fund R&D or that promote industry R&D. Early government funding of R&D in energy, transportation, and other sectors can demonstrate that certain technologies are possible and identify promising directions for the R&D efforts of private industry. The amount, focus, and type of government R&D can reinforce carbon lock-in or generate seeds that undermine lock-in. Indeed, "public policy has had a very significant influence on the development of new technologies in the area of renewable energy" (66). Government policies on R&D and research infrastructure have been shown to foster renewable energy innovations, especially for technologies that are near a tipping point at which such investments "could enable these attractive but generally marginal providers to become major contributors to regional and global energy supplies" (67, 68). Such investments can prompt even already strong industries to diversify into the sustainable energy sector (69). Over the past decade, there has been strong growth (~8% per year) in government R&D in renewable energy among both developed and developing countries (70). Unlike corporations, governments may have longer time horizons, greater risk tolerance, greater resources, and greater concern with environmental benefits necessary to make the type of investments that could overcome the transition costs and set the system on a more carbon-neutral trajectory. At present, however, global R&D in renewable energy appears to be below levels needed to prompt such a transition (67, 70).

Even a successful transition is likely to proceed in fits and starts, with resistance both within the institution initiating change and in other institutions and sectors; for example, international and transnational efforts to promote environmental goals with respect to climate, fishing, and pollution have been challenged in the World Trade Organization and the European Union (71). Because the dynamics of lock-in work against transition and transformation, institutional break-out will depend on policies appropriate to the stage of the transition, from helping new knowledge and technologies develop, to helping infant industries grow in niche markets, to facilitating the emergence of larger markets, to promoting competitive pressures that reduce prices, to establishing regulations and tax policies on mature industries (49). Those seeking to promote a decarbonizing transition will be well served by having prodecarbonization legislation and institutional rules ready for adoption during those usually brief and unpredictable moments when "windows of political opportunity" open up (72). Further, governments and businesses will need to "make heavy commitments" if the costs of transition to a decarbonizing trajectory are to become surmountable (73). Ensuring that national and international infrastructure projects for dams, power plants, and the like are designed to minimize their lifetime carbon emissions could have significant impacts; the greening of the World Trade Organization, the World Bank, and international aid demonstrates that such gradual institutional changes are possible, if challenging (74–76).

Institutional rules that strengthen carbon lock-in but are costly may prove politically vulnerable. Proposals to end the subsidies, tax provisions, and other costly policies that favor carbon-intensive industries have a ready-made constituency among the taxpayers who currently bear that financial burden. Removing such policies could enhance institutional plasticity, making a decarbonization transition more likely. The growth of various renewable energy technologies in various European countries illustrates more incremental but intentional interventions. Development and diffusion of wind and solar power and lower-carbon buildings in Britain, Germany, and Spain reflected self-conscious institutional initiatives, including changes in science policy, R&D investments, regulatory structures, and tax and subsidy policies (49, 63, 77–79). Early investments, sometimes against significant political resistance, fostered initial growth that created opportunities for further development of alternative technologies. Investments in technology development appear to be particularly effective if undertaken in those economic niches where resistance is lower and lock-in is less embedded (9).

Given the range of human activities implicated in anthropogenic climate change, the transition to a virtuous cycle of decarbonization depends not only on sequencing but also on promoting the diffusion of successful policies and actions to multiple levels and realms of governance and across multiple economic and social sectors. Break-out from carbon lock-in will require a meta-institutional transition occurring not only in ministries of energy and environment but also in those of commerce, transportation, housing, agriculture, and national security. They need to occur in most, if not all, countries and at municipal and provincial levels. Transitions will need to take place in international institutions, including the United Nations, the World Trade Organization, the World Bank and International Monetary Fund, the International Energy Agency, the European Union, and the Organisation for Economic Co-operation and Development. The nature of lock-in means resistance is likely in all these venues, with the success of any transition depending on a piling up of successes that become mutually reinforcing over time and across venues (53).

3.3. Promoting Positive Institutional Lock-In

Most scholarship on carbon lock-in assumes that such lock-in is suboptimal from an environmental perspective. But the preceding discussion reminds us that institutions are locked into trajectories that produce intended, desired, and often optimal outcomes not only for the powerful political actors that promote them but sometimes more generally, as in the benefits that the general public in developed countries receive from access to cheap and reliable energy. Thus, whether institutional lock-in is positive or negative depends on one's perspective and the range of stakeholder interests being considered, in terms of economic sectors, political groups, and governance levels. Escaping the institutional component of carbon lock-in depends on increasing institutional plasticity, inducing institutional change, and, as appropriate, fostering institutional lock-in of a new, decarbonizing trajectory. Generational turnover and secular trends toward postmaterial (i.e., more proenvironmental) values may induce gradual political, social, and economic shifts that will foster institutional plasticity and a transition to a decarbonizing trajectory (80–82). Yet, such a passive approach is likely to take longer than a more active strategy of escaping carbon lock-in.

The foregoing discussion suggests the value of reinforcing a decarbonizing trajectory once a transition begins. Positive environmental trends can be set in motion by institutions, but later gain a momentum of their own. International negotiations to protect the ozone layer prompted research by chemical firms that identified chemical substitutes for ozone-depleting chlorofluorocarbons (CFCs) that proved cheaper than CFCs, with market forces then leading to CFC reductions that occurred faster than the Montreal Protocol required (83). Likewise, considerable research has shown that many multinationals exhibit a variant of lock-in, requiring that overseas factories, subsidiaries, and contractors meet a single, environmentally stringent standard that serves to "export environmentalism" (84; see also 82).

Policies can be designed to create incentives for decarbonizing trajectories to emerge, for example, by designing them to be of indefinite duration, to ratchet up over time, and/or to require unanimity for their revocation. Policies can be designed to nudge people and firms toward decarbonization. Utilities, for example, could require consumers to opt out of—rather than into—purchasing renewable energy (85). Similarly, initially setting gas and carbon taxes in percentages rather than currency units ensures taxes can maintain their effectiveness without requiring reauthorization. Loosening institutional lock-in is crucial to overcoming the obstacles that are currently hindering the decarbonization transition; but if and when such a transition begins to gather speed, strategies that promote institutional lock-in may provide valuable ways to stabilize and reinforce that new trajectory. At the same time, policy humility is warranted: Our current state of carbon lock-in reflects past policy decisions, many of which were considered welfare-enhancing at the time. To the extent that efforts succeed in promoting a carbon-reducing trajectory, they will surely lead to unwelcome future surprises as well. Policy makers should expect and plan for unforeseen externalities, for example, by incorporating systems that require institutional review and promote some degree of institutional plasticity and flexibility.

4. BEHAVIORAL LOCK-IN

Climate change is largely caused by unsustainable patterns in human behaviors, such as where we live, the size of homes we prefer, what we buy, and how we travel. Household energy use varies considerably across societies largely because of the social context for consumption consisting of lifestyles, habits, routines, and preferences. For example, the rise in the popularity of the refrigerator is correlated with increased household access to energy, but it also parallels changes in cultural norms around hygiene, modernity, efficiency, convenience, and material culture (86, 87). Though behavioral in nature, mitigation research and policies historically have focused primarily on technological solutions—energy efficiency over energy conservation and changes in energy practices, low-emission vehicles over changes in mobility habits, and high-performance buildings over shifts in the lifestyle habits of residents and workers.

This gap in our conceptualization of the climate mitigation solution space has spilled over into the lock-in literature. Carbon lock-in has primarily been considered a technological characteristic of sociotechnical systems addressed without its social counterpart. Whereas government policies and legal structures may change on timescales of decades, these social norms and cultural values are examples of slow-moving institutions that tend to evolve over centuries. There are, however, exceptions to this. Social norms regarding smoking; family size; and the lesbian, gay, bisexual, and transgender communities have changed relatively quickly, for example. A lack of understanding of how behavioral patterns and routines emerge and if and how they can be altered has led to increases in energy consumption, despite improvements in energy efficiency and heightened environmental awareness (88, 89).

Research from the social sciences can help conceptualize the formation, persistence, and alteration potential of behaviors that contribute to climate change and can inform public policy as to the appropriate levers to trigger behavioral change. Most applied research on behavior change has grown out of the health sciences, and there is still a paucity of behavioral lock-in research that is specifically related to climate change. Therefore, the literature reviewed in this section primarily comes from three largely disconnected sources: (*a*) psychological and economic literature on habits and behavioral momentum; (*b*) literature on behavioral transitions related to proenvironmental action, resource management, or lifestyle choices; and (*c*) sociological literature on the formation of lifestyles, social norms, and routines. All literature reviewed focuses on the persistence of carbon-intensive behaviors, rather than the behaviors themselves, which are discussed in previous reviews (90).

In this section, we focus on the lock-in of environmental behaviors through two distinct mechanisms: lock-in of carbon-intensive behaviors through individual decision making and lock-in of carbon-intensive behaviors through social structure. In each subsection, we discuss the current understanding of how lock-in occurs and the obstacles and conditions for change. We argue that gaps in the literature—specifically pertaining to the longevity and path flexibility of different types of behavioral lock-in—need to be addressed.

4.1. Lock-In of Individual Behaviors

Though rational choice theory is still the predominant behavioral model used in policy, models of psychological decision-making have evolved from conceptualizing individuals as fully rational actors (91, 92) to incorporating the powerful role of context and repetition in cognitive processes (93). For decisions such as daily transportation choices, product preferences, and how and when to use household electricity, decision making starts as a conscious deliberation process and progressively becomes more automatic with repetition, until an association between the situation and behavior is created (94). Past performance can become automatically associated with context cues (95), triggering both active (e.g., turning off the lights) and inactive (e.g., not turning off lights) behaviors (96). The purpose of habit formation is to minimize the amount of cognitive effort needed to make a decision (97)—a lock-in mechanism that is not inherently helpful or harmful to climate mitigation efforts (98) but whose character depends on the behavior that it perpetuates.

Habits can exert significant influence over regular behaviors and have been extensively studied in relation to commuting. Estimates show that a shift in travel behaviors could reduce transportation CO_2 emissions by 50% by the end of the century (99). However, these reductions assume behavioral sensitivity and flexibility to changes in the utility-cost structure of transportation choices. This is a problematic assumption considering that travel behaviors have been shown to be habitual (100, 101). Travel habits limit the information used to make decisions about how to reach a destination (100, 102) and often are paired with other synchronic habits (e.g., listening to the news or eating breakfast) (103) that reinforce the mode choice. Considering that personal automobile users are more likely to be influenced by habits than public transport users (104), behavioral lock-in in the transportation sector is a distinct obstacle for reducing carbon emissions.

There is little consensus on the potential and ethical use of policy interventions to change habits. In a review of 77 travel behavior change studies, less than 20% were judged to be methodologically strong, and only half of those were successful at reducing car use (105). Because habits exert their influence outside of conscious cognitive processing, strategies like informational campaigns that rely on changing attitudes underpinning transport choices have not been effective (106, 107). More successful interventions comply with the habit-discontinuity hypothesis—which posits that behaviors are more pliable when a context change disrupts the routine (108). These interventions take advantage of naturally occurring life transitions, such as a relocation, retirement, or a new job, to establish new behavioral practices (103, 109). For example, in a study of 14,000 residents in Brussels, those who had recently moved were more likely to apply for energy subsidies than those who had been in the same home for more than three years (110). A similar tactic is to temporarily dislodge habits by incentivizing alternative options. For example, in a study where drivers were given a free one-month bus pass, attitudes toward bus ridership were more positive and the frequency of bus use had increased—a month after the pass had expired (111). These incentive-based interventions have significant short-term impacts, but longer-term effects are questionable, especially if alternative behavioral options are not in line with individuals' preferences (112).

Worldwide, the strongest predictors of how seriously individuals regard climate change risks are education level and beliefs about the cause of climate change. These beliefs often have less to do with awareness than with ideology. Over 75% of the population in developed countries are aware of climate change, but a much lower percentage perceive it as a serious risk (113). In 2009, the American Psychological Association (APA) Task Force on the Interface Between Psychology and Global Climate Change reviewed decades of psychological research and practice in climate change. They identified numerous psychological barriers that explain why people do not feel a sense of urgency regarding climate change, including habit and other ingrained behaviors that are extremely resistant to change, limited cognition about the problem, worldviews that preclude proenvironmental behaviors, undervaluing risk, discredence toward experts and authorities, and a sense of lack of control over being able to make a difference (111, 112). Moreover, the reaction to climate change risks is mediated by cultural values and beliefs (114). One of the key insights of the task force is that psychological barriers are key in preventing action on climate change. This is a significant departure from the dominant information-deficit model commonly assumed by economists and natural scientists. The results of the APA task force suggest that if we are to break free from lock-in of climate change inaction, we must address the psychological barriers.

Apart from habits, avoidance of risk can also lock in both repetitive and nonrepetitive environmental behaviors. Changing behaviors involves increased functional, physical, financial, social, psychological, and temporal risks above the status quo (115). For example, installing solar panels on a house requires an investment in time and product research, an investment of finances, and a social investment of publicly espousing a product that is functionally untested or that may invite societal judgment. Individuals are also commonly risk adverse when it comes to exploring new travel alternatives (116, 117), creating a learning-based lock-in effect that deters transitions to new modes of transportation.

Another psychological obstacle that locks in behavior is related to the nature of climate change as a type of collective action problem. In collective action problems, individuals act as free riders, feeling that they have little behavioral control and therefore little incentive to take care of global environmental public goods (114, 118). In this context, behavioral lock-in has similarities to technological lock-in, having increasing returns to scale. Behaviors are locked in not by path dependency over time but by declining individual agency compared to the number of actors that are perceived to be part of the problem.

Overcoming these obstacles will likely require what Thaler & Sunstein (85) call nudges: any aspect of the choice architecture that alters people's behavior in a predictable way without forbidding options or significantly changing their economic incentives. To count as a mere nudge, the intervention must be easy or cheap to avoid (85). Their argument draws from the observation that people make suboptimal choices or mistakes not because of a lack of information, but rather because their choices are informed by heuristics and shaped by social interactions (85). Though choice architecture is unavoidable—whether exploited to benefit climate mitigation or not—nudging is controversial because it can be perceived as paternalistic, experimental, and dismissive of the role of personal responsibility (119).

4.2. Lock-In of Social Structural Behaviors

Psychological studies are often criticized for understating the importance of context to behavioral momentum. Indeed, individual behavior is constrained not only by cognitive processes but also by structure—embedded in existing infrastructures, technologies, cultures, norms, and routines. Some scholars describe individual lock-in and structural lock-in as completely distinct and incompatible processes (120). Whereas the former focuses on the individual as having agency over behaviors and habits, in structural lock-in the practices and contexts themselves have agency over individual behavior (120).

Sociologists theorize that lock-in emerges not from practitioners that choose practices but through practices that recruit practitioners (121). Socially shared practices refer to routines and norms that coevolve with the technologies, infrastructures, social networks, markets, policies, and cultural norms in place (122, 123). Practices are dynamic over time (124), responding to changes in the larger sociotechnical environment where they are embedded. For example, the work of Norgaard (125) shows that climate change denial is a socially organized process. Yet social practices are also path dependent (126), persisting because they are rooted in a complex and involved web of individual cognitive processes; technology and infrastructure; and social norms, values, and institutions (127). Therefore, transforming social norms and routines cannot be achieved through policies that disregard the interconnected nature of practices (e.g., policies that target behavior change or technological change in isolation) but instead must respond to the system as a whole (128, 129).

Given that everyday routines like travel, heating and cooling buildings, personal hygiene, and diet have significant energy and emissions implications, how these shared practices emerge, standardize, transform, and persist has great importance for understanding climate lock-in (120, 130). Often technological innovation alters the sociotechnical landscape so that alternative practices cannot compete. For example, though cycling was the dominant form of commuting in the 1940s, its decline as a practice was the direct result of the automobile competing for investment, road space, and time and offering personal comfort (131). Similarly, though human thermal comfort in buildings is quite flexible, performance requirements of electronic and computer equipment have driven an increasingly standardized practice of heating and cooling buildings to a narrow window of 22°C (132)—a practice that imposes energy-intensive loads on mechanical heating, ventilation, and air conditioning systems. It is worth noting that the social landscape can be altered through nontechnological means as well. For example, norms regarding family size have changed drastically over the last century, but it is unclear that this was primarily due to technological innovation. In all examples, a change in the technological and social infrastructure causes a change in routine practices, locking in an unsustainable demand for resources and increased emissions.

A common criticism of social practice theory is that it is not immediately policy applicable (133). Although this is true, the literature also suggests that nudges directly change outcomes and social practice, and advertising can indirectly change social practice by shaping public consciousness. Norms of drinking while driving and of smoking are examples of social practices that are directly addressed by public policies. Policy solutions target people or products more easily than the routines and cultural norms that connect them (127), and it can be difficult to know how to disrupt the systems that lead to structural lock-in (106). Another challenge is that there is limited empirical evidence from existing policies, because few draw on social practice theory to target structural transformation (134). Though specific directives can be hard to pinpoint, there is consensus that successful climate change interventions will strategically embed new practices in the existing sociotechnical landscape, instead of fundamentally challenging existing practices (135, 136).

Theoretically, system transitions happen when practices change and evolve. Routines change when (*a*) the elements required to accomplish them change, (*b*) the populations practicing them change, or (*c*) related and interdependent practices change (137). London's bike-share program and Bogota's bus rapid transit system are two examples of interventions that change the elements of practice. Instead of improving transport technologies or relying on an individual to change values or habits, lock-in in travel behaviors is disrupted by changing the way individuals interact with existing technologies (134). Targeting social connections where routines develop is another method for disrupting behavioral lock-in. Interventions could facilitate connections and social networks that strengthen desirable practices. For example, cyclists sharing information about safe commuting routes could lead to increasingly strong communities of alternative transportation (124).

To fully understand behavioral lock-in, more work is needed to imagine a unified conceptual framework that describes how individual and structural lock-in may interact (135). Terminology for behaviors and practices is used inconsistently in the literature, and it is unclear whether individual lock-in and structural lock-in are two sides of the same coin, completely unrelated processes, or embedded inside each other. Furthermore, additional studies of behavioral lock-in outside of the transportation sector would add depth to the theoretical arguments proposed for both types of lock-in. While this section discusses some of the approaches useful for overcoming barriers to behavioral transitions, there is very little evidence or means for comparability of the persistence and longevity of different manifestations of behavioral lock-in. These types of data are needed to forecast how behavioral lock-in may constrain climate change action in the future.

5. INTERDEPENDENT LOCK-IN EFFECTS AND TRANSFORMATIVE CHANGE

There are numerous interconnections and interactions within and between technological, institutional, and behavioral lock-in (**Figure 3**). Changes in institutional and behavioral systems can

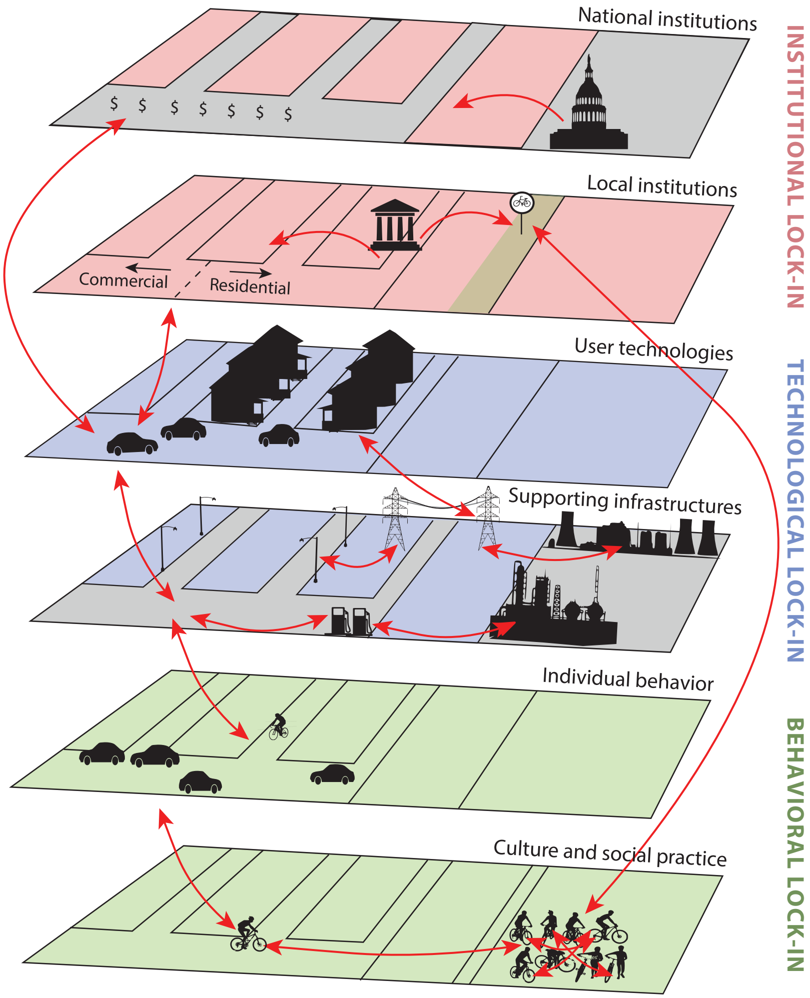

Figure 3

Interconnections and interactions (*red arrows*) among and within different levels of carbon lock-in. Carbon lock-in occurs in multiple dimensions (institutional, technological, behavioral), at multiple scales (local to national or individual to structural), with multidirectional causation between and among the levels. For example, governments can influence technology through regulations and legal frameworks, but technology also influences government decision making through activities such as lobbying and political donations. The red arrows demonstrate the multidirectional causation between and among the levels of lock-in and are intended to be illustrative only.

reinforce the increasing returns to scale that drive technological lock-in. For example, the lock-in of gasoline-powered automobiles reflects development, introduction, and marketing by automobile companies that also lobbied for transportation policies and subsidies for relevant highway and energy infrastructures that both created and responded to social and cultural preferences for individual transportation. The dominance of automobile transportation further enabled rural, suburban, and urban development patterns that, once established, reinforced the need to maintain and expand automobile-oriented infrastructures, creating resistance and obstacles to government efforts to install mass transit systems and personal preferences against using them. Thus, lock-in effects can be interdependent and mutually reinforcing. One important implication of the interconnectedness is that there is multidirectional causation between and among the different types of carbon lock-in.

In developing countries, energy supply and demand pathways appear to be somewhat more plastic because much of the infrastructure to meet the needs of their growing economies has not yet been built. There may be opportunities to place these countries on less carbon-intensive trajectories because they do not need to overcome the significant advantages of an entrenched, incumbent technology. Of course, extant carbon-intensive transportation and energy infrastructures are advantaged in the economic contests over economic market share and the political contests over development paths that are central to determining what type of lock-in occurs in developing countries. Scholars and the Intergovernmental Panel on Climate Change (IPCC) have discussed the value of leapfrogging for avoiding lock-in of the carbon-intensive technologies and development patterns characteristic of developed countries. However, the risks of alternative development paths as well as the significant resource constraints they face often will lead developing country governments to prefer those technological infrastructures that have already been developed, refined, and proven in developed countries, without regard to their carbon intensity.

The paths that developing countries choose reflect interactions among the different systems we identify: Technological and economic forces influence what infrastructural options are available and their relative costs; institutional forces influence the actors, interests, and processes that influence the choices made among those options; behavioral preferences that reflect cultural and economic influences influence demand; and increasing personal wealth in many developing countries is generating new technological options, new demand cultures, and rapid changes in the interactions among these different realms. Developed country patterns of regional planning, transportation policies, and preferences for private mobility and dedensification—coupled with the expansion of transnational corporations and markets—create a context in which developing countries are likely to choose similar development strategies. For example, gas-powered cars benefit from a well-developed technology with corresponding low costs, already-powerful domestic and multinational corporations that build demand through advertising and lobby for government projects for car-friendly roads and other infrastructure, and a global norm that suggests that one of the markers of development is an automobile-based economy. Historical cases of technological leapfrogging, for example, cell phones, have usually involved mature technologies that had already proven scalable in developed countries. When climate-concerned developing states implement lower-carbon-intensity policies, they help relevant technologies mature, reduce their costs, and initiate and build new norms of what development means; developing countries are then far more likely to adopt such practices than they are when developed countries argue for such policies but have not implemented them.

The foregoing discussion of the factors and processes that lead to lock-in suggests conditions that might facilitate breaking out of carbon lock-in and fostering local, national, and global transitions to more climate-friendly trajectories. The first insight is simply that lock-in is hard to undo because it is overdetermined. Once one of several initially comparable technologies or development paths is chosen, processes of lock-in lead those not chosen to become less available, more costly, and less attractive while those that are chosen gain the advantages of incumbency, inertia, and support from the economic, political, and social groups that benefit from them. But in some countries and sectors, major commitments to a particular technology or development path have not yet been made. Where such choices have been made and lock-in has developed, moments of plasticity may arise that create windows of opportunity. In both situations, lock-in can emerge in response to relatively small differences in initial choices.

The overarching carbon lock-in of the global system biases such choices toward further carbon lock-in. But early stage situations provide excellent and important opportunities for those concerned about climate change by lowering the costs of choosing or transitioning to low-carbon-intensive technologies and trajectories. In such settings, relatively small efforts in relatively limited domains may have effects that are disproportionately large and long-lasting. However, lock-in and break-out are not symmetric. Once the technological, economic, institutional, behavioral, and anticipated inertia that characterizes lock-in has emerged, greater efforts have to be made in more domains and systems to unsettle the mutually reinforcing stability of the system. Lock-in is a characteristic of the system as well as of the system's components: Therefore, transitioning a locked-in system requires surmounting large obstacles to transition in most or all of those components. Thus, seizing opportunities before lock-in emerges or during moments of plasticity is far more likely to succeed than pushing for transitions in realms and during moments in which carbon lock-in is strong.

A second insight is that success in surmounting the challenges of lock-in will be fostered by the involvement and cooperation of actors from different sectors. The fact that lock-in poses large challenges in multiple sectors suggests that success will depend on sometimes-coordinated efforts by people in the legislative and executive branches of government; in the research, development, and marketing departments of corporations; in international policy-making institutions; in financial institutions and capital markets; and in the nongovernmental sectors. Each of these realms contains people and entities whose interests and values lead them to prefer carbon lock-in. But each also contains people and entities whose interests either support or are consistent with a transition to less-carbon-intensive trajectories.

Politicians, policy makers, and policy-making institutions at the local, national, and international levels have strong incentives to maintain the status quo and to support pressures from powerful economic interests. At the same time, they are also expected to be responsive to political, social, and cultural pressures and to provide leadership as well as representation. The fact that the U.S. president recently promoted climate action through executive branch actions taken only in his second term of office illustrates the factors (e.g., levels of political support, concerns with individual legacy, divided government) that make adoption of policies that disrupt carbon lock-in difficult but not impossible. International efforts, including much of the work of the United Nations Framework Convention on Climate Change and the IPCC, have fundamentally shifted the terms of debate such that almost every country in the world felt the need to make emissions commitments at the 2015 Paris Climate Agreement and to frame them as reductions, even if doing so required making those commitments in terms of emissions intensity rather than total emissions.

Businesses and financial markets are motivated by profits but also desire the stability that increases predictable financial returns on long-lived capital investments. Thus, they often can be convinced to support transition policies if they see how they will reduce uncertainty, stabilize economic markets, improve economic efficiency, or promote standardization and industrial concentration. Locked-in systems foster the emergence of large networks of resource-rich corporations that have a stake in system perpetuation, with those corporations becoming favored actors in political and institutional contests. However, competitive economic markets also reward innovation and disruption in ways that, at least under certain conditions, foster market place plasticity and transition: Automobiles displaced horses and carriages; electric lighting displaced gas; airplanes have displaced trains; and cell phones have displaced landlines. The reduction in global carbon lock-in requires efforts to increase the odds that we seize future opportunities for transition to choose technologies and pathways that are less, rather than more, carbon intensive.

Individuals also have an important role to play in these transitions. Individuals play multiple roles in the processes that contribute to lock-in and foster break-out. People's choices matter: what they consume and what energy and transportation choices they make, what jobs they choose and how they perform those jobs, who they vote for and what policies they support, and the values they express through their behaviors and their words. If the dynamics we have discussed make lock-in difficult to avoid, the aggregate effect of these individual choices matters in whether we lock in low-carbon or high-carbon technologies and trajectories. If lock-in is a feature of system structure, then the plasticity of the structure, its equilibrium at any point in time, and opportunities to alter it can be influenced by the conscious and coordinated efforts of individuals.

Additionally, transformative change will require reconciling the temporal asymmetries of the human and natural systems involved. Technological, institutional, and behavior lock-in often lead to suboptimal environmental outcomes because the underlying processes operate on multiple and different timescales. Human systems evolve and become locked in on annual and decadal timescales and persist on centennial scales. In contrast, important natural, climatic, oceanic, and geologic systems evolve on centennial and millennial timescales and can persist for eons. This almost guarantees that human systems will become pervasive and locked in before unforeseen environmental externalities become apparent. This is both because natural systems work on generally slower time frames and because the scientific methods we use to discover environmental externalities require that environmental effects first be observable and that the research process then measure and demonstrate cause and effect to the satisfaction of the scientific community.

6. CONCLUSIONS

Our current trajectory of carbon emissions reflects, in important respects, the phenomenon of carbon lock-in. Technological and economic, political and institutional, and social and individual factors and dynamics tend to create stable equilibria that may be suboptimal for planetary health but are difficult to disrupt. The realms of infrastructure and technology, institutions, and individual behaviors contain distinct but parallel dynamics that favor existing carbon-intensive technologies and development paths. Lock-in in each of these realms and the global-scale systemic lock-in that emerges because of their mutual reinforcement pose significant obstacles to adoption of less-carbon-intensive technologies and development paths. This article has reviewed current understandings of the conditions under which and reasons why such lock-in emerges among the distinct system components we have identified as well as at the higher system level. Current understandings of lock-in demonstrate that lock-in is highly likely because of unintentional features of these systems as well as because powerful actors often benefit from creating and

Table 1 Summary of three types of carbon lock-in and their key characteristics

Lock-in type	Key characteristics
Infrastructural and technological	■ Technological and economic forces lead to inertia ■ Long lead times, large investments, sunk costs, long-lived effects ■ Initial choices account for private but not social costs and benefits ■ Random, unintentional events affect final outcomes (e.g., QWERTY)
Institutional	■ Powerful economic, social, and political actors seek to reinforce status quo that favors their interests ■ Institutions are designed to stabilize and lock in ■ Beneficial and intended outcome for some actors ■ Not random chance but intentional choice (e.g., support for renewable energy in Germany)
Behavioral	■ Lock-in through individual decision making (e.g., psychological processes) ■ Single, calculated choices become a long string of noncalculated and self-reinforcing habits ■ Lock-in through social structure (e.g., norms and social processes) ■ Interrupting habits is difficult but possible (e.g., family size, thermostat setting)

maintaining a state of lock-in. Those actors lobby for policies that reinforce initial movements toward lock-in.

Understanding how and when lock-in emerges also helps identify windows of opportunity when transitions to alternative technologies and paths are possible. Such transitions prove easier to accomplish when the costs of transitioning to an alternative are low. Systems can be more plastic, and hence more open to low-carbon-intensive choices, either in emergent realms and sectors where no technology or development path has yet become dominant and locked-in or at moments when locked-in realms and sectors are disrupted by technological, economic, political, or social changes that reduce the costs of transition or make relevant actors more willing to incur those costs.

SUMMARY POINTS

1. Carbon lock-in can be conceptualized as comprising three major types: (*a*) lock-in associated with the technologies and infrastructure that shape energy supply and indirectly or directly emit CO_2; (*b*) institutional lock-in associated with governance and decision making that affect energy-related production and consumption; and (*c*) behavioral lock-in related to habits and norms associated with the demand for energy-related goods and services (**Table 1**).
2. The ability to break out of infrastructural or technological lock-in will depend on the anticipated technological and economic viability and lifetimes of the systems, the costs of moving away from those systems, and options for alternatives.
3. Escaping institutional carbon lock-in depends on increasing institutional plasticity, inducing institutional change, and fostering institutional lock-in of an alternative decarbonizing trajectory.
4. Transforming behavior will require overcoming individual habits and preferences and socially constructed practices that are often entrenched in culture and other social norms.
5. The three types of carbon lock-in are mutually reinforcing, characterized not merely by individual inertia but also by a collective inertia in which any movement out of lock-in in one of the three spheres induces a response in the other spheres that results in further hardening the collective inertia.

FUTURE ISSUES

1. How do interactions among the economic incentives of private sector actors influence individual and collective choices in ways that reinforce carbon lock-in?
2. Under what socio-economic and political conditions are transitions to low-carbon pathways likely to occur? At what temporal, spatial, and institutional scales are these likely to occur? When and what proactive steps can proponents of such transitions take to promote them?
3. To what extent can we transfer lessons from the phase transitions characteristic of thermodynamic systems to better understand such transitions in socio-technological systems?

4. How do values, incentives, ideas, and constraints promote or inhibit individual and collective decision-making that reinforces the status quo or fosters transitions to low-carbon pathways?
5. How do economic, social, political, and normative conditions inhibit or foster social-scale transitions out of carbon lock-in?
6. How do the causes, types, and pathways of carbon lock-in differ between developed and developing countries?
7. What are the primary factors and conditions that promote plasticity in technological systems, institutions, and individual behaviors?
8. In what ways and under what conditions are behavioral lock-in, social innovation, and policy design mutually-reinforcing or disruptive?

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