

ADVANCED REVIEW

Designing the mid-transition: A review of medium-term challenges for coordinated decarbonization in the United States

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Edited by: Simone Pulver, Domain Editor, and Mike Hulme, Editor-in-Chief

Abstract

Decarbonizing the energy system is critical for addressing climate change. Given the dominance of fossil fuels in the energy system, decarbonization requires rapid and significant industrial transition of the energy supply at scale. This includes explicit and coordinated plans not only for zero carbon phase-in, but for fossil carbon phase-out. Even very rapid decarbonization will likely take decades, leading to a medium-term future where the conventional, fossil-based energy system coexists with a new, zero-carbon energy system. Each imposes operational constraints on the other: what we call the mid-transition. Notably, this coexistence means that the new, zero-carbon system will develop under fossil carbon system constraints. The mid-transition will therefore likely require specific analytical metrics designed to support decision making under dynamic and uncertain conditions. Many aspects of transition will be felt, and shaped, directly by individuals because of our direct interactions with energy systems. Even rare missteps are likely to have significant and potentially system design-relevant impacts on perception, political support, and implementation. Comparisons of the new system to the old system are likely to rest on experience of a world less affected by climate change, such that concerns about lower reliability, higher costs, and other challenges might be perceived as inherent to zero-carbon systems, versus energy systems facing consequences of climate change and long-term underinvestment. This review assesses and evaluates medium-term challenges associated with the mid-transition in the United States, emphasizing the need for explicit planning for joint and coordinated phase-in and phase-out.

This article is categorized under:

- The Carbon Economy and Climate Mitigation > Decarbonizing Energy and/or Reducing Demand

KEYWORDS

decarbonization, deindustrialization, fossil fuels, macroenergy systems, transition

1 | INTRODUCTION

Decarbonizing human activities, particularly via the energy system, is a crucial task for stopping anthropogenic contributions to ongoing climate change (Davis et al., 2018; Intergovernmental Panel on Climate Change, 2021; Rissman

et al., 2020; Williams et al., 2021). Decarbonization requires rapid and significant supply-side industrial transition at scale, both to build out new systems and to retire existing ones (Geels et al., 2017; Grubert, 2020b; McGlade et al., 2018; Rissman et al., 2020; Williams et al., 2021; Zhao & Alexandroff, 2019). The potential scale of this industrialization required for decarbonized energy systems depends heavily, however, on the degree to which demand-side options are exercised (Pye et al., 2021). Although processes to create and deploy new industrial facilities are widely researched and reviewed, research explicitly focused on phasing out existing, carbon-emitting infrastructure, and the effects of doing so, is much less common (Rosenbloom & Rinscheid, 2020). Such research largely focuses on restricting future fossil fuel extraction and use (Buck, 2021; Muttitt & Kartha, 2020; Piggot et al., 2018; Piggot et al., 2020; Zhao & Alexandroff, 2019) or lessons and frameworks from the deconstruction of previous industries (Normann, 2019; Turnheim & Geels, 2013). Detailed research and modeling focused on issues like anticipated future energy prices (and potential price shocks) under decline; capital investment trajectories; remediation and reclamation triggers and implementation; labor and training requirements; and minimum viable scale for conventional energy systems—questions crucial to investigate if we assume we will successfully decarbonize—are notably missing from the literature.

Lack of attention to coordinated planning for joint phase-in of zero-carbon and phase-out of fossil fuel-based systems and the associated infrastructure that enables emissions generation represents a major risk to a successful, just energy transition (Wang & Lo, 2021) on the rapid timelines required to reach domestic US (The White House, 2021b) and international climate goals (Intergovernmental Panel on Climate Change, 2021). This risk is particularly due to the social embeddedness and material and political dominance of existing, emitting fossil fuel systems that create carbon lock-in (Unruh, 2000; Wang & Lo, 2021). Without explicit planning, the transition is likely to face major challenges like local economic busts, highly inequitable access to high quality energy and infrastructure systems, and poor coordination for system-level characteristics like reliability, accessibility, and affordability. Already, evidence from the uncoordinated US coal transition shows increased potential for negative outcomes like economic hardship (e.g., from lost tax revenues and jobs), unfunded obligations (e.g., pensions, remediation commitments, maintenance and monitoring), identity and governance disruptions, and loss of resilience (Haggerty et al., 2018; Macey & Salovaara, 2019; Roemer & Haggerty, 2021).

During the transition period where zero-carbon and emitting fossil fuel systems co-exist at scales where each imposes operationally relevant constraints on the other, which we call the mid-transition in this review, success and justice will require explicit planning underpinned by specialized metrics for coordinated zero-carbon infrastructure ramp-up and emissions-enabling fossil infrastructure phase-out. During the mid-transition, neither zero-carbon nor carbon-emitting infrastructure can fully support all energy services on its own, and the overall system is not optimized for either infrastructure's sociotechnical particularities. Risks of maladaptations, overlooked opportunities for synergies, and uncoordinated decision-making are high during the mid-transition, particularly as infrastructures encounter simultaneous climate, technology, and societal dynamics that are not well characterized by past experience. For example, renewable electricity systems might develop with the assumption that natural gas backup generators will always be available to provide low-cost grid support services (Phadke et al., 2020; Williams et al., 2021), or gas stations in a given region might all face simultaneous loss of profitability past a certain penetration of electric vehicles. System performance metrics and other evaluative tools designed specifically for dynamics of the transition will be needed to both measure progress and identify emergent challenges in time to address them, particularly since some constraints can be more easily temporarily relaxed in pursuit of long-term benefit (e.g., short-term cost increases counterbalanced by long-term cost savings and market structures attentive to impacts on energy burden) than others (e.g., safety and reliability).

Even decarbonization rapid enough to pose challenges for responsible acceleration (Skjølsvold & Coenen, 2021) will likely take decades (Williams et al., 2021), creating a significant time over which failure to coordinate could exacerbate existing structural challenges (Wang & Lo, 2021) and create new ones. Energy transitions, including the present decarbonization transition, have historically been slow (Fouquet, 2016). Global carbon intensity of energy has been flat for decades, and fossil fuels still supply about 80% of marketed energy (Hanna & Victor, 2021). Large increases in contributions from renewable resources in the United States and elsewhere have largely been in addition to, rather than instead of, ongoing use of unabated fossil fuels, particularly under demand growth.

Although policy tends to treat the transition as a “problem of addition” (Aronoff et al., 2020), in practice, the decarbonization transition cannot be completed without de-carbonization, which means that companies, livelihoods, and ways of life associated with emissions-enabling fossil fuel infrastructure and systems will disappear. In addition to obvious challenges like job and revenue losses, this disappearance (and anticipation thereof) could enable very concrete, potentially distressing sociotechnical imaginaries and identity threats for those engaged in fossil-dependent activities (Grubert & Skinner, 2017; Jasanoff & Kim, 2009; Smith, 2019) while creating the conditions for resistance to the transition from incumbent regime actors (Geels, 2014) and ultimately slowing the transition. Efforts to enact a just transition

(Chapman et al., 2018; Evans & Phelan, 2016; McCauley & Heffron, 2018; Newell & Mulvaney, 2013; Wang & Lo, 2021; White, 2020) are challenged by the need to transition rapidly while also recognizing acceleration as a key challenge for trust-based, just, and participatory processes enabling coproduction and respect for deeply held values (Haggerty et al., 2018; Skjølsvold & Coenen, 2021). Prior transitions in specific regions (e.g., in Appalachia) have demonstrated the potential for very negative outcomes associated with violent, high conflict processes with long-term effects, like poverty and mistrust (Hess et al., 2021). That is: even assuming widespread support for transitions in concept, success—and particularly success characterized by justice and improved societal conditions—is by no means guaranteed.

Although challenges of transition are widely recognized in the Society and Technology Studies (STS), geography, and broader energy and natural resource social sciences literatures (e.g., Carley et al., 2018; Colvin, 2020; Haggerty et al., 2018; C. A. Miller et al., 2013; Miller et al., 2015; Roberts et al., 2018; Smith & Tidwell, 2016), explicit attention to the logistics of the mid-transition is rare in policy, models, and other structures granted authoritative status. This review investigates issues of the mid-transition in the United States in an effort to highlight the need for such attention. In Section 2, we define the mid-transition and motivate the need to design it. In Section 3, we characterize the technical context of the mid-transition. In Section 4, we review the social context of the mid-transition. We conclude with recommendations for analyzing the mid-transition and envisioning the post-transition world.

2 | WHAT IS THE MID-TRANSITION?

Here, we define the mid-transition to be the period during which energy supply—in this review, focused on the US energy system—is (1) constrained by a goal of reducing or eliminating greenhouse gas emissions and (2) comprised of fossil carbon-emitting systems and zero-carbon systems that both exist at sufficient scale to impose operationally relevant constraints on the other. That is, the mid-transition is the period between two stable end points (where systems are largely operating as they were designed and under conditions structured around their needs) during which change is directional and coexisting systems must make compromises to accommodate the other. (See Section 3 for a discussion of technical parameters that could identify the mid-transition.)

BOX 1 How does carbon-based infrastructure fit into the mid-transition framework?

Modeling efforts widely suggest that decarbonized energy supplies are likely to be dominated by non-carbon-based infrastructure, which in turn suggests carbon-based systems will shrink. In theory, however, there are many pathways to decarbonization, including those where carbon-based infrastructure is used to decarbonize and could thus expand. For example, a fully fossil-fueled energy supply could theoretically be greenhouse gas neutral via extremely carbon capture and storage (CCS)-dependent energy systems that also include fossil fuel-fired carbon dioxide removal (CDR), like direct air capture and storage (DACS). Such pathways would not eliminate other impacts of fossil fuels, and they would rely on much larger use of depletable fuels while also requiring substantial CO₂ transportation and storage networks, but they are possible. Pathways combining carbon-emitting and zero carbon-based systems would still undergo a mid-transition characterized by operational concessions from both emitting and non-emitting infrastructures. For example, CCS and DACS are both energy intensive, and these supplies and loads would be prioritized under a decarbonization constraint. Note also that decarbonization is potentially achievable without a complete transition. That is, a decarbonized system could remain indefinitely in a state of mid-transition where carbon-emitting and zero-carbon infrastructures coexist and constrain one another. Imagine a setting where unabated natural gas-fired power plants continue to operate at meaningful scales, with emissions compensated by CDR (via DACS or other pathways): this setting might be decarbonized, but still constrained by qualitatively different infrastructures accommodating one another, for example, via allocation of marginal renewable power to compensatory CDR and rapid ramping of natural gas-fired power plants. Both the carbon-based and perpetual mid-transition pathways to decarbonization are possible but likely less optimal than deeper phase-out of fossil fuel infrastructure, based on current understanding of costs and non-climate impacts. For a thoughtful treatment of some of these issues, including the relational and material context of fossil industry transformation, see (Buck, 2021).

As the transition progresses, carbon-based infrastructures are expected to shrink (see Box 1), potentially leading to loss of certain economies of scale, while the zero-carbon system grows, potentially encountering emergent economies and diseconomies of scale. In a future, mostly zero-carbon system, carbon-emitting components might require operational accommodations from the zero-carbon portion of the energy system, but what these accommodations might be is not completely clear yet. In defining the mid-transition as policy-meaningful, we aim to investigate the kinds of emergent dynamics that might be both anticipatable and mitigatable, given the rapid but still decade-scale planning processes at play.

2.1 | Why design the mid-transition?

The need to design the mid-transition as a national process (in addition to designing local end-point transitions; Haggerty et al., 2018) is emphasized by the potential for weak medium-term policies to increase both the cost of transition and the likelihood of locking in carbon intensive policies (Hidalgo-Gonzalez et al., 2021). Single-target policies without interim checkpoints, like “zero carbon by X”, do not necessarily foster near-term actions compatible with the eventual policy goal, especially when penalties are unclear and no phase-out is required. Similarly, emissions reductions goals, like “80% reductions in GHG emissions by X,” might not be compatible with long-term goals of reaching 0 GHG emissions if they encourage investment in long-lived infrastructures that achieve the interim goal but cannot achieve the ultimate goal, or if they do not encourage disinvestment in existing, incompatible systems.

From a resource allocation standpoint, complying with an 80% GHG reduction target by decarbonizing 80% of the system is very different from complying by investing in new systems that emit 20% as much GHG, or investing in technologies that could attain emissions reductions but not explicitly designing the transition away from emissions intensive activities. Recognizing this dynamic of “bridging” rationalities contributing to delays (Low & Boettcher, 2020), particularly as existing legacy infrastructure liabilities (like pipeline networks) become meaningful cost burdens as stranded assets (Bos & Gupta, 2019) that could have particularly high impacts on the least wealthy (Grubert, 2020b), is important for designing the mid-transition.

As one example, consider the proposed decarbonization sequence of a coal-to-gas switch, then a gas-to-renewable natural gas (RNG) switch: in neither case does the infrastructural investment actually enable an eventual zero GHG goal, because neither natural gas nor RNG (Grubert, 2020a) is zero GHG at scale. Thus, not only interim goals, but also interim goals with an explicit pathway to zero are needed. Careful evaluation of whether allocating resources to incumbents to reduce emissions rather than invest in pathways to eliminating them (e.g., investing in low hazard methane leak reduction or low-carbon gases rather than building electrification, even if the near-term emissions benefits are similar or favor the pathway that does not include a path to zero), should be the charge of regulators, policy makers, and advocates during the mid-transition.

The mid-transition requires design because phase in and phase out must be aligned in time, with multiscalar challenges associated with continuing to provide crucial services while emphasizing sustainability and justice. These challenges are heavily affected and amplified by the need for the rapid transformation of entire systems (e.g., from highly centralized to a centralized and decentralized mix), and with the introductions of new interactions between historically siloed sub energy systems with disparate governance and institutional structures (e.g., through the electrification of sectors previously dependent on liquid fuels). How well does academic research support these challenging design problems of simultaneous zero-carbon phase in and carbon phase out? Although the literature touches on some explicit efforts to intentionally eliminate industries (Haas & Sander, 2016; Haggerty et al., 2018; Hess et al., 2021; Huang & Chen, 2021; Zhao & Alexandroff, 2019), largely associated with coal and nuclear fleets with widely understood negative local impacts, the scope of contraction addressed by this type of research is quite limited relative to the decarbonization of the energy system as a whole. In addition, these examples largely involve a one for one replacement of infrastructure and technology with an alternative with relatively similar parameters. In general, academic research has devoted limited attention to the “how” of de-transition—the practical operational and political constraints of carbon phase out (though see Buck, 2021; Grubert, 2020b; McGlade et al., 2018; Mildenerberger, 2020; Pai, Zerriffi, et al., 2020). By contrast, similarly practical issues related to industrialization are relatively carefully covered, including by influential studies that derive authority in part from their detailed underlying technical and theoretical models (Davis et al., 2018; Geels et al., 2017; Jacobson et al., 2015; E. Larson et al., 2020; Mayfield et al., 2021; Phadke et al., 2020; Williams et al., 2021). This gap is significant, and urgent, given both the pace and extreme complexity of successful alignment of resources to achieve decarbonization.

2.2 | What is the design goal? Normativity in sustainability-oriented transitions

Sustainability transition studies emphasize the status of sustainability-oriented transition as a political process: that is, such transitions have normative goals (e.g., zero GHG emissions) to be achieved in nonlinear, multisystem, and multiscale processes under high uncertainty and high degrees of contestation (Geels, 2011; Köhler et al., 2019). One implication of normativity is that there is an explicit design goal: in this case, elimination of greenhouse gas emissions. Thus, progress toward the goal can be measured, in addition to typical “snapshot” style descriptive technical measurements. Similarly, decisions can be evaluated for compatibility with the goal, using a directed understanding of mechanisms of influence and contestation. The mechanisms through which the decarbonization process can be influenced—a combination of “technologies, institutions, and behavioral norms” that create carbon lock-in—are understood (Seto et al., 2016). Contestation arises in part from the fact that the normative goal of decarbonization is misaligned with private incentives. For example, fossil fuel companies have limited private incentives to decarbonize absent a strong market signal, and instead resist decarbonization where it threatens their market share, and user benefits of transition might be unclear (Geels, 2011). Particularly in fields that often (falsely) suggest research is value-free (Grubert, 2017a; Rykiel, 2001), acknowledging that decarbonization is a normative transition could inform more design-relevant research that incorporates these mechanisms.

On its face, the decarbonization transition is largely motivated by a need to reduce environmental harms—most obviously those associated with climate change—rather than to provide obvious and immediate benefits like a new service, like air conditioning, that was characterized by rapid uptake (Sovacool, 2016). One crucial point, though, is that in practice, largely because of the deep integration of carbon-emitting systems into society, decarbonization entails a remaking of the energy system that encompasses the potential for deep, structural, and multicriteria changes that go well beyond the core goal of eliminating greenhouse gas emissions and reducing climate harm (see, e.g., Eschrich & Miller, 2021). That is, “the” normative goal of decarbonization is, in practice, a diverse set of multicriteria normative goals for various socioenvironmental outcomes, with a shared goal focused on greenhouse gases. The multiplicity of values and directions associated with this transition lead both to additional areas of contestation and to significant opportunities for visioning and decision support that can enable thoughtful choices about major infrastructures with deep implications for sustainability, justice, and societal structures.

Notably, the societal embeddedness of carbon-producing systems means that transition enables not only environmental harm reduction, like limiting climate change, reducing air pollution, and otherwise reducing environmental harms with health, safety, ecosystem, and other consequences (Anderson et al., 2018; Chapman et al., 2018; Ekholm et al., 2014; Hertwich et al., 2014), but also the potential for actively and normatively improving socioenvironmental outcomes by reversing injustices, structuring systems to provide higher quality of life, and other mechanisms. Goals beyond decarbonization itself, however, are less obviously shared, less clearly envisioned as concrete sociotechnical imaginaries (Jasanoff & Kim, 2009), and less easily characterized by authoritative metrics accepted as valid than are greenhouse gas emissions reductions. One major task for decarbonization researchers, then, must be to ask both: what is success, and what would we study if we took the prospect of that success seriously? Although this review focuses somewhat narrowly on evaluating the decarbonization transition from a technical and greenhouse gas emissions-focused perspective, we note that designing the mid-transition matters not only because of emissions trajectories, but also because of the deep structural implications of the specific transition pathways that are ultimately undertaken.

3 | TECHNICAL CONTEXT OF THE MID-TRANSITION

In order to assess and improve outcomes during the mid-transition, we first need to identify when a system is in the mid-transition state. We propose the mid-transition be quantified in terms of the percent penetration of the new system on a relevant and easily identified metric, like percentage of total energy provision, or total infrastructure deployed. In this case the mid-transition period starts when the penetration of the new infrastructure reaches a level where it imposes operationally meaningful constraints on the existing system through incompatible characteristics. The mid-transition period ends when the new infrastructure is sufficiently dominant that it is no longer meaningfully constrained from optimal operation by the legacy infrastructure.

Further analysis is required to define appropriate mid-transition cut-off metrics that characterize conditions when systems meaningfully constrain each other. As a rule of thumb for identifying when an energy supply system is in the mid-transition, we suggest the period of roughly 20%–80% penetration on a supplied-energy basis. Although this rule of

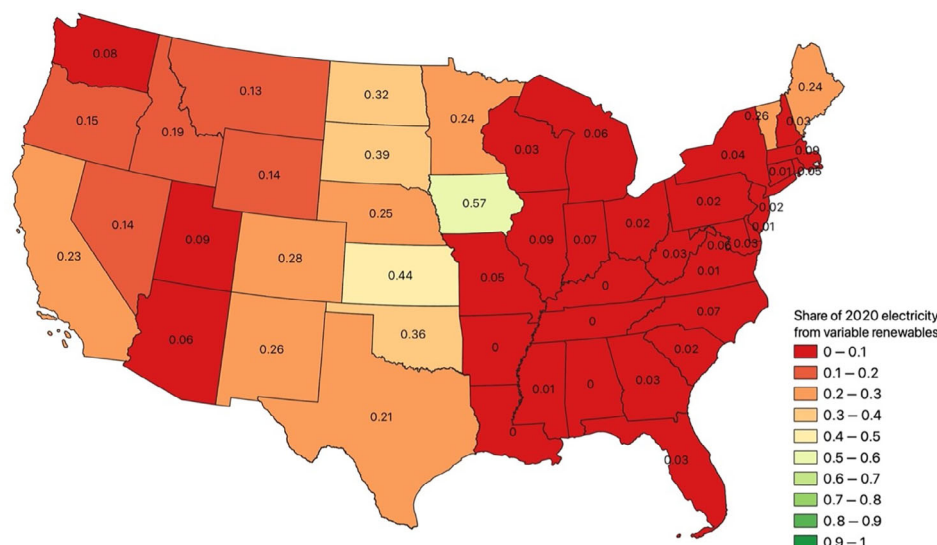


FIGURE 1 Some US states already have >20% variable renewable electricity penetration, a sign they might have entered the mid-transition. Note that total zero-carbon electricity rates are higher but conventional zero-carbon electricity is adapted to the previous system. Source: EIA 860/923

thumb is extremely coarse and should be empirically tested for compatibility with the results-oriented definition emphasizing when systems constrain each other, it is supported by some prior observations. For example, the current energy system is approximately 80% fossil fuel-based (Hanna & Victor, 2021), suggesting that 80% is a reasonable threshold for identifying a system as dominant. Supporting the notion that 20% penetration by a qualitatively different system becomes operationally disruptive, the California “duck chart” identifies a phenomenon where, around 20% of annual energy being provided by solar, the conventional system is highly challenged by the need for fast ramping at the same time as its business-as-usual constraints lead to large (>30%) marginal curtailment rates for the emerging solar system (Denholm et al., 2015). In the United States, some electricity systems are at the beginning of the mid-transition from fossil-based power systems to variable renewable electricity (VRE) systems under this rule-of-thumb (recognizing that VRE is not the only possible end-dominant system for electricity, and also that in both cases, infrastructure like hydroelectricity or other potential “clean firm” generation resources might not belong neatly to the operationally dominant system), whereas transportation and industrial heat have not yet entered the mid-transition (Figure 1).

Under the timelines suggested by current US climate targets, all energy systems are expected to rapidly enter and traverse the mid-transition (by 2035 for electricity; by 2050 for all energy systems). For perspective, the time left between now and 2050—when the United States aims to achieve full decarbonization of the economy (net-zero emissions), and roughly when global net zero is advised if warming is to be limited to 1.5°C (Intergovernmental Panel on Climate Change, 2021)—is roughly the same as the time between the establishment of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 and now. Success, then, requires a very rapid mid-transition relative to historical pace.

3.1 | Technical heuristics for the mid-transition

Particularly in the context of a normative, goal-oriented decarbonization transition, one major consideration for the mid-transition is whether currently applied heuristics serve our design, deployment, and maintenance systems well. Heuristics that have historically served well as proxies for endpoint indicators of interest, like successful provision of energy systems, might not be fit-for-purpose at various points in the mid-transition, or long-term as we transition to a fully zero-carbon system (though note that ongoing climate dynamics are likely to continue to require flexibility).

Metrics like heat rate (or thermal efficiency), historically related to intuition about energy costs, do not make sense for nonthermal systems—especially those with free fuel. The idea of dispatching the plants with highest conversion efficiency first makes very little sense for wind and solar plants. Broader and more deeply embedded heuristics, like general concepts of what is needed or available to promote grid reliability (e.g., supply side only versus supply and

demand), or the idea that energy extracted at a particular site becomes more expensive over time due to resource declines, also fail as the system changes. Furthermore, existing metrics tend to be focused on the costs/benefits within an existing system over the lifetime of the infrastructure under question. In some cases, this is inherent in the metric, such as levelized cost of electricity (LCOE) for electricity generation. But even attempts to account for the costs and benefits within a given energy system, such as levelized avoided cost of electricity (LACE), are typically done within a static system.

The length of the mid-transition, which may be short compared with the lifetime of new infrastructure if we assume the mid-transition must be completed by 2050 and in many cases has not yet begun, introduces the need for new considerations given to the relative costs when lifetimes are shorter. For example, a power plant converted from coal to gas may be higher cost compared with the construction of a new combined cycle natural gas plant, but lower over a shortened lifetime of operation. Or the economics of deploying energy storage rather than new natural gas today in some regions may be favorable despite higher costs in today's calculation because of a future need to retire the gas plant before the end of its useful lifetime.

The mid-transition is likely to need three sets of heuristics: (1) those designed for the legacy system; (2) those designed for a fully zero-carbon system; and (3) those designed for the dynamic mid-transition period where the overall energy system still needs to deliver services, but in addition must create a transition to the zero carbon system while facing challenges of decadal dynamics as the zero-carbon system grows and the legacy system shrinks. Recognizing that each system will likely be operating in a way that accommodates the other for decades, and that such accommodations could be maladaptive in ways that might be locked in without careful attention to the differences between integrated carbon-emitting and zero carbon systems versus fully zero carbon systems, is critical. Explicitly designing and using fit-for-purpose mid-transition heuristics could be a valuable near-term contribution by the modeling and analysis community.

3.2 | System design

Fundamentally, at least for the supply side of the energy system, the mid-transition is a sociotechnical but highly material process of simultaneously deploying and retiring industrial systems like power plants, fueling stations, and vast networks of other infrastructure supporting highly diverse energy service provisioning. Implications for justice, equity, and the environment are in large part functions of system design, itself heavily inflected by political processes (Harrahill & Douglas, 2019; Healy & Barry, 2017). Although this review focuses on the United States and recognizes that political setting varies across nations, Mildenerger identifies the issue of “double representation,” where carbon incumbency receives policy advantages through representation in both left-leaning and right-leaning political coalitions, as a core feature of climate policy conflict in advanced economies broadly (Mildenerger, 2020).

During this transition, neither the older carbon-emitting system nor the new zero-carbon system will be fully optimized for its own needs, and the two systems will likely both need to adapt to accommodate the other. Importantly, this transition will be dynamic: a 30% zero-carbon system will likely behave very differently from a 70% zero-carbon system in its relationship with the carbon-emitting system, for example. Further, there will likely be significant justice and environmental considerations for managing times when both systems are working in ways that are somewhat hindered by the other, including operational issues (e.g., fossil fuel ramping), responses to market and ownership structures (e.g., solar curtailment in the context of electricity rates designed to encourage people to avoid using electricity during the day, when solar output is highest, due to historically high fuel costs during those periods), and competing public perceptions. These considerations highlight that just as fit-for-purpose technical heuristics are needed to evaluate progress toward the normative goal of eliminating greenhouse gas emissions, so too are indicators designed to accommodate mid- and post-transition dynamics needed to characterize progress toward normative social and justice goals (see, e.g., Cha, 2020; Healy & Barry, 2017; Thomas et al., 2019; Waisman et al., 2019). Developing theoretically grounded, usable, and valid metrics to evaluate social impacts and justice outcomes is a major and very challenging project of the socioenvironmental assessment community (Fortier et al., 2019; Grubert, 2018a; Hale et al., 2019) that is even more important in the context of major system dynamics. Decarbonization will create both acute and long-term challenges and opportunities with major implications for people's health, opportunities, and material well-being, grounded in the context of existing structural injustices that could be exacerbated without careful planning and the ability to quickly identify and correct problems.

The transitioning system will be characterized not just by the coexistence of zero carbon with carbon-emitting systems, but active reliance by maturing technologies on the existing system for support as they develop and gain experience at scale. That is, a system that is 50% zero carbon actively requires the rest of the system—the carbon-emitting system—to provide energy services, and if that carbon-emitting system is prematurely lost, there are likely to be dire consequences for society and energy users. This reliance is one reason that careful attention to phase-out is needed, potentially including incentives for workers to “stay on the line” operating carbon-intensive systems even well after it is clear they will be phased out.

Even within large and slow transitions, collapses can occur rapidly (Cohn, 2021) and with major consequences for those they affect (Snyder, 2018). Legacy infrastructure closures can occur essentially overnight, but deploying replacement infrastructure can take years given permitting, construction, and other timelines—a major motivation for closely coordinating phase-out and phase-in. Further, without active design and agreement on how the integrated and dynamic blended system will function, conflict over which critical energy functionalities each system needs to be able to provide is likely to emerge, with consequences for people. For example, if zero carbon system operators assume they do not need to solve the problem of clean firm power provision (Sepulveda et al., 2018) until 80% penetration, but profits decline sufficiently that operators of flexible natural gas-fired power plants depart at 50% zero carbon penetration, a crucial resource will have been lost.

Similarly, recognizing that emergent issues associated not only with learning (i.e., growing) but also with unlearning (i.e., shrinking) might occur, and planning for contingencies will be critical. For example, decarbonization studies commonly assume small amounts of natural gas will be available to the power sector to support the grid under relatively infrequent, challenging conditions, at prices and accessibility similar to what is observed today (E. Larson et al., 2020; Phadke et al., 2020; Williams et al., 2021, and see Committee on Climate Change, 2019) for a similar assumption in the UK context—but this assumption presumes that private extraction companies, pipeline operators, and other supply chain actors (that might not have a positive obligation to serve) continue to participate in the system despite clear messaging that there is not only no growth expected, but active decline, in these high capital intensity industries (McGlade et al., 2018). Implications of industry shrinkage for prices and markets are essentially not discussed. As such, attempts to secure participation under existing market structures could be highly inefficient and require significant subsidization of private sector profits.

We note that these issues are likely to manifest differently across countries with different planning, regulatory, and industry ownership contexts than the United States (Blondeel & Van de Graaf, 2018; Carter & McKenzie, 2020). The global nature of the fossil energy system, however, suggests that issues of unlearning in high capital intensity industries with meaningful international private sector participation, even for state-owned companies (de Graaff, 2012; Karl, 1999), will be widely experienced. Such dynamics are particularly relevant given that the existing system will likely continue to receive replacement-level investment (e.g., through repairs and equipment replacements), especially if there is not an explicit advance plan to disrupt steady-state replacement activities (see, e.g., Grubert, 2020b). A designed transition recognizing the dynamics not only of zero carbon system growth, but also carbon-emitting system decline, could enhance safety and welfare by anticipating these types of challenges and gathering the appropriate groups early enough to codesign workable solutions before crises emerge. Again, even fast decarbonization will likely take decades, allowing for some lead planning time.

The optimal length of the mid-transition period is typically determined based on the pace of emissions reductions required to constrain temperature increases, but a better understanding of the dynamics of the mid-transition and the potential for costs to change as a function of the length of the transition is an important input to policy making. For example, Way et al. suggest that as a result of the dynamics of learning processes through the transition, a faster transition can be less expensive than a slower one (Way et al., 2021). The point that infrastructure needs to be replaced as it ages, and that those replacements might be more or less compatible with a zero-carbon future (e.g., a natural gas turbine; a fossil hydrogen turbine that could convert to renewable hydrogen; or a fully decarbonized asset) depending on pacing, reinforces this observation. Full accounting of the costs from the interaction of the fossil and zero carbon systems during the mid-transition could further increase these cost savings.

3.3 | Resource constraints

Importantly in the context of designing the de-transition of high-hazard carbon-emitting energy systems, systems anticipating decline and closure will likely experience even more pronounced disinvestment than is already observed.

Markets are unlikely to function as they have in the past, and price shocks associated with unplanned and/or uncoordinated closures of large and capital-intensive facilities and infrastructures should likely be anticipated. Particularly given large outstanding liabilities associated with labor and environmental reclamation and remediation, careful attention will be necessary for managing multiple objectives in an increasingly resource-constrained context. Costly maintenance programs, specialist training, and worker recruitment for the carbon-emitting system are likely to decline over the next small number of decades, with major potential implications for safety, reliability, and other performance metrics that the integrated system might rely on. Mid-transition design should recognize and include the need to attract and retain skilled workers to operate the declining system as long as they are needed, while also recognizing the need to secure the future for workers in industries that are going to disappear, particularly given the extensive history of sudden bankruptcy and abandonment of worker and environmental obligations in the fossil transition to date (Macey & Salovaara, 2019). Simultaneously, labor requirements for phase-in of zero carbon systems are expected to be very large but often temporary, with potentially different skillsets, locations, and wage structures than are currently experienced by energy workers (Cha et al., 2021; Mayfield et al., 2021; Pai, Harrison, & Zerriffi, 2020). Training both short-term and long-term workers, and ensuring material security, safety, and equitable access will be major challenges of phase-in, just as they are for phase-out.

In addition to financial and labor constraints, energy systems are subject to material resource constraints. New systems, as with old systems, are resource constrained. During initial system buildout, zero-carbon systems could be constrained both by raw materials and by factory capacity due to the sheer rapidity of transition requirements. Such constraints can also give rise to oversupply and resulting market volatility, a dynamic that has been observed in the scale up of solar PV production which has been characterized by alternating periods of oversupply and scarcity (Bloomberg, 2020). Resource market volatility is not specific to zero carbon systems; rather, it is high growth rates that underpin the challenge.

Longer term, though, the transition from underground to aboveground resources (Mulvaney, 2017) means that the dominant constraint will likely be land with appropriate characteristics rather than a depletable fuel resource like coal, oil, or natural gas. As such, redeveloping the same sites with better technologies over time could actually improve productivity for some resources, in contrast to fossil fuel-based systems. Even still, this land-based resource constraint is relevant. Relatively low power density for flow resources like wind and solar as opposed to stock resources like fossil fuels (accumulated solar energy; Diaz-Maurin, 2016; L. M. Miller & Keith, 2018) means that powering a fully zero-carbon, electrified system will require many individual plants, all with siting processes and multicriteria non-GHG socioenvironmental impacts that need to be carefully evaluated to minimize cumulative harms (del Río & Burguillo, 2008; Grubert, 2021; Figure 2) and improve on the experience with fossil resources (Jenner & Lamadrid, 2013; Olszynski, 2014).

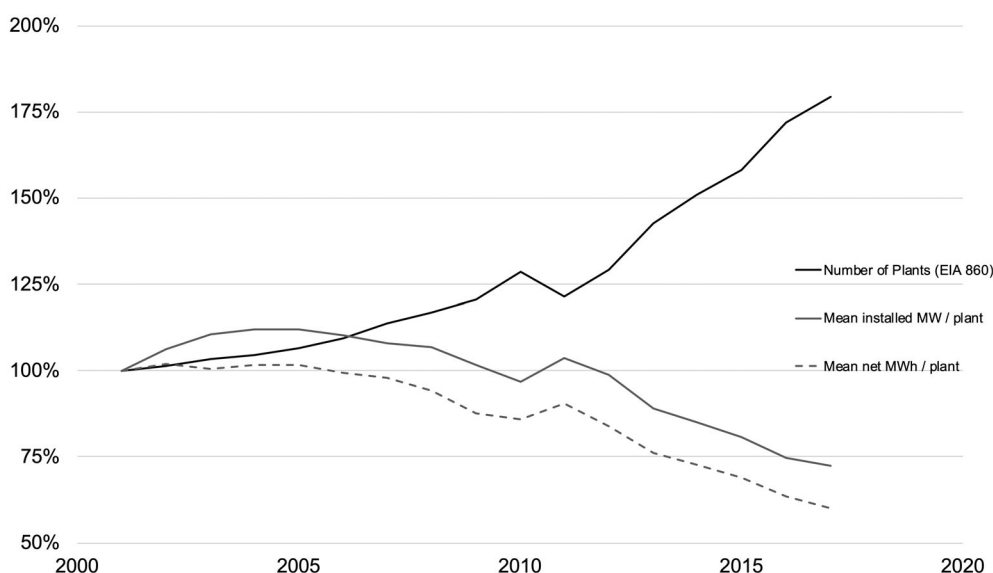


FIGURE 2 US power plants are growing smaller and more numerous over time, correlated with growth in renewable energy penetration. Indexed to 2001 = 100% of metric. Source: EIA 860

The pace of transition, mediated by social license and the confluence of potentially tens of thousands of siting processes, is relevant not only for climate but also because fossil fuels are depletable (Farrell & Brandt, 2006; Grubert, 2012; Höök & Tang, 2013; Patzek & Croft, 2010). Depending on carbon-based systems in the long-term, particularly if doing so requires high energy intensity activities like carbon capture, could result in the need for ongoing innovation in and development of the fossil fuel industry even as it is being phased out, representing major resource allocation conflicts. Further, oil extraction gets more climate intensive (and often more expensive) with oilfield age (Masnadi & Brandt, 2017), and the fossil industry is energy, capital, and emissions intensive (S. A. Miller & Grubert, 2021), with high requirements for technical expertise requiring large training infrastructures. Relatedly, building out zero operational carbon infrastructure can be emissions intensive depending on background contexts (Di Felice et al., 2018), so specific pathways matter.

4 | SOCIETAL CONTEXT OF THE MID-TRANSITION

The mid-transition will present numerous challenges beyond technical design and integration challenges, in many cases due to societal contexts like existing power structures, direct impact of policy-mediated transition on people, and mirrored impacts of people on technology. A status quo bias favors incumbents (Samuelson & Zeckhauser, 1988). As noted above, one major challenge for the mid-transition is that the carbon-based system is not being phased out because it does not work (although climate change and extreme events are increasingly obvious challenges to this perception), but because previously acceptable harms (largely, GHG emissions) are no longer acceptable because the environmental context, and environmental knowledge, has changed. There is no guarantee the future system is obviously better from an individual's perspective (see, e.g., [She et al., 2017] on people choosing to “wait and see” about battery electric vehicles), particularly given clear and present dangers like excessive heat that seem to emphasize the need to retain systems that have always been reliable in the past. As such, understanding the context of power, perception, and experiences people are likely to have is also crucial for understanding the mid-transition.

4.1 | Political power

Transition away from carbon-based systems requires destabilization of existing power structures (Haas & Sander, 2016) rather than the pure technological change that is more easily represented in models. Particularly given the size and power enjoyed by some of the major actors in the carbon based economy (Kenner & Heede, 2021), and their active efforts to slow or prevent rapid decarbonization transition (Černoch et al., 2021; Franta, 2021; Geels et al., 2017; Kenner & Heede, 2021; Mildenberger, 2020), phase-out is unlikely to happen on its own. Rather, it will likely require active and repeated political decisions in highly contested contexts, leveraging understanding of coalitions, feedbacks, and contexts just as for acceleration of the forward transition (C. A. Miller et al., 2015; Roberts et al., 2018).

4.2 | Public perception and experiences

Both decarbonization-oriented industrialization and deindustrialization could face significant challenges associated with the fact that both activities are intended to create national (and global) benefit at the expense of local harms, and that host and prospective host communities are likely to understand, and oppose, concrete and easily communicated negative impacts. Accusations of NIMBYism fail to recognize that there are often good reasons to oppose specific projects, even when people support transition in general—a phenomenon sometimes called the “social gap” (Batel & Devine-Wright, 2015; D. Bell et al., 2013; Devine-Wright, 2009; T. Measham et al., 2021; Sward et al., 2021). Particularly given the roles of trust (T. Measham et al., 2021), identity and deeply held values (S. E. Bell & York, 2010; Cha, 2020; Chan et al., 2016; Colvin, 2020; Colvin et al., 2015; Devine-Wright, 2009; Grubert, 2018b; Klain et al., 2017), and understanding that focusing on issues that are granted authority in decision contexts can be the expedient way to gain value-consistent outcomes (Fischhoff, 2013) in siting, social license, and transition processes generally, explicit and advance planning for transition that recognizes values and aims to create positive futures is crucial (Abraham, 2017; Grubert, 2017b; Haggerty et al., 2018; Snyder, 2018).

The perception that the existing system is still essentially functional, despite the serious local and global threats associated with ongoing use of fossil fuels and the increasing awareness that existing systems are not resilient to climate change and extreme weather (Busby et al., 2021; Guliasi, 2021; Malcolm et al., 2021; Wong-Parodi, 2020), poses additional inertial challenges associated with the extant carbon-based system. Problems during the mid-transition, including those that also affect carbon-based systems, could be blamed on the new entrants perceived as the reason the system is not as effective as it used to be—take, for example, the case of the Texas Freeze during Winter Storm Uri, when natural gas system failures in the face of extreme weather that lead to dangerous and widespread blackouts were instead publicly and authoritatively blamed on the wind system (Busby et al., 2021). Similarly, challenges with new technologies, like avian mortality from wind turbines (May et al., 2015), could have major and long-term implications for public perception and social license even if the problems are solved. Consider that compact fluorescent lightbulbs, introduced in the 1980s, faced major perceptual barriers due to early challenges whereby consumers did not value benefits (efficiency, lifetime) relative to losses of incandescent bulb characteristics like instantaneous lighting and low purchase prices (Menanteau & Lefebvre, 2000). As such, particularly early in the mid-transition, even rare missteps—let alone new and difficult-to-mitigate impacts, like the large land impacts of renewable energy systems that rely primarily on above-ground rather than below-ground resources (Mulvaney, 2017)—could be extremely challenging for technology deployments.

Early-stage deployment often suffers from challenges associated with immaturity that might not be permanent (Rosenberg, 1976), but performance challenges relative to alternatives—in this case, the pre-climate change fossil fuel-based energy system—could be meaningful barriers to successful normative decarbonization transition in a way that mid-transition design should account for. Especially because people often value losses more highly than gains (i.e., gain-loss asymmetry, or loss aversion) (Bateman et al., 2009; Horowitz & McConnell, 2002), and because gains associated with avoiding more severe future climate change are difficult to parse, even new technologies with significant benefits might be seriously hindered by perceived losses. For example, personal electric cars might be quieter, less polluting, cheaper to run, easier to charge at home, and safer than internal combustion engine vehicles, but charging times relative to filling up a vehicle at a gasoline station remain a major perceived barrier to acceptance (see Box 2).

Because people use energy directly, many of these technology transitions will be felt personally by people who will need to modify relationships to the energy system (Geels et al., 2017). Simultaneously, people's relationships to the energy system will in turn shape the energy system, as users interpret and participate in the mid-transition (Kline & Pinch, 1996). That is, just as the technical setting of the mid-transition will likely affect society, the social setting of the mid-transition will affect technologies. Beneficial electrification (Dennis, 2015; Williams et al., 2021) of currently fuel-based services like natural gas furnaces, natural gas stoves, and gasoline cars will have direct impacts on user experiences, likely with some advantages (e.g., lower indoor air pollution) accompanied by required behavioral changes and unfamiliarity that might be seen as a negative (see Box 2). These changes, directly integrated into people's lives, are social processes that might be felt as major impositions and injustices without care dedicated to how, and by whom, the systems are detransitioned (Hu, 2020; Itten et al., 2021). Misalignment with collective values and cultural models, particularly those typically excluded from “expert” narratives, can also pose challenges, including when groups self-select out of technical systems that they do not see as relevant, accessible, or appropriate for themselves (Tidwell & Tidwell, 2018). Although technological systems can impose structural boundaries, motivating emphasis on responsible

BOX 2 Why might the mid-transition be particularly challenging for new technologies?

Consider the case of electric cars: they are quiet, have low total cost of ownership relative to petroleum-based cars, and can be fueled at home. They reduce air pollution, and they require less maintenance than petroleum-based cars. Advances suggest that they could soon be cost competitive with petroleum-based cars even from a capital cost perspective. These benefits, however, occur in the context of wide acceptance of petroleum-based cars and the problems they create. As such, perceived disadvantages of EVs relative to the acceptable status quo are seen as additive problems, without the benefit of recognizing subtractive harms. Consider the situation where a society accustomed to EVs was transitioning to petroleum-based vehicles. Just as we now see concerns about fueling time, availability of fuel stations, and costs, EV users being asked to transition to petroleum-based cars might have major concerns about needing to travel to refuel, using highly flammable liquids, creating air pollution, noise, and maintenance cycles. For systems that are already widely accepted, incumbency is favored.

innovation (Stilgoe et al., 2013), people can also generate novel and potentially unexpected approaches to using technology that push these boundaries and contribute to feedbacks that make the mid-transition an intertwined socio/technical process (Kline & Pinch, 1996).

Simply planning how zero carbon systems will come to be without also planning for how carbon-based systems will be phased out is not adequate for major sociotechnical systems like energy. The mid-transition is a potentially decades-long process of achieving both goals, with familiarity and other forms of inertia strongly favoring preservation of the fossil system, especially given that high-impact, distressing events associated with the failure of industrialized systems in general to perform well under climate change could easily be blamed on the new, immature entrants that will likely have some major flaws.

Focusing on public “acceptance” of energy transitions can sometimes miss the point not only that publics are agents of energy transitions (Kline & Pinch, 1996), but also that public attitudes are nuanced and can be very well informed in contexts of general support for a transition but opposition to particular projects or processes (Sward et al., 2021). Just because a project provides something of value, like zero-carbon energy, does not mean that it performs well on all socioenvironmental criteria of interest—some of which are extremely important to people (Grubert, 2017b). The public participates in transition, sometimes explicitly as part of decision processes—a role that is increasingly incorporated (Komendantova et al., 2018; Ulibarri, 2019; Xavier et al., 2017)—and always as users, hosts, and constructors of technologies. Transitions can be extremely disruptive (Jacquet et al., 2018; Theodori, 2018), with ambivalence about mixed positive and negative impacts.

Notably, some of the most well developed literature on public response to energy transition in the United States focuses on response to the very recent industrialization associated with the rapid expansion of natural gas and oil production since about 2010 (Brasier et al., 2011; Jacquet, 2015; Jacquet et al., 2018; Junod et al., 2018; Theodori, 2012, 2018; Zanocco et al., 2020)—an important reminder that transitions are not linear, and also important societal context that some of the most visible recent transition has been fossil-based, with attendant impacts (T. G. Measham et al., 2015). US oil production represents an interesting transition case study also in the sense that one resource (conventional oil) has declined, while another (unconventional oil) has grown rapidly (Manfroni et al., 2021): although the consumer products are largely the same, this transition has been real and could be instructive. Similar social scientific attention to solar development is also emerging (Carlisle et al., 2014; Carlisle et al., 2015; Carlisle et al., 2016; E. C. Larson & Krannich, 2016; T. Measham et al., 2021; Tidwell & Tidwell, 2021), with recognition that public attitudes toward energy systems are not simplistically positive or negative based on GHG emissions profiles, nor static in the face of processes in which the public participates.

Practical design constraints, like how to manage which infrastructures are preserved as carbon-based systems shrink, also pose challenges. For example: fully electrifying personal transportation implies not only substantial build-out of charging infrastructure (The White House, 2021a), which will happen unevenly in space and time, but also a simultaneous and similarly uneven phase-out of gas stations (many of which have substantial environmental liabilities due to hydrocarbon spills and tanks), a major and increasingly urgent issue that has received little to no research or policy attention in the United States. Given the messaging challenges associated even with phase-out of coal for electricity, particularly related to jobs and local impacts in a relatively small industry (Bureau of Labor Statistics, 2021), inattention to processes likely to result in widespread job losses and environmental liabilities is both politically understandable and likely a grave mistake in the deeply political process of transition (Healy & Barry, 2017). The unplanned and unmanaged phase-out of coal, which is relatively easily substituted in ways that electricity users likely do not even notice, has resulted in widespread shedding of labor and environmental liabilities (Macey & Salovaara, 2019), long-term structural harm to host communities, and other challenges likely to be amplified in larger and more consumer-integrated fossil-based industries. A transition where gasoline stations make decisions to close independently, without design, could leave entire groups of people in very difficult situations, but forcing gas stations to remain open is not easily achieved under current regulatory structures. Careful design will be necessary to prevent the most vulnerable from bearing disproportionate costs both of increased cost of service associated with shrinking systems and of lack of service in general, across multiple consumer-facing carbon-based infrastructures. Conflict between public and private decision making on siting is also emerging for electric vehicle charging stations (Asensio et al., 2020; Globisch et al., 2019; Guo et al., 2016; She et al., 2017), suggesting that more centralized planning might be necessary to facilitate the transition period when neither gas stations nor EV chargers will be fully ubiquitous.

5 | CONCLUSION

The mid-transition will be characterized by climate and energy system non-stationarities. Failing to plan for the phase out of the carbon-producing energy system, while also planning to phase in the zero carbon system, could seriously

threaten this normative transition of decarbonization. Emphasizing justice and energy service provision, including via focus on providing for material needs, is likely to be core to a successful transition. One major finding of this review is that the mid-transition is not widely evaluated as a simultaneous process of addition and subtraction, starting from a failure to define and characterize the mid-transition period. Specifically, the mechanics of carbon phase out are poorly represented in the literature. As a side effect, this review almost certainly overlooks some key considerations on the technical and social context of the decarbonization transition, and we urge additional work focused explicitly on these issues at local through global scales. Meanwhile, we make several recommendations based on our evaluation of the current landscape.

Analytically, the mid-transition period should be better represented, starting with a definition and identification of the mid-transition period for different energy systems. Then, quantitative models (often granted high authority in decision processes) should explicitly account for phase-out and phase-in in ways that can be used to test various impacts of interest across multiple designed pathways, with careful attention to which services each system will be providing and whether there are sufficient incentives and/or requirements for those provisionings. For example, simply assuming for-profit companies that have historically participated in the energy system due to market incentives and expectations for stability or growth will continue to operate in qualitatively similar ways could be a major mistake. New heuristics should be developed for the mid-transition period that include the temporal dimension and allow for better comparisons between different options for resources in different transition pathways.

The role of governance and institutional structures could be particularly important to track, given their impact on how systems respond to change. Consider how unplanned fossil fuel phase-out might unfold for gasoline-fueled services, where individual service stations remain in business or exit the market based on profitability pressures, versus natural gas supply to residences, where utilities have an obligation to provide residential services that might conflict with practices like distribution system pruning. Further, in both cases, electrification (and subsequent reliance on electric utilities) could significantly change the regulatory context of service provision. Explicitly designing models to be updated based on shifting baselines and climate/energy dynamics relevant for decision support is also likely to be a fruitful area of inquiry (Joyce & Björklund, 2021).

From a visioning perspective, it will be crucial to design the mid-transition as a pathway to a post-transition world that fulfills needs and confers opportunities, shaped by participants during both planning and implementation. Mid-transition choices that result in dead ends, like replacement investments in capital infrastructure almost certain to be stranded by later emissions and other targets, should be extremely carefully evaluated, particularly given resource constraints. The mid-transition is likely to be painful in some ways, both due to learning (e.g., about new technologies and navigating the world under ongoing and dynamic climate change) and to maladaptations associated with two fundamentally different systems accommodating each other, and so ensuring that the vision of the future is clear and positive is likely to be important for success in this political process of change. One particular recommendation is to focus on ensuring material security for all, consistent not only with the goal of infrastructure systems to enhance health, safety, and welfare for all (ASCE, 2020) but also with observed pathways to public support for transition (Bergquist et al., 2020) and particularly under deindustrialization (Snyder, 2018).

Transition, and climate change, is concerning for people. In part, this is because of fears that we will lose things we need or value, like healthcare, job security, and a healthy future for generations to come. Ensuring that there is space to raise and act on these values and concerns in decision processes could help clarify what people want from a transition, while also avoiding situations where people correctly recognize that certain issues have more decision power than others, and that attacking those issues can be the only reasonable path to addressing other perceived challenges (Fischhoff, 2013). It is important to understand the technological needs for future energy systems. But also crucial for a successful mid-transition in the United States, and globally, will be understanding the role of power, agency, and politics in the social context of transitions expected to result in losses for some (Köhler et al., 2019; C. A. Miller et al., 2015).

ACKNOWLEDGMENTS

No specific funding was received for this work.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Emily Grubert: Conceptualization (lead); formal analysis (lead); visualization (lead); writing – original draft (lead); writing – review and editing (lead). **Sara Hastings-Simon:** Conceptualization (supporting); investigation (supporting); writing – original draft (supporting); writing – review and editing (supporting).

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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How to cite this article: Grubert, E., & Hastings-Simon, S. (2022). Designing the mid-transition: A review of medium-term challenges for coordinated decarbonization in the United States. *Wiley Interdisciplinary Reviews: Climate Change*, e768. <https://doi.org/10.1002/wcc.768>