initiative that US Secretary of Energy Steven Chu launched in 2010.[12] The Hydrogen Earthshot is necessary to create a hydrogen economy, but it is not sufficient.

Second, the R&D should be integrated with a private-public partnership for technology demonstration programs to address economic, regulatory, supply chain, and policy considerations and thereby establish a credible de-risking approach to attract private investors.

Third, federal and/or state authorities must adopt policies to support a hydrogen market either by a charge on GHG emissions or via clean energy standards that involve GHG-free H_2 as an option, or a combination of the two. These policies should also include the enabling market creating policies for solid carbon produced via methane pyrolysis. Furthermore, governments should use their purchasing power to create a demand for GHG-free H_2 and, most importantly, consider using a reverse auction to foster a globally competitive supply chain in the private sector.

Finally, despite the strong interest in green hydrogen from electrolysis, the economic reality suggests that there could be a significant fraction of GHG-free hydrogen originating from natural gas. Therefore, a holistic hydrogen strategy should also be aligned with a national carbon management plan, which should include an infrastructure for carbon capture, transport, and sequestration derived from processes yielding either gaseous (SMR) or solid (pyrolysis) carbon co-production.

DECLARATION OF INTERESTS

A.M., J.M.D., and R.S.P. serve on the scientific advisory board of Breakthrough Energy Ventures (BEV). T.P.G. is an employee of BEV. BEV has interests in investing in the hydrogen industry, especially in early-stage commercial efforts. A.M. serves on the advisory board of *Joule*.

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Commentary

Toward carbon-neutral electricity and mobility: Is the grid infrastructure ready?

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The electric power and transportation sectors are the two largest contributors to greenhouse gas emissions in the U.S. and in most other nations. A critical path toward carbon neutrality relies on decarbonizing electric power generation and simultaneously electrifying a major portion of the transportation sector. If successful, this path will fundamentally change the way energy is converted, delivered, and utilized for a sustainable society.

This piece takes an "electric grid-centric" viewpoint to directly address infrastructure changes that have long lead times and often pose public acceptance issues. A key challenge in the ambitious carbon neutral transition lies in the scale and speed of accomplishing this transformation. We address the following questions that underpin this global endeavor to grapple with climate change. Is today's electric infrastructure ready to facilitate such an ambitious decarbonization effort? If not, how should investments be prioritized to leverage feedback from vehicle electrification and further expand the electric infrastructure? This piece summarizes key challenges and opportunities in the electric grid sector as we make an ambitious transition toward carbon neutrality. We have written with two audiences in mind: (1) decision makers from government agencies and related stakeholders (e.g., Regional Transmission Organizations) and (2) climate challenge-aware young researchers who wish to make an impact in the electric grid sector. We argue that there exists a feedback loop between the electricity and transportation sectors. Whereas the electricity sector should plan for an aggressive electrified charging demand from the transportation sector, mobile batteries in cars can also be viewed as an important resource of energy during times of stressed grid conditions. How to design a coordinated incentive and operational architecture between these two sectors remains a key intellectual challenge for the research and policy-making communities.

Is today's electric grid infrastructure ready?

Based on a study by the U.S. Energy Information Administration, the levelized cost of electricity (with applicable tax and subsidies) of onshore wind and solar photovoltaic generation has reached economic parity with the natural gas combined cycle.[1] While this is very encouraging news for the argument of further decarbonizing by addressing the electricity and mobility sectors, it remains largely unclear regarding the readiness of today's electric grid infrastructure in facilitating such an ambitious decarbonization effort.

The discussions are motivated through a representative example. There has been increasing evidence on the impact of uncoordinated electric vehicle charging on the electric distribution grid such as transformer overloading at a modest level of EV penetration.[2] This is further exacerbated by the more stringent limits imposed by the electric distribution grid protection design, which assumes one-way power flow and very distinctive electric current patterns that could be used to separate normal from faulty conditions.[2] With aggressive vehicle electrification goals, there will be a lack of hosting capacity of today's distribution networks in handling massive distributed energy resources and EVs. Economic incentives and smart scheduling could offset the peak-to-valley ratio; however, even in the most optimistic case (i.e., a flattened total load curve), the limit of the substation transformers will still likely be exceeded. This will be further bottlenecked by protective relay settings that are not tuned for two-way power flow.[3]

At the bulk transmission power system level, challenges exist regarding how to control and monitor dynamic swings induced by decarbonization and electrification. For example, there is increasing evidence in many regions of transient subsynchronous oscillations.[4,5] This is particularly challenging because it illustrates that even with installation of modern power electronics controllers and state-of-the-art transmission hardware technologies, there are still many challenges in real-time operation of large renewable generation, especially when they are far away from the load centers.

The above engineering examples illustrate how increasing interdependencies between mobility, renewable energy, and the electric grid infrastructure will render today's operation and design of the electric grid ill-prepared for the ambitious decarbonization goals. There are many more open questions. (1) How do we tap into the large wind resources, which may be far away from load centers, by using improved long-distance transmission? (2) How do we replace conventional generators with low carbon energy resources to provide all the grid services because of their differing characteristics? (3) How do we create scalable market mechanisms to ensure efficient and reliable electricity services with human-in-the-loop grid edge-level resources? (4) How do we value and protect data and computation assets for a carbon-neutral electricity and mobility infrastructure?

In the next section, we provide our comments about how to reinforce the infrastructure for such an ambitious decarbonization effort.

How to prioritize electric grid expansion for carbon-neutral transition?

Recognizing the limitations of today's electric grid infrastructure in support of an ambitious carbon-neutral transition, we argue that a holistic approach will be needed to align the societal choices, business incentives, and technological innovations in order to prioritize expansion of the electric infrastructure system. While logistically presented in a separate manner, these aspects are fundamentally intertwined and will synergistically contribute to enabling a more sustainable electric grid. There are indeed many experiences that can be learned from regions with deeper penetration of renewables;[6] however, to the best of our knowledge, how to reliably and cost-effectively integrate massive renewables with large amount of vehicle electrification at a continental scale remains an open question.[7] It is our sincere hope that this manuscript will generate more interest and attention to the "infrastructure" aspect of the climate solution.

We summarize the key research challenges below and substantiate them in the rest of the article.

1. Whereas conventional power grid dynamics are primarily dominated by inertia-driven physical interactions, carbon-neutral power grid dynamics will be primarily governed by the algorithmic control of power electronic inverters. What will be the proper algorithmic control protocol that would ensure the physical and cyber security of a large-scale stochastic dynamic system?
2. Whereas reliability performance of conventional power grids is conventionally achieved by diversification of location and technologies of generators with firming capacity (e.g., coal and natural gas), a carbon-neutral power grid will be supplied predominantly by generation that does not exhibit firming capacity. What will be the theory and cost-risk analysis of reliability performance of a power grid with deepening penetration of intermittent supply and demand?
3. From the market design perspective, what will the pricing construct be for uncertainty and flexibility in carbon-neutral electricity systems? A market for carbon-neutral electricity needs to charge resources that create uncertainty and reward resources that mitigate uncertainty by providing flexibility. Markets for flexibility and market clearing mechanisms that account for uncertainty will go a long way toward mobilizing demand side resources and edge technologies to provide reserves and accommodate renewables.
4. As the key resource that brings electric and transportation networks closer, mobile EVs require special attention. How could one imagine and construct a market for EV storage? Potentially, cars can travel to a location that has an outage and provide it with power. Such interaction puts an uber-like market on top of an electricity market.
5. At the foundational level, it remains far from clear what the proper architecture will be for the grid infrastructure that supports carbon-neutral electricity and mobility. It remains open research questions how to properly conceptualize, model, and

analyze the interdependencies across multiple functional layers for such a complex power infrastructure ecosystem.

The electrification of the transportation sector undoubtedly requires attention to a wide range of transition, including heavy-duty, air traffic, as well as light- to medium-duty vehicles.

Whereas the primary motivator driving this change comes from decarbonization, the possible paths toward decarbonization may vary from region to region. We address some of the common infrastructure challenges that arise from decarbonization. As a particular subset of research focus, a distributed approach to realizing the goal of decarbonization is of particular interest in this article. Therefore, we will highlight some of the unique research challenges and opportunities in distributed energy resources as society tackles deep decarbonization.

Starting from the infrastructure hardware perspective, substantial investments will be needed to expand the bulk transmission grid infrastructure in order to allow reliable delivery of abundant renewable resources to load centers. At the more local level, substantial investments are needed to modernize the control and protection of power distribution networks and to enable them to handle two-way AC power flow with much more overlapping patterns of normal versus abnormal operational conditions. A large portion of these investments will be needed for information gathering, coordination, and actuation (i.e., the "software/analytics" aspect) in order to maximize the hosting capacity of the power grid hardware. Much attention should be paid to the investment of new control/informatics in addition to wiring-and-transformer expansion.

It is important to stress the need to revisit power system reliability in the context of decarbonization. Electricity supply in the US and most developed nations has historically enjoyed a very high level of reliability. This has been ensured by detailed long-term planning against uncertainties stemming from equipment failures and load forecasting. Going forward to full decarbonization of the power grid will require penetration levels of renewable energy that today's power industries have no experience with.[8–10] If reliability is to be maintained at the customary levels, considerable long-term planning with reliability in mind needs to be done to understand these issues and find solutions. Typically, maintaining reliability in the presence of variable energy can be achieved by geographical diversification and resource diversification, including storage and flexible demand strategies. These strategies need to be studied, planned, and executed by performing simulations long before actual implementation. As an example, for global diversification, suitable transmission facilities need to be built, which will entail extensive lead times. Energy storage will provide value to both the short-term power swing and the longer-term power availability challenges. Storage requirements will be substantial and may have consequences like disposal and cycling. It is worth stressing that reliability can be maintained, but successfully doing so requires working out these strategies and implementing them over a long period of time. All aspects need to be thoughtfully considered before plunging into the whole-scale conversion to renewables. The nature of this problem is complex, both structurally and computationally, and there will be an increasing need for real-time decisions. It is not possible just to replace conventional energy sources with renewables without ameliorating consequences of the variability of these resources. All this is made more difficult in the absence of a central planning entity.[11]

From the business and market perspective, it is important to recognize that electricity market design varies significantly across different regions. Markets provide mechanisms for regulating consumption or sharing distributed resources. If designed well, they can have serious impact on the (physical) infrastructure requirements. As much promise as renewable energy and storage technologies may offer, the complicated and oftentimes conflicting interests within the electricity ecosystem in most regions makes the adoption of technology much more complex than a single top-down decision-making process. Conventional utility business models based on volumetric charges at mostly fixed rates are rendered much less conducive toward large-scale adoption of grid-edge distributed energy resources such as solar and EVs. From an implementation point of view, it is imperative to allow new business models and incentive structures be tried out in different localities. "Learning by doing" is a most pragmatic approach to stimulate technological adoption and market acceptance at the customer end. As a crucial ingredient for scalable adoption of energy storage, we argue that EVs can be assets as opposed to constraints during this transition. With the emerging technologies that will allow for charging and discharging batteries while idle, EVs can become a major storage asset with spatial and temporal distribution.

It is worth pointing out that, as a key component which couples the electricity and mobility sectors, mobile electric loads from vehicle charging will likely be a game-changer for infrastructure expansion in technological, business, and regulatory aspects. The commitment to produce 100% EVs by 2035 from major car manufactures such as General Motors will accelerate the infrastructure's adoption of new technologies as well as market constructs to not only serve these mobile demands, but to actively exploit their flexibilities and meet the increasing

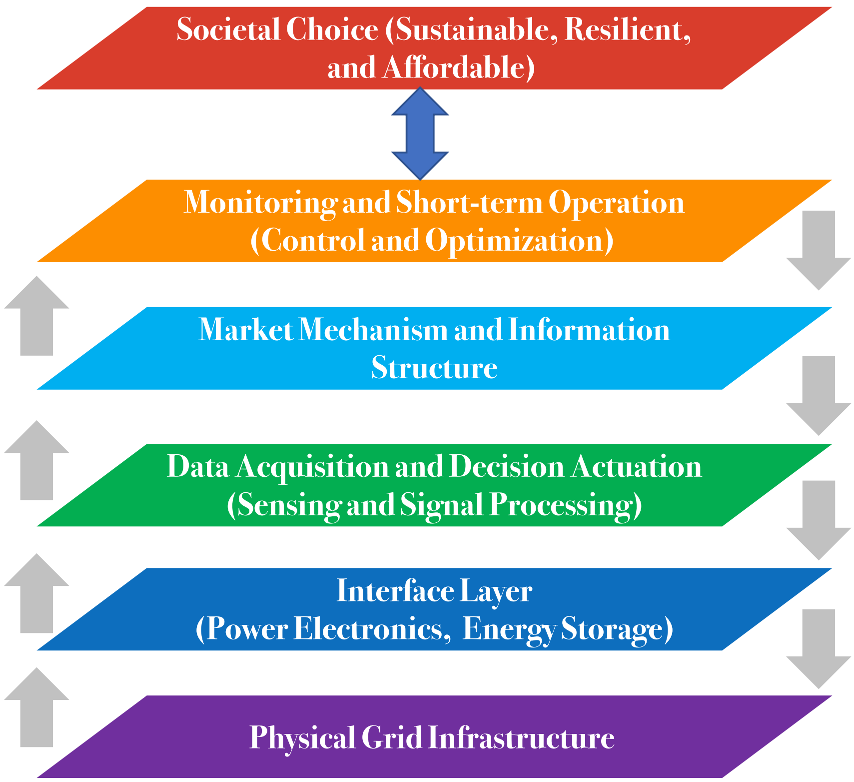

Figure 1. A possible architecture of the future grid

intermittency from renewables.[12] In this context, planning for expansion of the infrastructure will need thoughtful coordination between the electricity and transportation sectors.

At a more fundamental level, it requires extensive research efforts to properly conceptualize, model, and analyze the interdependencies across functional layers for such a complex power infrastructure ecosystem. It is our conjecture that a qualitatively different architecture is required to synthesize the cyber, physical, and societal interdependencies for electric infrastructure systems. While it still remains an open question as to which architecture would eventually prevail in the energy transition, here we postulate a functionally layered architecture for a massively digitized and decarbonized power grid. We take inspiration from some of the classical works in data communication networks and distributed control[13,14] to visualize one possible architecture as shown in Figure 1. It illustrates the interdependencies that underpin the carbon-neutral electricity delivery ecosystem. Each horizontal layer represents a functional decomposition of the ecosystem. The arrows refer to the interactions across two adjacent functional layers. The interaction variables between adjacent layers encapsulate the key functional features of a given layer. What distinguishes this architecture from the present operational practice is that conventional architecture rests on the premise of a centralized hierarchical information and decision-making framework,[15] whereas the future grid operating architecture will have to be much more interactive between producers and consumers (prosumers), and information flow becomes more distributed. An example would be that vehicle-to-grid services would imply very different information flow (two-way) as compared to that of deferrable charging (one way). Risk requirement coming from societal choices would dictate the design of redundancy, or reserve. Carbon requirement impacts the renewable penetration, which then impacts the infrastructure design. We believe that one cannot talk about infrastructure upgrades without talking about markets and regulation. A well-designed architecture for the future grid will need to address the five issues raised at the beginning of this section.

When it comes to implementation paths toward carbon-neutral goals, our perspective is that societal choice, the top layer of the architecture, will most likely dictate the outcome. There are many possible paths to achieve the eventual objective of carbon neutrality. These paths will likely vary from region to region because of the structure of the US power grid and variations in local energy resources. The "endgame" of carbon neutrality might have more than one scenario. With the deepening level of renewables, energy storage, carbon capture, utilization and storage, and behind-the-meter rooftop PVs, planning and operation strategies may need to be revisited and extensive research and development will be needed to plan for the transition from the current status to the endgame.

The current structure of regional transmission organizations' lack of an overall planning and executive authority plus social activism makes the transmission grid expansion very challenging.[4] Because of lack of this central authority, it remains far from clear how and whether a national transmission overhaul project will be feasible to facilitate the large amounts of renewable integration from wind and solar resource centers. Given the complex and interconnected nature of electricity flows, it makes technical sense to have a coordinated approach to evaluating the overall electric infrastructure, especially given the vast geographical diversity of energy resources and population/demand mixtures in the U.S.

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AUTHOR CONTRIBUTIONS

L.X. initiated and wrote the article. C.S., S.K.M., M.A.D., and S.S.O. participated in the writing and discussion of this article.

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