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the electric economy

moving toward a low-carbon future

REDUCING CARBON DIOXIDE (CO_2) emissions to the level needed to stabilize the climate will require very deep reductions in emissions from energy suppliers and end users. In Europe, the United States, and other industrialized countries, this means reducing CO_2 from fossil-fuel combustion at least 80% below present levels by mid-century and eliminating the emissions altogether a decade or two after that. The technology pathways for achieving such reductions, while maintaining an energy system that supports a modern economy, have recently begun to be spelled out in considerable detail in many countries, across sectors, and over time.

Electricity and Deep Decarbonization

Everywhere, the basic formula is the same. There are three pillars required to support a decarbonized energy system: highly efficient energy use, electricity produced with virtually no carbon emissions (much lower than possible with a natural-gas-based generation fleet), and end uses that mostly run on low-carbon electricity. These pillars stand up across geographies and stages of economic development because they embody basic physics and chemistry.

There is a role for other types of low-carbon fuels; for example, biofuels may prove essential in aviation and shipping. But biofuels are fundamentally constrained in quantity, given existing technology and land-use practices. Carbon capture and storage (CCS), which could allow the continued use of fossil fuels in power generation and industry, are constrained by the slow pace of technology development and, frankly, a lack of interest among policy makers and the fossil-fuel industry. The upshot is that currently there is no feasible alternative to electricity in most end-use applications—automobiles, buildings, industry—for supplying the low-carbon energy required.

A mostly fossil-fuel-free energy system means a major increase in electricity generation in the United States, roughly a doubling from current levels by mid-century, even accounting for the offset of some load by behind-the-meter solar photovoltaics (PVs). This realization has not yet been absorbed in some quarters. Many utilities see low or negative load growth at present and project that into their long-term load forecasts. Yet an economy-wide low-carbon transformation by mid-century will require light-duty vehicles and buildings to be more than 90% electrified and for industry to double its current electrification rate. This means a lot of new load to be met by a lot of new low-carbon generation.

Without a revival of nuclear power, or an unexpected emergence of CCS, most of the low-carbon electricity needed will be provided by renewable energy, especially wind and solar. Great progress has already been made in actual practice in integrating renewables at levels of around one-third of total generation, and there is now widespread confidence in the ability of many systems to reach well above this share. However, above about a two-thirds share of intermittent power, especially with a limited carbon budget for gas generation, a new mix of solutions for addressing energy imbalances will be required, including thermal, curtailment, storage, and increased load and resource diversity from expanded regional integration. Flexible electric loads, including the production of fuels like hydrogen and synthetic natural gas, may become key parts of the balancing mix by mid-century.

Electrification and Energy Efficiency

Integrating high levels of renewable generation poses some engineering-economic challenges, but it has a market driver in falling wind turbine and PV module prices, and it is widely understood to be the path forward for power systems in a climate-friendly world. The next frontier of decarbonization is widespread electrification. This will be driven, in part, by consumer demand and technological improvements, as we are beginning to witness with electric vehicles (EVs) and battery prices. But markets often need to be kick-started by policy, and that will require broad-based support. The need for electrification hasn't yet been universally embraced, especially in buildings

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and industry, and there is some historical animosity toward it that needs to be acknowledged and laid to rest.

In the U.S. utility context, electrification has a close historical association with load building. Since the early days, utilities have had strong incentives to grow load to increase profits, expand rate bases, and reduce average rates. During the first half of the 20th century, when access to inexpensive electricity transformed first urban and then rural life in the United States, electrification served a powerful social purpose. But since the 1970s, in the face of energy security and environmental concerns, electric load growth has often been viewed negatively.

In the energy efficiency paradigm pioneered by people like Art Rosenfeld and Amory Lovins decades ago, using less primary energy to provide the same energy services made compelling sense on many levels: lower fuel demand for thermal generation, less pollution from burning that fuel, and less need for generating capacity and, with it, lower capital requirements and fewer conflicts over licensing and land use, as was (and is) often the case for large hydro dams and nuclear power plants.

In thermal-dominated systems where the variable cost of fuel was the lion's share of generation costs, saving BTUs meant saving money, and in the 1970s when much of the generation fleet was oil powered, it meant less economic dependence on that volatile and conflict-fraught commodity. Using electricity to heat water and space in thermal-dominated systems was about three times as energy intensive, counting thermodynamic and line losses, as bypassing the conversion to electricity and using natural gas directly in furnaces and water heaters.

While much of the logic of primary energy efficiency remains valid today, it has limitations when seen through the lens of a low-carbon transformation. In a power system dominated by renewable energy, with near-zero variable cost, saving primary energy does not translate directly into lower marginal or average cost. More important, even when the direct combustion of fossil fuels is more efficient in a given end use from a primary energy standpoint, it is generally a worse option from an emissions standpoint if the electricity is low carbon. Carbon, not energy per se, dictates the logic of energy systems in a climate-friendly future.

It is critical for industry, regulators, and policy makers to recognize that deep decarbonization cannot be achieved through energy efficiency alone or even a combination of energy efficiency plus renewable electricity. Electrification is absolutely required, and in many applications, it may complement or even displace a focus on energy efficiency. Beyond a certain level, conventional energy-efficiency investments can produce diminishing returns for carbon reduction compared to a similar investment in electrification, as long as the electricity is low carbon. Electrifying end uses is not counter to the fundamental purposes that motivate investments in energy efficiency. Indeed, modeling shows that, in a U.S. low-carbon transition, the largest source of energy efficiency will be electrification itself, due to the thermodynamic superiority of electric drive trains and heat pumps over their combustion-based alternatives.

Getting energy efficiency and electrification to play nice with each other in the regulatory and policy arenas may be challenging. Clean-energy advocates have fought hard to incorporate renewable generation and building energy efficiency in utility plans, and many will be skeptical about electrification if they see it as threatening decades of hard-won gains. That may change as the primary energy-efficiency paradigm is reconsidered in the light of deep decarbonization.

But there is also no clear mandate for promoting electrification in current policy. Indeed, if anything, there are formidable barriers to fuel switching, not least of which are the interests of oil companies and gas utilities. Current energy-efficiency programs are designed to stay within their fuel-type lanes and not change the game by switching to new energy supplies.

There's no question that energy efficiency remains essential for decarbonization. Some say that natural gas is the bridge to a low-carbon future, but the real bridge is energy efficiency. It will play an outsized role in sectors with limited fuel-switching potential, for example, freight trucking and industrial process heat. In parts of the United States with no history of efficiency programs, grossly inefficient building shells, oversized HVAC systems, and antiquated infrastructure, efficiency will still be the first tool out of the clean-energy toolbox. Efficiency provides a brake on irresponsible, high-carbon load building in coal-based power systems with no transition plan. Even in a decarbonized system, energy efficiency can help reduce the scale, cost, and land use impacts of a low-carbon infrastructure buildout.

Long-Term Policy in the Electric Economy

Article 4.19 of the Paris Agreement calls on all countries to develop mid-century strategies for decarbonizing their economies. The commitments made at Paris are near term, out to 2025 or 2030, and only promised modest emission reductions. But the Paris emphasis on the long-term future provides a platform for strategizing and enacting transformational changes. Given the multidecade lifetimes of the most critical infrastructure on both the supply and demand sides of the energy system (e.g. power plants, buildings, industrial boilers, and cars and trucks) and the potential for emissions lock-in and stranded assets, the long-term perspective must be a factor in near-term decision making and investment. A key revelation that emerges from long-term planning—and is seldom visible in shorter-term analysis—is the need for electrification as the third pillar accompanying energy efficiency and low-carbon generation.

Deep decarbonization requires a suite of policies to transform infrastructure and markets, covering all three pillars.

The usual suspects of policy approaches are unlikely to be sufficient, particularly for electrification. Carbon pricing alone is inadequate for sending long-term investment signals, especially where emissions reductions are a function of interactions across sectors and measures and over time (as in the case of EVs, where net emissions depend on the vehicles being replaced, the changing carbon intensity of electricity, and their uptake rate). Policy mechanisms must be tailored to situations, but some general areas of need are clear

A Regulatory Strategy for Electricity Demand Under Decarbonization

The necessity of electrification requires rethinking regulatory strategy for electricity demand. This includes the mechanisms and relative priorities of energy-efficiency and electrification programs and investments and how both of these relate to decarbonized generation. The recent Illinois decision to retain Exelon's existing nuclear plants in return for reducing demand is a step behind in this thinking: the incentives for the utility to reduce demand work against low-carbon electrification. Instead, a new paradigm is needed, similar to the decoupling of demand from utility revenue requirements to encourage energy efficiency: electrification of current fossil-fuel end uses, when accompanied by generation decarbonization, should be considered "good load" for purposes of incentivizing utilities.

A Planning Vehicle for Cross-Sectoral Planning and Coordination

Industrial, transportation, and building electrification all need to be coordinated with electricity sector planning, across geographic boundaries and jurisdictional levels, to be effective and economical. Yet neither market nor regulatory mechanisms exist for such coordination. Policy must drive joint planning that aligns investment decisions and timing in sectors that currently have little interaction but must interact much more in the future to reach climate goals.

A Grand Bargain for Utilities

Deep decarbonization won't be achieved without a massive expansion of low-carbon generation and electrification. Distributed generation cannot meet the first of these requirements affordably and does not address the second. While distributed generation has a role to play, it cannot be the tail that wags the dog in electricity policy. A grand bargain with utilities is needed, in which they commit to a timely schedule for meeting these goals (providing supporting infrastructure, such as vehicle charging, in the case of electrification) in return for the long-term assurance of a viable business model.

Wholesale Electricity Market Design

Deep decarbonization means an entirely new market environment for electricity from what it has been historically. The economics of a decarbonized electricity sector need clear articulation in scholarship and expression in regulation and wholesale market design. Some of the areas requiring new theory, observation, and experimentation include the following:

- ✔ A very high renewables system will be dominated by fixed costs, with variable energy costs near zero. Current wholesale electricity markets were not designed to efficiently allocate fixed costs.
- ✔ In a system with very high levels of inflexible supply, such as wind and solar, the demand side may contribute as much to system balancing as the supply side. Efficient wholesale markets must provide symmetric rewards for flexible capacity without regard to supply or demand.
- ✔ Large-scale flexible loads such as hydrogen electrolysis could potentially play a major role in addressing seasonal imbalance while also providing low-carbon fuel, but the economics of electricity-produced fuels is undertheorized, including areas such as long-term market signals, ownership, and the relationship to supply-side planning.
- ✔ The definition of asset utilization from the utility and regulatory perspective will need to change when net load factors (i.e., net of generation and load, especially when generation is inflexible) replace ordinary load factors as the utilization paradigm.

The wholesale market design problem is complicated by a transition period of two or three decades, in which what works in the decarbonized future also needs to work in the carbonized present. One potential feature of the transition that could provide benchmarks for the timing of future changes is the changing time signal of energy imbalances with increased penetration of intermittent renewables, from hours to days in low renewables systems to weeks to months in high renewables systems. The economics of decarbonized electricity will reflect this changing imbalance signature, as markets must respond to it to keep the lights on.

The earlier these problems are thought through, the better future obstacles can be anticipated and addressed before they sabotage the low-carbon transition. This is already a domain in which practice has moved beyond theory, due, in part, to the limitations of current analytical approaches. The 2050 time horizon has little utility or regulatory motivation on the power-system planning side, so it is far outside of the usual scope; while the limited granularity of integrated assessments models, still the dominant tool used to inform climate policy discussions at the national and international levels, undermines their ability to engage in such discussions. Recent progress in the long-term, multisector analysis of deep decarbonization that also includes granular, bottom-up treatment of both the supply and demand sides of the electricity sector is an important first step toward bridging these disparate worlds.