POLICY FORUM

Networked fossil fuel infrastructure, such as in this oil field near McKittrick in California's Central Valley, can face nonintuitive failure modes as the size of the system declines.

ENERGY TRANSITION

Fossil energy minimum viable scale

Unseen infrastructural threats to safety and decarbonization may arise as fossil energy systems are phased out

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The nascent global energy transition involves two parallel, mirrored processes: the retirement of existing fossil fuel–based infrastructure, and the widespread deployment of alternatives in its stead. Most energy transition research and policy have focused on the latter process of development, adoption, and buildout. Far less attention has been paid to the challenges and emergent behaviors associated with the decline of legacy fossil energy systems. We identify a risk of collapses in service availability as specific elements of fossil infrastructures reach what we term "minimum viable scale," a level of throughput past which existing physical, financial, and managerial infrastructures can no longer effectively operate as expected. We establish a framework of different types of constraint that can impose a minimum viable scale and identify such constraints in several example fossil systems within the US. Evidence of widespread minimum viable scales should motivate a paradigm shift in system and decarbonization planning.

The fossil-fueled systems that currently supply about 80% of global energy consumption are complex, high-hazard networks of networks. These systems have developed through decades-long processes of accretion and adjustment, gradually producing complex interdependencies that often developed opportunistically and with limited coordination or documentation. The resultant networks of networks rely on their near-universal coverage and the foundational expectation of long-term demand growth to support economies of scale. As demand for fossil fuels stagnates or declines, these economies of scale will invert, leaving shrinking user bases to carry growing liabilities, and infrastructure designed for expansion to instead weather contraction.

Ensuring that fossil energy systems can continue to provide necessary services to remaining users until replacement systems are ready, even as they shrink, is critical not only for completing the energy transition, but also for doing so safely and justly. Carefully coordinating service provision is especially important given the potentially unpredictable dynamics of both infrastructural decline and climate change impacts. Even under stable conditions, fossil energy systems are hazardous and support a wide range of life-safety services: Failures can be deadly for both workers and those who rely on these services. Even short of failure, sudden facility closures can cause economically disruptive price or supply shocks and can leave behind severe, long-lasting environmental and health threats. Collectively, these shocks and failures are forms of collapse—rapid, unplanned desynchronizations of a networked system that lead to meaningfully lower system throughput, process efficiency, or reliability. Such collapses could also undermine public trust in the energy transition itself, posing the possibility that backlash could stall energy systems

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in an expensive, unstable mid-transition state, with both fossil and nonfossil systems necessary for service provision but incapable of meeting demands alone (*1*).

Yet much decarbonization-related modeling and policy tends to assume without evidence that shrinking, interdependent fossil fuel extraction, processing, and delivery systems will be able to consistently function—possibly for several decades—as safe, reliable backstops for universal energy services that replacement systems are not yet ready to provide (*1*). Modeled decarbonization trajectories often expect relatively smooth declines in fossil-based service provision (*2*), but so far, the challenging, asset-level planning necessary to support that expectation has been rare.

When a fossil energy system drops below its minimum viable scale, we anticipate nonlinear increases in cost, hazard, and outage, or outright inoperability. If this occurs while end users still depend on the system, loss of viability poses a serious threat to public health, safety, macroeconomic stability, and justice (*3–5*). If minimum viable scale is relatively large, then this problem also constitutes a core, unexamined barrier to energy transition and decarbonization. We assert that minimum viable scales for current oil, natural gas, and coal systems are likely much larger—and therefore much nearer in time—than many energy modelers and policy-makers realize.

Fossil energy infrastructure: Current scales and functions

This table tabulates networked fossil infrastructures that likely possess policy- and modeling-relevant minimum viable scales, lists key energy system and non-energy services provided by each that could constrain or be constrained by their larger systems, and shows each system's scope within the US. All entries are drawn from the below sources and presented to two significant figures to standardize across data sources and reflect uncertainty inherent in that data. Data from US Energy Information Agency, US Bureau of Transportation Statistics, Statista, American Petroleum Institute, and US Pipeline and Hazardous Materials Safety Administration.

Infrastructure	Number in US	Energy system services	Co-services
Petroleum refineries	130	• Gasoline • Diesel • Jet fuel (kerosene) • Liquefied petroleum gas • Bunker fuels Heating oil	• Petrochemical precursors • Lubricants • Asphalt • Metallurgical anodes • Refrigerants
Fueling stations	150,000	• Gasoline • Diesel • Other motor fuels	• Food and convenience products • Restroom facilities • Compressed air
Crude petroleum gathering and transmission pipelines	84,000 miles	Refinery supply	
Refined petroleum product pipelines	64,000 miles	• Gasoline • Diesel • Jet fuel • Heating oil	
Natural gas transmission pipelines	300,000 miles	• Power plant fuel • Industrial fuel or feedstock • Gas utility (local distribution)	Petrochemical precursors
Natural gas distribution pipelines	1,300 networks 1,400,000 miles (mains) 990,000 miles (service)	• Building fuel (residential, commercial) • Industrial fuel or feedstock	
Major surface coal mines	17	Power plant fuel	Major consumer of rail freight capacity

MOVING BEYOND MARGINAL MODELING

Today, most energy models and policies understand acts of fossil decommissioning as marginal, in the sense that they assume a system of networked units can be scaled smoothly, one unit of service provision at a time. This simplification is likely accurate at relatively low levels of decarbonization, when systems are composed of enough individual units that asset- and network-level "lumpiness" is masked (*6*). At the deeper levels of decarbonization demanded by international climate targets, though, the number of remaining discrete assets that make up a fossil network is far smaller. Because unit-level operational constraints exert more influence over the system as a whole, actual marginal impacts of per-unit changes become nonlinear in a way that models rarely capture. This nonlinearity represents a serious problem for decarbonization, especially because asset-level representation is rare in normative models explicitly designed for decision support, with long time horizons—the types of models that are often used as decarbonization planning models and can easily be overconstrained (*7*).

Most such normative deep decarbonization planning models have treated the future scale of fossil systems as an output based on demand for "difficult-to-decarbonize" services that are challenging for nonfossil resources to provide (*8*), rather than as an input based on supply-side infrastructural constraints. For example, models of greenhouse gas–neutral pathways for the US commonly find that electric grids will retain, and even add, natural gas–fired generators, but at very low utilization and high availability (*2*, *9–11*).

This finding follows from model requirements that electrical system load is met during challenging periods of high demand and low renewables generation on a highly decarbonized future grid. But this is based on assumptions that fail to adjust for the cost and engineering challenges of maintaining a vast amount of infrastructure—not only the generators themselves but pipelines, processing facilities, production and storage fields, specialized labor pools, and regulatory apparatuses—for occasional use under extreme conditions. Natural gas–fired power plants' assumed future output levels are likely incompatible with assumptions that natural gas–fired electricity costs and reliability will remain relatively stable.

As the energy transition advances, similar inaccurate simplifications in modeling assumptions will increasingly reveal themselves in system performance, creating a mounting need for new policy tools that take account of minimum viable scale. Tools focused on detailed implementation over shorter time horizons should account for fossil systems' constraints, starting by considering what scale of fossil service provision is actually viable at societally acceptable levels of safety, reliability, and cost. Assessing viability requires attention to the physical characteristics of the fossil assets themselves and the financial and managerial structures that enable them to operate, which likely means sacrificing model parsimony in favor of higher representational accuracy in additional tools that might more closely resemble detailed engineering models than current long time-horizon planning models do (*7*).

IDENTIFYING MINIMUM VIABLE SCALE

Unexamined cases of potential minimum viable scale are prevalent across different fossil systems. As a way of understanding the different forms that minimum viable scale can take within an energy system and as a heuristic for identifying it, we identify three categories of constraint on linear decline: physical, financial, and managerial. These categories frequently coincide, in the sense that a given system might face multiple constraints that could, in some cases, be able to compensate for one another. For example, investment might enable a facility to resolve a physical bottleneck. Here, we use these categories

As fewer users shoulder the costs of the entire system, they will face growing incentives to exit, producing conjoined cost and reliability spirals.

to illustrate cases and identify whether physical asset characteristics, system finance, or operational decision structures explain a fossil infrastructure's minimum viable scale. Our examples illustrate how these different constraints obstruct fossil systems' linear decline and should prompt deeper, multidisciplinary effort to characterize specific constraints in real systems.

Petroleum refineries

We identify the physical constraint on energy services that depend on the US' 132 operating petroleum refineries (see the table) as most binding. Individual refineries process particular blends of crude oil into particular sets and ratios of products, meaning that the supply of any one petroleum product depends on the design details of a particular subset of refineries. Many refinery components have minimum limits, known as turndown capacities, below which operation becomes unsafe, unreliable, inefficient, or lower-quality. One industry group estimates that these component-specific turndown limits aggregate to an average refinery-wide minimum viable scale of ~65 to 70% of capacity (*12*)—a high value that challenges assumptions of long-term linear decline in petroleum product provisioning. Further, because many areas of the US lack the infrastructure necessary to support seamless exchange of refined products across existing supply boundaries, even a single refinery closure could produce serious local supply or price shocks despite wider availability of excess capacity. In the US, refinery design typically prioritizes gasoline production, with coproducts depending on which types of crude the refinery can accept and which process units it contains. Gasoline demand is forecasted to drop faster than demand for many other petroleum products, suggesting that refinery design could lead to increased price or curtailed supply of some of those products (e.g., jet fuel) long before current decarbonization models suggest.

Turndown capacities can be lowered by tailoring equipment, feedstocks, and additives, as refiners have proven during past periods of weak demand or changing supply—but often only at the cost of substantial new capital investment or operational expenses. In the context of declining demand, refiners are progressively less likely to make major new investments—a risk that is exacerbated by refineries' intensive maintenance demands. On top of regular operational upkeep, refineries depend on regular overhauls known as "turnarounds," which occur roughly every three to five years. Turnarounds are a physical constraint of complex refinery systems that require major commitments of capital. By creating periodic decision points for refiners to weigh expected future profits against significant upfront reinvestment costs, turnarounds exacerbate the risk of sudden refinery closures, which can create price or supply shocks given that direct coordination among actors often qualifies as illegal collusion under US law.

Natural gas pipelines

We identify the financial constraint on natural gas services that depend on the US' 2.7 million miles of gas distribution and transmission pipelines (see the table) as most binding. The costs of this pipeline infrastructure are diffused across a diverse base of end uses—from home heating and cooking to power generation and industrial processes—at relatively high spatial density. As end users transition away from gas, progressively smaller revenue bases will be available to meet pipeline networks' fixed costs. This presents complementary problems for gas distribution and transmission systems. For gas distributors, departing customers will leave a sparser but not a less infrastructurally intense pipeline network, because remaining customers are likely to be distributed widely across neighborhoods and service territories. As fewer users shoulder the costs of the entire system, they will face growing incentives to exit, producing conjoined cost and reliability spirals (*13*).

Gas transmission pipelines are similarly constrained by the financial consequences of uncoordinated customer loss. Long-distance pipelines serve relatively few large gas users directly, each of which is forecast to transition away from gas at different rates (*14*). As some large end users transition, remaining consumers will be forced to carry fixed maintenance costs that cannot decrease with lower utilization—and might even increase as pipelines operate further outside their design parameters. As in gas distribution, cost and reliability spirals result. Because few transmission customers are large enough to support a transmission pipeline on their own, even relatively small customer exits may spark a cascade of larger exits, raising the risk of sudden collapse. Transmission pipelines also possess a secondary financial constraint: their fixed-term service contracts. These contracts impose periodic decision points that, like turnaround schedules for petroleum refineries, could exacerbate the risk of sudden pipeline or customer-facility closure. Lastly, because gas distribution networks are often supplied by a small number of transmission pipelines, and constitute major customers of each, gas transmission and distribution's financial constraints are mutually self-reinforcing, a dynamic that could further accelerate the arrival of minimum viable scale.

Coal-fired electric generation

We identify the managerial constraint on electric services that depend on the US' 17 major surface coal mines (see the table) and 462 coal-fired generators (distributed across 219 power plants as of 2024) as most binding. In this case, minimum viable scale is imposed by the uncoordinated decision-making of coal users and coal suppliers, whose viability is linked but whose largely separate ownership prevents the planning necessary for stable operation at low utilization rates. Coal mines depend on multiyear extraction plans that determine which resources will be accessible and profitable in the future. Both equipment and geology impose physical and financial constraints on how quickly and whether mine plans can be amended, meaning mines may not always be able to accommodate plant-level decisions. For example, mining equipment can take months to move, or mine plans might foreclose the possibility of mining certain areas to access higher-quality zones during high price periods. Though many major coal mines supply numerous power plants, their dependency on stable demand means that relatively few sudden plant closures could destabilize a mine. Because coal-fired generators are physically constrained to burn certain, geographically specific types of coal, and coal transport networks limit each generator's sourcing options, a sudden mine closure could create a cascade of additional plant closures and follow-on electricity supply crises (*15*). Taken on their own, coal mines' constraints constitute relevant minimum viable scales, but examined in the context of mines' and generators' decision-making processes, they also impose a larger, multisystem minimum viable scale that might be even more constrictive. In short, power plant closures can drive mine closures, but mine closures can also drive power plant closures.

MANAGING MINIMUM VIABLE SCALE

Although current energy models have effectively highlighted core transition strategies, like the need to electrify energy end uses to maximize access to zero-carbon resources, more specific, detailed efforts to coordinate and manage energy service provision will be needed to support declining energy systems through the mid-transition period. Such coordination can mitigate severe safety, reliability, and economic transition risks—many of which are predictable—while enabling faster progress toward more just, more sustainable approaches to energy service provision. Likewise, coordination could facilitate effective repurposing of fossil sites, reducing the impacts of closure and establishing new revenue streams to support both fossil remediation and energy transition. Advance planning for decline also creates new opportunities for academics and policy-makers to communicate to the public about the risks and challenges of the mid-transition before moments of increased risk arrive.

Modeling and policy tools that aim to support a just and successful energy transition will need to address the minimum viable scales of different critical fossil systems, especially because the failure of a single component within a network of networks can threaten the viability of other, conjoined components. In particular, modelers should seek to develop tools with high-resolution representation of fossil assets, the services they provide, and the risks relative to benefits of continued operations at specific facilities. Policy-makers should seek to establish management structures capable of identifying and mitigating minimum viable scale by coordinating investment and operational decisions across asset and ownership boundaries, guaranteeing payment of long-term liabilities, and improving the resiliency and flexibility of adjacent, dependent systems. As energy transition advances, minimum viable scale constraints are likely to threaten even systems that are not being managed for complete decarbonization. For example, even when decarbonization is not a binding target, competition between fossil and nonfossil systems could undermine fossil systems in ways that lead to sudden collapses. Developing methods of assessing minimum viable scale offers a valuable strategy for targeting and prioritizing policy interventions into fossil energy networks and other, interdependent systems. One promising approach might be to adapt the detailed, asset-level planning models common in utility and similar settings to the exploratory, decision-support oriented context of system models, but in the context of system contraction rather than expansion. Success in the fossil energy context could also support inquiry related to minimum viable scale in other complex network-of-network settings that might face similar tendencies, like manufacturing or health care.

Achieving safe, just, and successful energy transition in the face of minimum viable scale will require committing to decarbonization pathways and actively managing the decline of critical fossil energy services. In the US, where many of these fossil networks are governed as agglomerations of mostly privately owned assets, regulators and courts have long used a case-specific stranded asset approach to address the operational and financial risks of unplanned shutdowns (e.g., through bailouts). These paradigms may well prove incapable of handling a drastically increased pace of depreciation, closure, bankruptcy, and abandonment of assets providing critical energy services, especially absent strategies for ensuring that replacement infrastructure is available. Although boundary-expanding solutions such as imports of previously locally provided fossil products might help to mitigate the closure of certain fossil assets in the short term, longer-term strategies will still be needed: Because the normative goal of global decarbonization requires global phase-out of fossil assets, imports will likely only be available to relatively well-resourced actors who act early in the overall arc of transition. New coordination between sectors and across present ownership boundaries will be crucial to temporarily keep specific, potentially unprofitable sets of assets online while needed, and to smooth the impact of major facility closures. If replacement, zero-carbon systems are not deployed fast enough, aging systems with declining revenues could require considerable new investments for short-term use that will likely have to be made on the basis of public needs rather than profitability. To meet these needs, and to prevent such investments from becoming indefinite private subsidies or obstructing decarbonization progress, declining energy systems will require more robust public management designed to anticipate and mitigate loss of services due to minimum viable scale issues.

Mitigating these constraints in advance can also enhance safety, improve cost estimates, and promote reliability as more fossil systems enter a paradigm where dominance and growth are not guaranteed. The data required to perform this mitigation, however, are frequently unavailable because of confidentiality constraints imposed by both regulation (e.g., anti-collusion laws) and market incentives (e.g., preserving a competitive advantage or accessing higher market power through information asymmetry) for private fossil system operators. Approaching minimum viable scale will increase a system's supply constraints, granting remaining entities increased market power. This dynamic can be expected to increase those entities' incentives to preserve information asymmetry, exacerbating the challenge of mitigating minimum viable scale. Nonetheless, focused modeling that acknowledges supply-side constraints driven by physical, financial, and managerial characteristics can likely approximate minimum viable scales. Likewise, more granular attention to the behavior of fossil systems under conditions of decline could help put solutions in place before constraints begin to take effect. As energy systems enter the mid-transition, the capacity for linear decline of fossil systems can no longer be assumed (*1*). □

REFERENCES AND NOTES

1. E. Grubert, S. Hastings-Simon, *Wiley Interdiscip. Rev. Clim. Change* **13**, e768 (2022).
2. M. Browning *et al.*, *Energy Clim. Change* **4**, 100104 (2023).
3. T. Measham *et al.*, *Resour. Policy* **90**, 104859 (2024).
4. G. B. Hansen, *J. Soc. Issues* **44**, 153 (1988).
5. A. X. Andresen, L. C. Kurtz, D. M. Hondula, S. Meerow, M. Gall, *Environ. Res. Lett.* **18**, 053004 (2023).
6. C. Wilson *et al.*, *Science* **368**, 36 (2020).
7. J. H. Merrick, J. P. Weyant, *Eur. J. Oper. Res.* **279**, 511 (2019).
8. S. J. Davis *et al.*, *Science* **360**, eaas9793 (2018).
9. R. Gao *et al.*, *Energy Clim. Change* **6**, 100196 (2025).
10. A. Phadke, S. Aggarwal, M. O'Boyle, E. Gimon, N. Abhyankar, "Illustrative pathways to 100 percent zero carbon power by 2035 without increasing customer costs" (2020); https://energyinnovation.org/wp-content/uploads/Pathways-to-100-Zero-Carbon-Power-by-2035-Without-Increasing-Customer-Costs.pdf.
11. J. H. Williams *et al.*, *AGU Adv.* **2**, e2020AV000284 (2021).
12. American Fuel & Petrochemical Manufacturers, "Refinery Utilization 101: The Other Half of the Capacity Story" (2022); https://www.afpm.org/newsroom/blog/refinery-utilization-101-other-half-capacity-story.
13. L. Davis, C. Hausman, *J. Assoc. Environ. Resour. Econ.* **9**, 1047 (2022).
14. G. Von Wald, K. Sundar, E. Sherwin, A. Zlotnik, A. Brandt, *Adv. Appl. Energy* **6**, 100086 (2022).
15. J. M. Cha, E. Grubert, *Environ. Res. Energy* **2**, 015017 (2025).

ACKNOWLEDGMENTS

The authors gratefully acknowledge contributions by three anonymous reviewers.

10.1126/science.aea0972

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