POLICY FORUM

ENERGY AND CLIMATE

Granular technologies to accelerate decarbonization

Smaller, modular energy technologies have advantages

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Of the 45 energy technologies deemed critical by the International Energy Agency for meeting global climate targets, 38 need to improve substantially in cost and performance while accelerating deployment over the next decades (*1*). Low-carbon technological solutions vary in scale from solar panels, e-bikes, and smart thermostats to carbon capture and storage, light rail transit, and whole-building retrofits. We make three contributions to long-standing debates on the appropriate scale of technological responses in the energy system (*2*, *3*). First, we focus on the specific needs of accelerated low-carbon transformation: rapid technology deployment, escaping lock-in, and social legitimacy. Second, we synthesize evidence on energy end-use technologies in homes, transport, and industry, as well as electricity generation and energy supply. Third, we go beyond technical and economic considerations to include innovation, investment, deployment, social, and equity criteria for assessing the relative advantage of alternative technologies as a function of their scale. We suggest numerous potential advantages of more-granular energy technologies for accelerating progress toward climate targets, as well as the conditions on which such progress depends.

We use "granularity" to describe technologies in terms of scale—physical, economic, or both. More-granular energy technologies have smaller and more variable unit sizes (MW/unit) and lower unit investment costs in absolute terms ($/unit), and are more modular or divisible, so they are more likely to scale through replication. We use "lumpiness" to describe the converse: larger units, higher unit investment costs, greater nondivisibility, and more likelihood of up-scaling in unit size. Granular-lumpy is a continuum, not a binary categorization. The figure shows bivariate relationships between measures associated with accelerated low-carbon transformation and granularity [see supplementary materials (SM) for detail and methods].

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RAPID TECHNOLOGY DEPLOYMENT

Rapid technology deployment depends on short diffusion time scales, attractive risk profiles for investors, and strong potential for cost and performance improvements (see the figure, red panels). These conditions are interdependent. Deployment generates experience, which feeds back into technology improvement. Improving competitiveness and reducing investment risk stimulate adoption and compress the time taken for technologies to diffuse through markets. Clear expectations for market growth attract further investment and strengthen the rationale for policy support. These dynamics are evident in recent trajectories of rapid solar photovoltaic (PV) deployment.

Short diffusion time scales

Early research on industrial process innovations found that smaller investment size and higher expected profitability predicted faster diffusion (*4*). We show that energy supply and end-use technologies with lower unit investment costs diffuse more quickly from 1 to 50% market share (see figure panel B and SM-1). Lower absolute unit costs mean that access to capital becomes less restricted or specialized, and opportunity costs decrease.

Attractive risk profiles for investors

Capital cost overruns on new energy infrastructure are a simplified measure of investment risk. Using a dataset of cost overruns in 350 electricity generation projects (*5*), we find that investment risk tends to increase for larger hydro, nuclear, and thermal plants but to decrease for larger solar and wind plants (SM-2). For more-granular renewable technologies, modular construction of standardized units means lower investment risks even at larger project sizes.

Cost and performance improvements

Learning describes how cumulative experience with each additional technological unit produced, installed, or used can lead to cost reductions and performance improvements. We show that learning is faster for more-granular energy technologies, using two different formulations of the learning rate (see figure panels C and D and SM-3). In both cases, more-granular technologies offer more opportunities for repetitive, replicative experience to drive faster improvement.

ESCAPING LOCK-IN

Useful energy services like mobility or heating are provided by hierarchical systems of technologies and infrastructures such as road networks, cars, and engines, or gas pipelines, buildings, and furnaces. Tackling climate change means overcoming "lock-in" or inertia in fossil-fuel–dependent systems (*6*) (SM-4). This depends, inter alia, on rapid renewal of capital stock, low technological complexity, and downsizing the system through end-use efficiency and demand reduction (see the figure, blue panels). Long-lived energy infrastructure and strong interdependencies between technologies increase switching costs and slow down change. Rapid innovation cycles in simpler, short-lived technologies create more opportunities to develop, test, deploy, and learn how to challenge incumbent processes. Downsizing the system by reducing aggregate demand for energy further reduces switching costs and counteracts the increasing returns to scale on which incumbent firms' dominant market positions are built.

Rapid renewal of capital stock

How long capital stock remains technically viable as well as economically attractive will determine renewal rates. More-granular technologies at the lower levels of the system hierarchy have shorter technical lifetimes (see figure panel F and SM-4). Obsolescence opens up opportunities for upgrades, substitutions, or replacements. Shorter lifetimes allow for more rapid turnover and so more rapid entry of low-carbon alternatives.

Low technological complexity

More-granular energy end-use technologies have fewer components and hence lower technological complexity (see figure panel G and SM-5). Less complex technologies present lower interoperability and coordination challenges at the component level, which in turn helps stimulate more rapid innovation cycles.

Downsizing through end-use efficiency

More-granular technologies offer larger potential efficiency gains, particularly for individual and household users for whom energy input costs have proven less salient than for industrial users of more-lumpy technologies (see figure panel E and SM-6). Improving the efficiency of end-use technologies leverages more than proportionate improvements in overall system efficiency. Currently, one unit of energy saved through end-use efficiency avoids the need for 3.2 units of primary energy resource (SM-6).

SOCIAL LEGITIMACY

Widespread support for political leadership on climate change enables the stringent policies required to incentivize decarbonization and overcome system inertia. Social legitimacy of accelerated low-carbon transformation depends on more equitable access to technologies and infrastructures for raising living standards, on job creation benefits from low-carbon technologies, and on social returns from public resources invested in innovation (see the figure, green panels). The political feasibility of expanding public funding for low-carbon R&D is strengthened by resulting societal benefits of employment, security, health, and a more productive economy. Jobs can be created by investments in new energy facilities. However, these potential benefits of low-carbon transformation can be distant from lower-income households, particularly in developing economies. Widening affordable access to modern energy systems is critical for raising living standards.

Access to technologies and infrastructures

Unit investment costs of end-use technologies range along a granular-lumpy continuum (see figure panel A), as do the unit costs of incrementally extending service infrastructures providing electricity, broadband, clean water, and sanitation to households previously without access. More-granular technologies and infrastructure extensions are widely accessible (see figure panel H and SM-7). Lower investment barriers promote more equity in raising living standards.

Net job creation

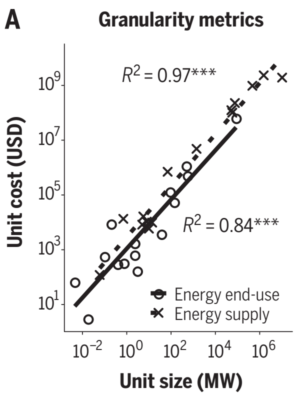
We draw on three metastudies that synthesized evidence from over 80 discrete studies of direct (construction and operation) and indirect (supply chain) employment effects of power generation and energy-efficiency investments (7). We find that energy facilities for more-granular technologies create more jobs over their lifetimes (see figure panel I and SM-8). We reason that more granularity is linked to greater breadth and diversity of application, which increase labor-capital ratios relative to large technological units.

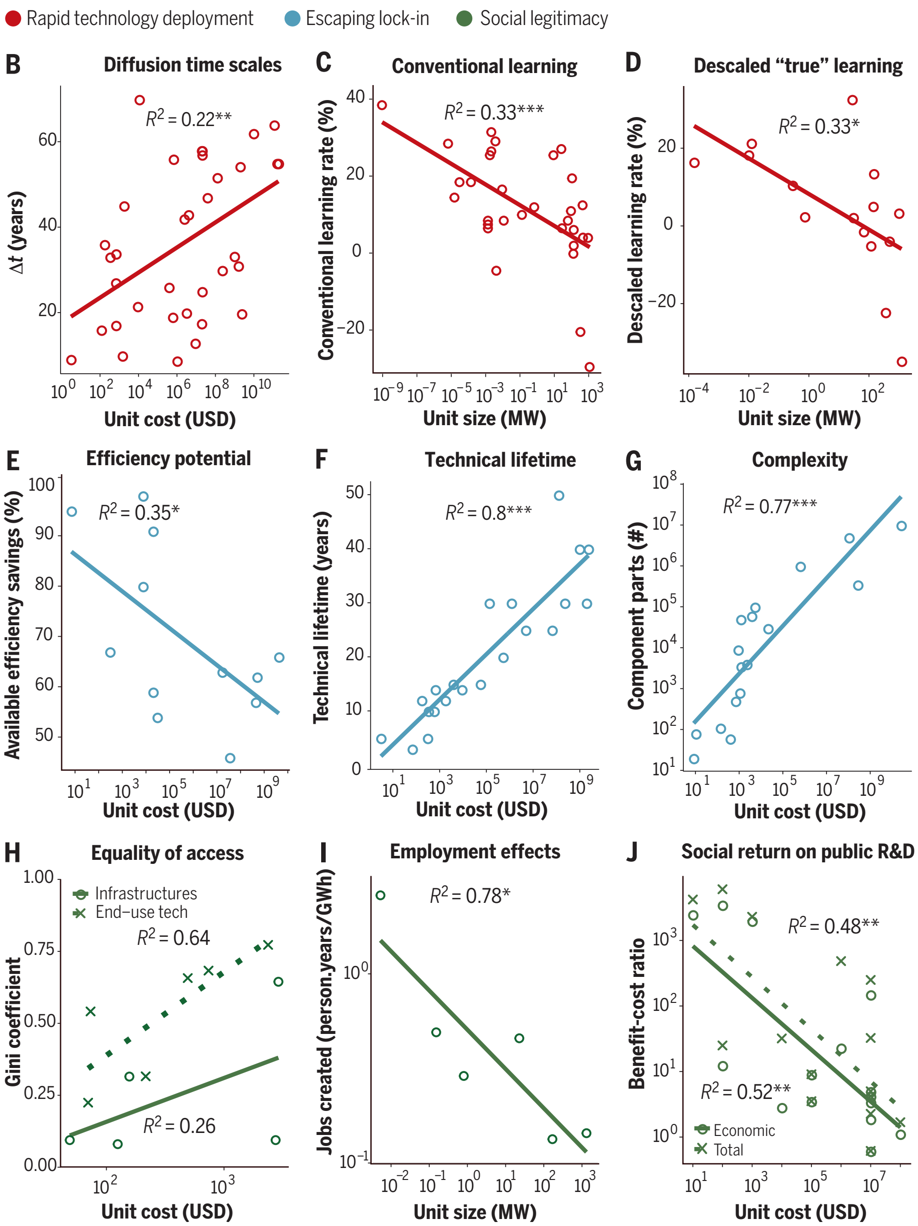
Social returns on public R&D investments

The U.S. National Research Council quantified the wider economic, environmental, and

Characteristics of accelerated low-carbon transformation on the granular-lumpy continuum

Data points in each panel represent an energy technology. Unit size and unit cost correlate strongly (panel A) and are used interchangeably as measures of granularity on log horizontal axes (B) to (J). Vertical axes show measures of rapid technology deployment (red panels), escaping lock-in (blue panels), and social legitimacy (green panels). Δt, the time period over which a technology diffuses from 1 to 50% market share. Conventional learning rate, % cost reduction per doubling of cumulative capacity, conflates two drivers of cost reduction: unit scale economies (more capacity per unit) and experience (more units). Descaled "true" learning rate, % cost reduction per doubling of cumulative numbers of units, strips out the effects of unit scale economies on cost trends. Gini coefficients measure (in)equality on a scale from 0 denoting perfect equality (every household has the same access) to 1 denoting perfect inequality (one household has all the access). R^2 and p values denoted by asterisks describe simple bivariate model fits (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). See supplementary materials for details on data and methods.





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security benefits of the U.S. Department of Energy's public R&D portfolio from 1978 to 2000 (*8*). This study is distinct in its use of a transparent and standardized case-study methodology based on data, not model simulations. This allows for comparative analysis across nine end-use efficiency and six energy-supply technology R&D programs. R&D investments in more-granular technologies generated higher social returns (see figure panel J and SM-9). We consider this benefit of more granularity to be associated with lower market barriers to entry, and the wider scope and number of commercial applications.

DISCUSSION

Underlying mechanisms for each of the relationships shown in the figure are well substantiated in the literature (diffusion speed, investment risk, learning), have simple explanations (technical lifetime, complexity, end-use efficiency, equality of access), or can be plausibly reasoned (job creation, social returns on R&D investment). Although we have measured each relationship in isolation, their importance lies in their interaction. Under conditions for escaping lock-in, social legitimacy enables rapid technology deployment, which further destabilizes incumbent fossil-fuel–dependent regimes. Lower investment risks and shorter diffusion times grow market share, which drives greater equality of access and job creation. Lower risks and barriers to entry for more-granular technologies are important, as low-carbon and energy-efficient alternatives to incumbents tend to be more capital-intensive.

The potential for accelerated change is not just technological but institutional. More-granular technologies enable simple and rapid project planning with distributed and less complex decision-making processes. This is particularly important in markets with weaker governance institutions, where lumpy projects are beset by even greater complexities, costs, and risks (*9*).

However, the benefits of more-granular technologies are neither deterministic nor realizable in all contexts. The nine measures in the figure do not paint a complete picture of accelerated low-carbon transformation. First, there are many omitted variables such as the effect of profitability on diffusion speed (see figure panel B). Relatively weak model fits for some of the relationships are explained by the diversity of technology characteristics and adoption environments in the data (SM-0).

Second, although we intentionally construct diverse samples to identify generalizable relationships, contextual factors are important. For example, the acceptability and legitimacy of new energy infrastructure vary by place and perspective. The entwining of climate action and social justice movements highlights the importance of perceived fairness in both the process and outcome of low-carbon transformation. Communities, companies, and countries left "stranded" by rapid decarbonization can weaken political capacity to drive transformative change.

Third, there are important characteristics of rapid technology deployment, escaping lock-in, and social legitimacy that we do not measure. For example, lock-in has institutional and behavioral dimensions for which there are no standardized metrics, particularly at the systems level (*6*) (SM-4). Fourth, interactions between the relationships in the figure can dampen as well as accelerate dynamics of change. Rapid turnover of short-lived capital stock may also fail to destabilize larger systems of interdependent technologies, infrastructures, and institutions.

Outliers are also informative. For example, in panel B of the figure, the data point at the top represents cars which, although relatively granular, diffused slowly over long time scales, as they drove systemic change in transportation infrastructure and social organisation (SM-1). In panel H of the figure, the data points at the bottom left and right both measure access to electricity but from solar lanterns and grid extensions, respectively. These granular and lumpy substitutes have very different qualitative impacts on living standards and economic opportunity (SM-7). In panels C and D of the figure, the data points with high rates of negative learning are nuclear power and flue gas desulfurization, which upscaled and diffused with strong policy and institutional support. These caveats and examples highlight important conditions for realizing the advantages of granularity: substitutability, standardization, economies of scale, system integration and access to infrastructure, and political economy.

> **"...portfolios of more-granular technologies... outperform lumpy alternatives"**

Substitutability and risks of granularity

In some cases, clear alternatives on the granular-lumpy continuum compete to serve a broadly equivalent function (e.g., nuclear and renewable power plants generating electricity). In other cases, more-granular technologies offer a similar service but with different attributes (e.g., e-bikes and cars for intra-urban mobility). But in some contexts, lumpiness may offer something qualitatively different and nonsubstitutable (e.g., long-haul flights). This limits the generalizability of the relationships shown in the figure.

Systems models, which represent both quantities and types of energy service, can test the feasibility, cost, and other conditions under which granular and lumpy alternatives are substitutable. The evidence is clearest for electricity systems in which distributed generation, storage, and demand-response technologies offer granular alternatives to historically centralized models (*3*). A recent global scenario study shows how portfolios of granular technologies throughout the energy system can limit warming to 1.5°C without relying on lumpy carbon capture and storage infrastructure (*10*). But none of these examples offer granular substitutes for long-distance air travel or steel and cement manufacturing.

The substitutability of lumpiness by portfolios of more-granular technologies introduces three potential issues: coordination and security, transaction costs, and pollution exposure and material waste. If large numbers of technological units need to interact in energy, transport, or building networks, then more granularity poses coordination problems. Digitalization enables "smart" system management but relies on high-resolution, real-time dataflows, which raise concerns about security, privacy, and data rights. If technology adoption and use take time and effort, then more granularity implies higher transaction costs. In some cases, this barrier to adoption can be reduced through aggregation (e.g., municipal shared vehicles), standardization (e.g., certified or off-the-shelf products), or third-party management (e.g., energy service companies).

If technologies are polluting, then more granularity can increase pollution exposure pathways and exacerbate adverse health impacts. End-of-pipe pollution controls can be effective if deployed in large numbers (e.g., catalytic converters, air and oil filters, heat recovery units), but highly distributed sources of pollutants such as CO_2 are hard to mitigate. Decarbonization strategies therefore rely heavily on electrifying energy end use in buildings and transport, as well as industry. Alongside air pollution risks, short-lived technologies with rapid innovation cycles can create considerable material waste unless careful attention is placed on material efficiency, life-cycle design, and product durability, modularity, and reparability (*11*).

Standardization and lock-in

Mass commercialization of more-granular technologies depends on standardization, which converges technological variety onto a dominant design, stimulates cost-reducing process innovation, enables mass production, provides quality control, and helps align user expectations with technology performance (*12*). Efficiency standards drive more rapid learning. Standardization of balance-of-system components in PV installations enables off-site fabrication at higher production volumes, driving quality and reducing cost.

However, "standardized granularity" raises two important concerns. Dominant designs can become locked in by interdependencies with complementary technologies or infrastructures that are reinforced by standardization (e.g., railway gauges, power-network frequencies). Historically, this helped give rise to monopolistic system operators. Positive network externalities—the value of a network to all users increasing with each new user—combine with standardization to generate increasing returns to scale and winner-takes-all incumbents. Granularity can help escape carbon lock-in while also risking new forms of system inertia and regulatory capture.

Replicated uniformity also risks disregarding local context (*11*). However, standardizing design fundamentals, production processes, and system integration still allows for differentiated applications. Small-scale fabrication units can 3D print locally adapted products using standardized design data. A mass-manufactured PV module can be configured in myriad arrays, installed and used by individuals or large firms.

Unit and manufacturing economies of scale

Rapid cost reductions associated with more-granular technologies (see figure panels C and D) are partly explained by large production runs, seeking scale economies and product quality through standardization and mass manufacturing. For more lumpy energy technologies, scale economies may be available at the unit level (building larger) rather than in manufacturing (producing more). Controlling for learning effects, unit scale economies have been demonstrated for energy technologies including nuclear, wind power, and bioethanol distillation (SM-3).

Unit and manufacturing scale economies therefore offer alternative drivers of cost reduction for different energy technologies. For example, order-of-magnitude increases in production output from solar PV manufacturing facilities explain over a third of observed cost reductions in module costs from 2001 to 2012 (*13*). Conversely, up-scaling of plant sizes explains almost three-quarters of observed cost reductions in U.S. coal power production from 1908 to 1970 (*14*).

Infrastructure and system integration

Turnover times vary at the different scales of a technological system: years for boilers, engines, consumer products (technologies); decades for building envelopes, cars, capital equipment (technological clusters); centuries for buildings, roads, industrial organizations (infrastructures) (*6*). Short-lived, fast-learning, rapidly diffusing technologies at the lower levels of the hierarchy allow for rapid improvement within more slowly changing contexts. How technologies integrate into systems and access infrastructure strongly conditions the impact of granularity. Accommodating large numbers of granular technologies may require infrastructure expansion, upgrade, or replacement. Infrastructure change that is large, costly, indivisible, and system-wide requires massive centralized direction and investment and imposes high switching costs (e.g., piped H_2 through gas networks, long-distance DC electricity transmission). But infrastructure change may also be incremental and modular [e.g., electric vehicle (EV) charging stations].

Political economy

Increasing alignment between incumbent firms and regulatory frameworks is an institutional characteristic of lock-in (*6*). Lumpiness has been favored during the 20th-century development of the energy system. High upfront costs, nondivisible risks, and high consequences of failure in more lumpy technologies reinforce the rationale for public policy to underwrite returns, collectivize risks, or protect market positions. Publicly directed innovation efforts historically have been skewed toward centralized energy supply. More lumpytechnologies are also attractive politically as they demonstrate commitment and materiality (mobilization of human, financial, and physical resources) (*15*).

In comparison, heat pumps, rolls of insulation, EV charging points, smart meters, rooftop solar modules, and shared "taxi-buses" are heterogeneous and dispersed. Coalitions of actors are concentrated in particular sectors like consumer electronics, automotive manufacturing, or power generation. This weakens the political economic influence of more-granular technologies in low-carbon transformation (*15*). It also makes more-granular technologies less analytically tractable as the functions they serve vary so widely.

More recently, a confluence of factors, including market liberalization, technological innovation, and digitalization, has strengthened political economic support for granularity. More-granular energy technologies vary in scale, have more heterogeneous applications, and involve a greater diversity of firms and users through which the legitimacy of new technologies is established and resistance from incumbent actors counteracted. By enabling smaller increments of capital investment, more-granular technologies de-risk research, development, and demonstration (RD&D) portfolios and open markets to the destabilizing force of new entrants.

Conclusions

Under certain conditions, more-granular technologies are empirically associated with faster diffusion, lower investment risk, faster learning, more opportunities to escape lock-in, more equitable access, more job creation, and higher social returns on innovation investment. In combination, these advantages enable rapid change. Unit scale in physical or cost terms is a readily available criterion for helping evaluate whether net-zero emission pathways, clean energy R&D portfolios, industrial strategies, and technology demonstration programs can deliver near-term decarbonization. Governments, firms, investors, and civil society organizations seeking to accelerate progress on decarbonization should include granularity as a criterion for designing mitigation strategies, targeting policy support, funding R&D investments, and supporting low-carbon innovation. More-granular technologies could then be assessed against emission-reduction objectives. Scientists also need to explicitly account for granularity in scenarios and assessments, which often prominently feature large-scale solutions, and in modeling tools and analysis, which are often scale-free. Diverse portfolios of more-granular technologies are not a universal solution, but in many contexts, they outperform lumpy alternatives as a means of accelerating low-carbon transformation to meet global climate targets. ■

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