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# The Technology– Markets–Policy Nexus for Energy Sustainability

## Analysis and Case Studies

By Himanshu Khurana<sup>1b</sup> and Tariq Samad<sup>1b</sup>

WE ANALYZE THE INTERPLAY OF TECHNOLOGY, markets, and policy in advancing energy sustainability. The history of energy innovation bears out the importance of the nexus, and it will remain central as societies pursue reliable and sustainable energy systems. Our discussion extends the oft-referenced “technology push”—“market pull”

coupling to incorporate the policy element, identifying “policy pump” as a crucial factor in energy and sustainability sectors, with their societal-scale impacts.

Substantial progress toward a transformation of the energy sector has occurred globally; we review past and present metrics in generation,

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Himanshu Khurana ([khurana.h@gmail.com](mailto:khurana.h@gmail.com)) is with Vector Insights, Excelsior, MN 55331 USA. Tariq Samad ([samad@ieee.org](mailto:samad@ieee.org)) is with the Technological Leadership Institute, University of Minnesota, Minneapolis, MN 55455 USA. Tariq Samad is the corresponding author.

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storage, infrastructure, and electrification. Examples from around the world are outlined, referencing how technology, markets, and policy have contributed. We also discuss carbon capture and storage, where progress has been limited, and data centers, which represent a new frontier, the polarity and extent of whose impact is still uncertain. The discussions and case studies in the article are from a variety of energy-related areas that the authors have worked on in the past decades: smart grids, building and facility energy management, utility-scale battery storage, carbon capture and sequestration, industrial automation and manufacturing, and microgrids. The article concludes by presenting several implications for technology innovators arising from the analysis of the nexus.

## Introduction

Over the past few decades, a near-universal consensus has developed on the critical need for energy sustainability, endorsed by multiple stakeholder communities, including governments, nongovernmental organizations, public and private companies, and consumers. Progress has been made on many fronts, if not at the rate or to the extent most analysts deem adequate given the magnitude of the challenge at hand—related primarily to climate change but also weaving in energy security and affordability considerations.

The energy ecosystem encompasses an extensive value chain, integrating generation, storage, distribution, and consumption, and it affects virtually all economic and societal sectors: manufacturing, buildings, transportation, retail, agriculture, information and communication technologies, and more. Achieving sustainability will thus involve a transformation of enormous magnitude: not megawatts but terawatts of power, not kilotons of CO<sub>2</sub> but gigatons, not billions but trillions of dollars at stake. At the same time, there's urgency for global action and impact.

The need, thus, is for exponential-scale acceleration. This rules out traditional linear pathways from exploration to product to market to globalization. We cannot wait for research initiatives to mature and economies of scale to be attained through business-as-usual processes.

In this article, we discuss how progress in energy sustainability is contingent on a nexus of technology, markets, and policy developments. The history of energy innovation bears out the importance of this convergence, and, going forward, achieving reliable and sustainable energy systems worldwide will require it too.

But there is nuance to the nexus. The pursuit of fundamental research breakthroughs may often be decoupled from markets, but the funding required for it is determined and allocated by policy makers. Market pull can, however, be a significant factor in late-stage research, although even in that case policy considerations are often necessary, for example, when externalities and tragedies of the commons are involved. The policy element is an additional enabler in both energy and sustainability sectors, given their societal-scale impacts.

We first discuss the interplay among technology, markets, and policy. Our discussion extends the “[technology push](#)” and “[market pull](#)” influences to incorporate a “[policy pump](#)” forcing function. We next provide an overview of progress in energy transition over the last decade or so. Several aspects of the transition are reviewed, including low-carbon electricity generation, energy storage, and grid infrastructure.

Although concern about energy sustainability is increasing as a consequence of its desultory progress, there are positive developments to highlight. The section “[Global Success Stories: Illustrating the Nexus](#)” illustrates how technology, markets, and policy have aligned in several cases.

But what happens when alignment is problematic? In the following section, we discuss a topic where exponential-scale progress will require further technology innovation: carbon capture and sequestration (CCS). We also offer a perspective on data centers (and the associated memory, computation, and communication), a rapidly emerging sector that has become a new focus of concern for energy sustainability—but one that is also potentially part of the solution.

We conclude with a few points of guidance for technologists seeking to advance the cause of energy sustainability, highlighting how an understanding of the nexus can help drive innovation.

## The Nexus: Technology Push, Market Pull, Policy Pump

The terms “[technology push](#)” and “[market pull](#)” are widely used in innovation strategy. We briefly discuss these terms here, and we also introduce another lever, which we refer to as “[policy pump](#).” We reference related tools or frameworks that are particularly relevant for energy and sustainability.

### Technology Push

R&D organizations focus on technology development, marking progress in terms of milestones that

relate to technical metrics. For sustainability-related initiatives, these metrics can include energy efficiency and emission reductions.

Technology readiness levels (TRLs) are often relied on to assess the state of maturity of a technology and to chart the path forward. Originally developed by NASA for space technology, TRLs are now standard practice in many domains. Domain-specific TRL ladders are available. For example, the U.S. Department of Energy (DOE) has adopted the tool, customizing it for energy innovations (Table 1).

As can be seen from the table, TRLs are technology-focused and exclude considerations related to commercialization and markets. This focus is by design: Maturing emerging technologies for their potential product and service offerings is the realm of R&D organizations, which are not expected to be well-versed in market analysis.

### Market Pull

Market pull is the set of demand-side conditions that turns a promising solution into something that can be deployed at scale. In energy systems, it is driven less by individual consumer choice and more by procurement and contracting decisions made by utilities, independent power producers, large commercial and industrial buyers, and public agencies. Economics still leads, but sustainability goals and reliability also—and increasingly—shape what buyers will adopt and finance.

**table 1.** TRL scale from the DOE.

TRL	TRL Definition
TRL 9	Actual system operated over the full range of expected mission conditions
TRL 8	Actual system completed and qualified through test and demonstration
TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment
TRL 6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment
TRL 5	Laboratory-scale, similar system validation in relevant environment
TRL 4	Component and/or system validation in laboratory environment
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept
TRL 2	Technology concept and/or application formulated
TRL 1	Basic principles observed and reported

Because these buyers work with long asset lifetimes, large capital expenditures, and regulatory constraints, market pull shows up as requirements for bankability and repeatability. Market-facing teams, such as product management, sales engineering, business development, finance, and regulatory affairs, help translate needs into deployable requirements, including performance and integration expectations, unit economics, contracting terms, and risk allocation.

Market readiness also follows clear milestones. Interest becomes real pull when a solution moves from a funded pilot to repeatable deployment, with clear success metrics, understood integration needs, standard contract terms, and financing that starts to feel routine. In practice, market pull strengthens not only when customers are willing to pay but when they are willing to commit through durable procurement and long-term arrangements.

A useful market pull framework for energy must reflect the sector's structure: regulated and hybrid markets, complex procurement pathways, multiactor risk allocation, and system integration constraints, along with public-value considerations, such as affordability, equity, and local economic impact.

### Policy Pump

Policies can serve as both market makers and technology catalysts. The motivation on the part of the policy-making body, such as a national or regional agency, is typically to support government priorities, especially those that market mechanisms by themselves will not advance as rapidly as desired. Policy incentives can take the form of carrots—e.g., R&D funding grants—or sticks—e.g., restrictions on the use of the incumbent technology.

The "policy pump" effect can be understood as a risk mitigation strategy using the well-known "real-win-worth" framework developed by George Day of the Wharton School, which succinctly captures the innovation-risk correlation from both technology and market perspectives. In Figure 1, we incorporate a third dimension—policy—to Day's innovation-risk map, showing how policy innovation can result in the movement of risk contours. Technologists, incidentally, can take heart in noting that the risk contours shown in Figure 1 are not symmetric: technology innovation is lower risk than market innovation.

Sustainability, including energy sustainability, has been a policy focus globally. Examples include the following:

- ▶ The 2007 Energy Independence and Security Act (EISA) in the United States set standards and requirements and provided funding for several major initiatives. For example, the deployment of smart meters in the country was substantially accelerated by EISA 2007 (although smart meters were widely used in Europe before then).
- ▶ China’s sustained policy drive for electrification has incentivized technology development as well as lowered market barriers. The country’s progress in photovoltaic solar panels—China manufactures more than 80% of the global output—has been especially dramatic and presents a textbook example of the nexus resulting in an exponential-scale learning curve. Costs have fallen from more than US\$125 per watt to about 25 cents per watt over 50 years (constant 2024 US dollars).
- ▶ The United Kingdom’s policy decision to phase out coal power generation created a clear system-level boundary condition for utilities, markets, and investors. Announced in the mid-2010s and implemented through the retirement of coal units by 2024, the policy signal reduced uncertainty about the role of coal in future capacity planning and strengthened the investment case for replacement resources such as offshore wind and flexible generation, reinforced by market mechanisms like Contracts for Difference (CfD).

Policies can have shorter or longer term horizons. In cases where the technoeconomic gap between an incumbent technology and an emerging alternative requires multigenerational advances, consistency of policies and regulations must be maintained over many years, even decades.

An assessment tool is especially relevant here: The World Bank Group has developed a set of regulatory indicators for sustainable energy (RISE) that can be used to score countries on related dimensions and can be useful for companies seeking to enter new geographical markets (see “[For Further Reading](#)”).

### Mapping the Nexus: Levers, Mechanisms, and Transition Markers

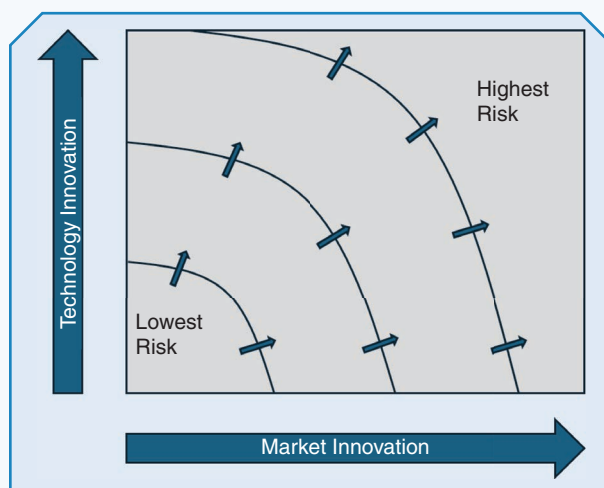
To make the nexus practical and not just descriptive, we distinguish among the three levers in the nexus (technology push, market pull, and policy pump) and the mechanisms by which they drive transition markers of progress from solution de-

velopment to scaled deployment (see [Figure 2](#)). Transition markers are the concrete signals that a solution is moving along that path: it is deploying beyond pilots, becoming repeatable and financeable, integrating reliably into the broader energy system, and delivering measurable sustainability impact.

The levers repeatedly act through three mechanism channels that reduce risk and compress time to scale:

- ▶ *Performance and reliability derisking*: Reducing technical uncertainty through validation, operational learning, integration tools, and proven reliability in real conditions
- ▶ *Revenue and financing derisking*: Creating bankable cash-flow structures (e.g., predictable pricing, contracted offtake, capacity payments) that lower the cost of capital and enable scale
- ▶ *Coordination and infrastructure derisking*: Overcoming multiactor barriers, such as interconnection and permitting timelines, transmission and supply-chain constraints, and “who builds what, when.”

The levers influence these channels in different ways. Technology push most directly advances performance and reliability and can also support financing by enabling integration at scale. Market pull primarily strengthens financials by rewarding performance with repeatable business models and investable returns. Policy pump can operate across all channels—by underwriting



**figure 1.** The “policy pump” effect on the risk associated with technology and market innovation, based on the work of George Day. Our overlay of the arrows conceptually illustrates how policy developments can push out risk contours.

early risk, setting durable boundary conditions, and accelerating infrastructure and market-rule evolution.

We note that the model presented here is different from innovation-policy frameworks, a term that typically refers to recommended pathways, often facilitated by government actions, to drive innovation in areas where market forces are inadequate. We are not proposing an operational prescription; instead, our focus is on understanding how technology, market, and policy aspects interact in the process of innovation. We believe such understanding is essential for effective and efficient innovation in energy sustainability, but more work is needed before an innovation framework based on this model can be developed.

In the examples that follow, we refer back to this map to clarify how each case achieved progress from development to scale (or why it stalled) and to separate technical bottlenecks from market-design and policy/governance bottlenecks—while still respecting local market and regulatory structure.

## Global Energy Transition: Progress in the Last Decade

Over the 2014–2024 decade, the energy transition has moved from proof to scale. Electricity is decarbonizing quickly, but networks, storage, and end uses have not kept pace, so total energy use and emissions remain high. A practical way to read progress is across four key attributes (see Table 2 for a summary): 1) low-carbon electricity supply, 2) energy storage, 3) grid infrastructure and system flexibility, and 4) end-use electrification in transport, buildings, heating, and industry; with the combined outcome being the total energy use

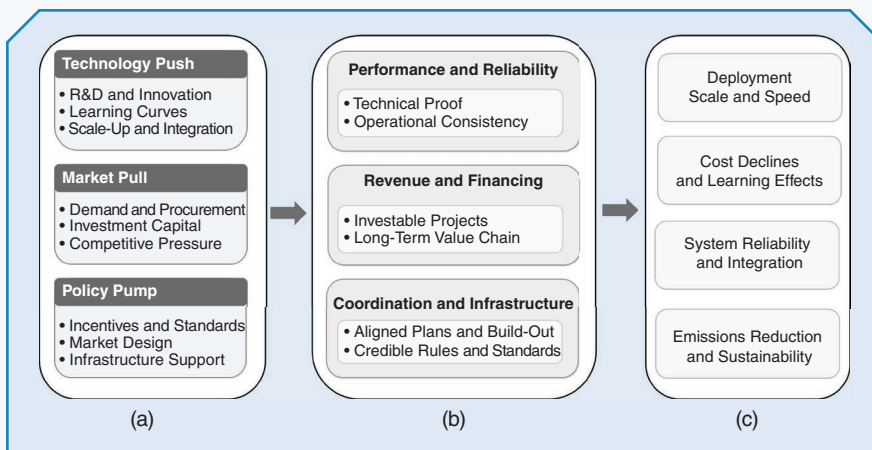
and emissions. Supply sets the ceiling on what can be delivered cleanly, grids and storage decide how much arrives when and where it is needed, efficiency and electrification shape how much energy is demanded and in what form, and the total energy lens tests whether these improvements add up to sustained emissions reductions. In the nexus terms of this article, Table 2 summarizes key transition markers and helps explain why progress differs across these attributes. Scaling depends not only on technology performance but also on financeable economics, coordinated infrastructure build-out, and durable rules and standards that make deployment routine.

In this decadal timespan, the transition has become visible in the power sector. Low-carbon sources have grown from roughly one quarter to nearly two fifths of global electricity output, with renewables alone supplying about one third. A decade ago, only a few systems regularly exceeded 40% renewable electricity; today, grids in Portugal, Spain, and the Netherlands pass the halfway mark, while Uruguay and Denmark operate for long periods with near-zero-carbon power. Renewables overtaking coal in global generation in the first half of 2025 marks a genuine turning point.

Energy storage has followed a similar arc. Ten years ago, batteries were demonstration projects measured in tens of megawatts. By 2024, more than 120 GW of grid-connected capacity were operating worldwide, with fleets in California, China, South Korea, and Europe dispatched daily for evening ramps, frequency control, and congestion management. Standardized lithium-ion systems have become part of normal grid operations, providing a fast-response, schedulable resource that

operators can value and procure. Together, these power and storage gains reflect a recurring nexus pattern: technology learning and operational proof, paired with bankable procurement and durable enabling policy, can move solutions from pilots to repeatable deployment.

These gains show where progress has been strongest. Generation technology, cost, and many integration tools are no longer the primary barriers they once were. Solar and wind are the lowest cost



**figure 2.** (a) Nexus levers, (b) derisking mechanisms, and (c) transition markers for energy sustainability.

new electricity sources in many regions, and batteries have proven that flexibility can be delivered in shorter time frames rather than through years of new infrastructure. Several countries now demonstrate that high-renewable grids

can operate reliably with appropriate planning and digital control.

Progress is slower in the supporting infrastructure and end uses that convert clean electricity potential into system-wide decarbonization.

**table 2.** Global energy transition snapshot.

Attribute	Around Year 2014	2024-2025	Mechanisms That Enabled the Observed Transition Markers (Nexus Lens)
Low-carbon electricity generation	Low-carbon electricity $\approx$ 31% of global generation; renewables in the low 20% range	Low-carbon electricity $\approx$ 41% of generation; renewables $\approx$ 32%; renewables surpassed coal in H1 2025; multiple grids near or greater than 50% renewable annually	Technology learning and manufacturing scale that improved cost/performance; bankable procurement and long-term contracting that reduced financing risk; durable policy and market frameworks that sustained build-out and integration planning
Energy storage (primarily grid-connected batteries)	Early-stage pilots and demonstrations; storage rarely integrated into dispatch or markets	$\approx$ 120 GW of battery capacity worldwide; multi-GW fleets dispatched daily for ramping, frequency, and congestion management; standardized 2-4-h systems are now routine in operations	Operational proof and standardization (repeatable performance in real dispatch); market products, procurement targets, and participation rules that made flexibility valuable and procurable; financeability as revenue pathways became clearer and more repeatable
Grid infrastructure and system flexibility	Curtailment and redispatch mostly local issues; short connection queues	Curtailment typically can be 4% or at times higher in major markets but higher where networks lag; documented volumes: CAISO 2024 $\approx$ 3.4 TWh, Germany 2023 $\approx$ 19 TWh, Chile 2024 $\approx$ 5.6 TWh, China H1 2025 $\approx$ 5%-7% of wind/solar; interconnection queues at system scale; United States $\approx$ 2.6 TW active with multiyear waits, Great Britain >700 GW pending	Improved operational practices can manage congestion day to day, but the dominant gap is infrastructure execution and governance. Planning, permitting, and cost allocation are not scaling as quickly as renewable build-out, so network constraints increasingly set the pace of deployment.
End-use electrification (transport, heating, buildings, industry)	EV sales <1 million per year; buildings focus on design standards and voluntary audits; heat pumps niche; industry largely fossil for process heat/feedstocks	EVs >17 million sold in 2024 (>20% of new sales and $\approx$ 3% of global fleet); heat-pump deployment expanding rapidly in Europe, North America, and China but still early on impact; industrial electrification still limited, especially for high-temperature processes; buildings $\approx$ 32% of final energy and $\approx$ 34% of CO <sub>2</sub> ; outcome-based programs deliver 20%-40% metered savings for select portfolios	Cost and performance improvements enabled adoption, supported by policy measures, such as tax credits and rebates, mandates and standards, and infrastructure enablement, along with financing models that reduce upfront friction. Scaling beyond early penetration is still ahead and will likely benefit from more durable incentives, faster build-out of enabling infrastructure and workforce capacity, clearer codes and standards, and stronger measurement and verification, with industry needing additional pathways for hard-to-electrify processes.
Total energy use and emissions	Fossil share $\approx$ 86% of global primary energy (using previous accounting methods); global demand steadily rising	Fossil share $\approx$ 86% of primary energy (physical-content accounting); energy-related CO <sub>2</sub> $\approx$ 37.8 Gt (2024, record high)	Power-sector decarbonization and early electrification mechanisms have advanced (clean supply, storage, EVs/heat pumps, verified efficiency in select programs), but economics, infrastructure readiness, and durable policy/standards have not yet scaled fast enough across fuel-heavy end uses—especially industry—to translate power progress into sustained reductions in total emissions.

H1: first half; EV: electric vehicle.

## Global Examples Illustrating the Technology, Market, and Policy Nexus

**Table S1.** Global examples illustrating the technology, market, and policy nexus.

Country/ Program	Transition Markers (Before → After)	Technology Push (Maturity/ Improvement)	Market Pull (Demand/ Market Design)	Policy Pump (Derisked/ Mandated)	Nexus Insight (Transferable Takeaway)
Uruguay: rapid shift to a renewables- dominant grid	Fossil reliant in 2008 → >90% renewable electricity by early 2020s	Wind/biomass/ solar integration; hydro balancing and operational coordination	Competitive procurement created scale demand; long- term offtake enabled private investment	Competitive auctions + utility-backed long-term contracts; durable national direction	Pairing bankable offtake with integration capability converts renewables from projects into a system outcome
United Kingdom: coal exit and offshore wind scale-up	Coal ≈ 30% (2014) → 0% by 2024; offshore wind >15 GW	Offshore wind scale- up; supply-chain maturation; grid integration practices	Long-duration price certainty attracted long-lived capital	Contracts for Difference plus clear coal-exit trajectory	Durable revenue certainty + clear boundary conditions compress risk and accelerate build-out
California (United States): grid flexibility via storage	Grid storage <0.5 GW (2015) → >10 GW (2024); high solar penetration with maintained reliability	Battery cost/ performance improvement; proven operational dispatch capability	Markets that value capacity and flexibility; operator need for ramping/frequency/ congestion services	Storage procurement targets + rule changes enabling storage participation and valuation	Flexibility scales when operational proof is matched to repeatable market value and procurement pathways
Australia: mandatory operational performance disclosure for buildings	Limited disclosure (2010) → ≈ 42% lower energy intensity in rated offices (2024)	Metering/ benchmarking and building analytics maturity	Tenants/investors value verified performance; efficiency becomes a market attribute	Mandatory operational performance disclosure (transparency/ratings)	Transparency and verification can convert efficiency from intent into a priced, investable asset
China: system-scale renewable integration	Wind + solar output ≈ 183TWh (2014) → 1,826 TWh (2024), ≈ 18% of generation	Manufacturing scale and cost reductions; UHV transmission and integration tools	System-scale build economics; large deployment pipelines supported by rapid execution capability	System planning and grid build-out to reduce curtailment and enable integration	Cost declines alone are insufficient; integration at scale requires coordinated infrastructure execution
Denmark: high-wind, high- reliability system	Wind share ≈ 20% (2010) → >55% (2024); outage minutes ≈ 20/ year	Wind technology and forecasting; grid operations for high variable renewables	Regional interconnection and market access support balancing and reliability	Early grid codes + strong interconnection and system rules	High renewables become routine when operating rules and interconnection make variability manageable

Kenya: geothermal as baseload decarbonization	Geothermal 15% (2010) → ≈ 47% (2024); renewables ≈ 85%–90% total	Geothermal development capability; firm low-carbon generation as backbone	Demand for reliable baseload and domestic energy security	Long-term policy support + concessional finance enabling firm low-carbon build	Firm clean resources scale when finance and development risk are reduced over long horizons
Chile: market-driven renewable expansion	Early auctions (2014) → ≈ 60% renewables (2024)	Rapid renewable cost/performance improvement; project execution learning	Competitive procurement and open markets accelerated investment	Transparent auctions/procurement design and open market rules	Transparent market design plus falling tech costs can drive fast adoption when projects are financeable
The Netherlands: offshore wind with grid planning	<15% (2014) → ≈ 50% (2024) renewables	Offshore wind scale and integration; grid connection execution	Growing demand for clean power; competitive offshore development	Coordinated offshore development + onshore transmission planning to avoid stranded assets	Coordinated grid planning is a policy “pump” that turns project pipelines into system deployment

Transmission and distribution expansion has lagged far behind generation growth. Cross-zonal transfer limits and operational headroom have become binding constraints, particularly in Europe, North America, and parts of Asia. Grid operators now spend billions each year on congestion management and redispatch to handle overloaded corridors, while interconnection queues have grown to terawatt scale and multiyear waits are common. The ability to move clean electricity across regions and across hours now defines the pace of renewable expansion more than the generation costs themselves. This is a different nexus problem: scaling is often gated by coordinated infrastructure build-out, permitting and governance, and clarity on “who builds what, when.”

Demand-side progress presents a mixed picture. Commercial building programs in Australia, Singapore, Tokyo, and several U.S. cities show that outcome-based standards can cut operational energy use by 20%–40% and that verified efficiency can become an investable resource. Electrification in transport and heating is advancing: electric vehicles account for more than one fifth of new car sales, and heat-pump adoption is expanding in Europe, North America, and China. These sales shares, however, still represent a relatively small installed base—roughly 3% of vehicles on the road and about 10% of the global heating demand.

Industry remains the most difficult frontier. High-temperature process heat in cement, steel, chemicals, and refining still rely largely on coal, oil, or gas. Few large-scale electrification or hydrogen projects have yet reached commercial maturity. The persistence of these fossil-intensive sectors, combined with steady growth in global energy demand, explains why total energy use remains dominated by fuels and why global emissions reached a new high in 2024 even as power decarbonized.

Two clarifications help frame the totals. The figure showing fossil fuels at 86% of global primary energy reflects a physical-content accounting approach. Other methods differ slightly but tell the same story: most nonpower sectors still burn fuels directly. The largest contributors are oil for mobility; gas for building heating, ventilation, and air-conditioning, and mid-temperature industrial uses; and coal or gas for high-temperature industrial heat and feedstocks. Until these loads are electrified, supplied with low-carbon fuels, or reduced through verified efficiency, total energy use and emissions will remain high despite the strong gains in clean electricity and storage.

Within roughly a decade, Uruguay shifted from a fossil-reliant system to more than 90% renewable electricity, improving resilience to hydrological and fuel-price shocks.

### Global Success Stories: Illustrating the Nexus

Across global energy systems, the nexus of technology push, market pull, and policy pump determines how quickly and reliably decarbonization improves. These success stories illustrate how the three levers translate into transition markers, moving from pilots to repeatable, financeable deployment, reliable system integration, and measurable sustainability impact. The pathways differ. In some settings, policy and market design set long-term direction and reduced financing risk. In others, operational needs pulled technology forward and market rules evolved to reward performance. In still others, transparency and verification converted efficiency into a market-valued asset. We provide a list of global examples in [Table S1](#), “Global Examples Illustrating the Technology, Market, and Policy Nexus,” with technology, market, and policy developments identified. The rest of this section covers four representative cases in more detail.

#### **Policy and Market Instruments Unlock Technology: Uruguay**

Uruguay’s transition began with policy and market design and then pulled technology in. Around 2008, the government and national utility set a clear direction to reduce exposure to imported fuels and drought and introduced technology-neutral renewable targets and an auction framework. Competitive tenders under long-term, utility-backed power purchase agreements followed, specifying price, volume, and risk allocation in a way that made projects financeable for international developers. Once this contractual and regulatory environment was in place, wind, biomass, and solar projects scaled quickly and were integrated with existing hydro resources. Within roughly a decade, Uruguay shifted from a fossil-reliant system

to more than 90% renewable electricity, improving resilience to hydrological and fuel-price shocks.

- ▶ *Technology*: Wind, biomass, and solar integration with hydro balancing and operational coordination
- ▶ *Market*: Competitive procurement created scale demand; long-term offtake enabled private investment
- ▶ *Policy*: Auctions and utility-backed contracting reduced risk and sustained deployment.

#### **Stable Policy Enables Complex Technology: United Kingdom**

In the United Kingdom, the sequence started with a coal phase-out decision and a durable policy framework and then moved through market design into large-scale deployment of complex technology. Government set a firm date to close unabated coal plants and embedded this direction in climate and energy plans, creating a clear boundary condition for asset owners and the system operator. To finance replacement capacity, the Contracts for Difference (CfD) mechanism provided a stable revenue profile for low-carbon generators. Offshore wind developers could then raise capital against contracted strike prices and build large projects in defined offshore zones. System operation and ancillary-service arrangements were adapted to support higher shares of nonsynchronous generation. By 2024, coal had fallen from roughly 30% of generation in 2014 to zero, and offshore wind exceeded 15 GW, becoming a central part of the generation mix.

- ▶ *Technology*: Offshore wind scale-up, supply-chain maturation, and integration practices
- ▶ *Market*: Long-duration price certainty attracted long-lived capital
- ▶ *Policy*: Coal-exit boundary condition plus CfD reduced financing risk and accelerated buildout.

## **Technology Proves Value; Markets Follow: California**

California followed a technology-led path in which operational needs drove deployment, and policy and markets evolved to reward performance. Rapid solar growth created steep evening ramps and net peak reliability stress. Early grid-connected battery projects were deployed to solve these operational needs rather than to fit an existing market template. As batteries demonstrated dependable performance for energy shifting and fast reserves, state policy introduced storage procurement targets, and the market operator updated capacity and ancillary-service rules so batteries could participate fully and be paid for the services they provided. With this alignment in place, installed storage grew from less than 0.5 GW in 2015 to more than 10 GW by 2024, and batteries are now integrated into daily dispatch, supporting one of the highest solar penetrations of any large grid.

- *Technology*: Battery cost and performance improvements and proven operational dispatch capability
- *Market*: Market products and operational needs rewarded flexibility, including capacity and ancillary services
- *Policy*: Procurement targets and rule changes enabled participation and repeatable valuation.

## **Measured Performance Drives Sustained Efficiency: Australia**

Beyond electricity generation, the nexus also plays out in end-use decarbonization through efficiency and electrification. Australia's commercial building sector shows a sequence in which policy transparency triggered a market response that then drove technical improvement. From 2010 onward, the National Australian Built Environment Rating System and the Commercial Building Disclosure program required large office buildings to obtain and disclose operational energy ratings when properties were sold or leased. That policy choice made energy performance visible and comparable, allowing investors, owners, and tenants to incorporate ratings into decisions. Market actors began valuing verified performance, creating a commercial incentive to improve scores. Building owners and managers then adopted better controls, commissioning practices, and plant upgrades to reduce metered consumption. During 2010–2024, rated offices achieved a roughly 42% reduction in energy intensity,

and operational efficiency became a durable feature of the asset class rather than a one-off project outcome.

- *Technology*: Metering, benchmarking, analytics, controls, and commissioning practices
- *Market*: Tenants and investors valued verified performance; efficiency became an asset attribute
- *Policy*: Mandatory disclosure and ratings converted transparency into sustained improvement.

Taken together, these success stories show that the technology, market, and policy elements of the system are most powerful when they move in a coordinated sequence. When a clear direction is set, whether through policy, market design, or a proven technical solution, and the other elements adapt to support it, low-carbon solutions move from pilots into the core of power systems and building portfolios. Risk is allocated in ways that make long-lived investments financeable, operational performance is measured and rewarded, and new capabilities, such as storage, high-renewable operation, or verified efficiency, become part of normal practice rather than special cases. In nexus terms, the repeatable pattern is that technical progress is reinforced by investment certainty, infrastructure and coordination capacity, and durable rules and standards, producing transition markers that can be replicated and scaled over time.

## **A Case Study in Complexity: CCS**

Even the most optimistic projections for the expansion of renewable and other noncarbon power generation (that have any realism to them) acknowledge the inevitability of relying on fossil fuels, especially coal, for decades yet. Power plants will thus continue to emit gigatons of CO<sub>2</sub> annually worldwide. Furthermore, as alluded to previously, electrification is not a viable alternative at present for some industrial processes dependent on carbon-emitting sources for high-temperature heating.

A potential solution to the predicament is carbon capture and sequestration: capture the emitted CO<sub>2</sub> from such point sources, compress it, and bury it underground permanently. Interest in CCS as an instrument to address global warming from greenhouse gas emissions accelerated a couple of decades ago, when the contradiction between the continued exploitation of coal and natural gas on the one hand and the urgency of

Doubling the irony, there are thousands of miles of pipelines in the United States that transport CO<sub>2</sub> extracted from existing natural underground reservoirs to oil fields for enhanced oil recovery.

the need to address global warming on the other became a matter of international concern.

CCS is an implemented technology. But with today's technology, market economics, and policy incentives, deployment at scale is still distant. The economics of CCS are a major hurdle. Capital costs aside, the energy required for operating a CCS unit for a power plant can consume a significant portion—a third or more—of the plant's power output. Plant efficiency is reduced and the cost of electricity proportionately increased. Technoeconomic challenges are even greater with direct air capture, which is at an earlier stage of maturity.

The CCS acronym is now often expanded to CCUS, to include "utilization" of CO<sub>2</sub>—for example, in the production of fertilizers, pharmaceuticals, and plastics, and for enhanced oil recovery (EOR)—although the CO<sub>2</sub> needs for all of these applications, combined, constitute a small fraction of power and industrial emissions.

The majority of CO<sub>2</sub> utilization today is for EOR. In this, rather ironic, application, CO<sub>2</sub> is injected into oil fields that are no longer productive, with the gas facilitating further extraction of oil and extending the life of the oil field by decades. Indeed, doubling the irony, there are thousands of miles of pipelines in the United States that transport CO<sub>2</sub> extracted from natural underground reservoirs to oil fields for EOR. CO<sub>2</sub> pipelines to oil fields are also being expanded in China. EOR thus provides a compelling value proposition for CCS—albeit one that is itself dependent on society's continued reliance on fossil fuels. Policies have been enacted for CCS and are making a difference. For example, in the United States, the 45Q tax credit offers US\$85 per metric ton of CO<sub>2</sub> captured and sequestered for industrial processes and power plants and US\$180/ton for direct air capture, including for sequestration through EOR.

Developments are continuing. According to the 2025 "Global Status of CCS" report by the Global CCS Institute, "77 commercial CCS

projects are in operation with a combined capture capacity of 64 million tonnes per annum," of which about half started operation in the 2020s. Another 44 Mtpa of capture capacity is under construction. Instrumental for this growth is the "significant CCS-specific policy, legal and regulatory progress in many countries." These are positive trends, and they need to be accelerated for the exponential scale required.

Technological innovation will be essential for CCS to meaningfully mitigate CO<sub>2</sub> emissions. A breakthrough in the energy efficiency of capture processes would be transformational. Avenues to pursue include new chemistries and materials (such as solvents, sorbents and membranes), new process designs using oxy-fuel combustion or pre-combustion, and overall system integration and optimization. The downstream systems of transportation and storage (and perhaps utilization) also offer opportunities.

### Looking Ahead: Data Centers

Data centers sit at the intersection of the digital economy and the power system, and their next wave of growth will interact directly with the energy transition themes discussed in this article. The critical question is not whether data center demand will grow, but whether that growth reinforces or competes with decarbonization priorities already underway, including renewable generation build-out, grid modernization, and electrification of end uses. The way this plays out will be a practical test of nexus alignment over the next decade.

From a technology perspective, the first driver is the energy efficiency of computation. Hardware and software advances continue to reduce energy per task, but the frontier is getting harder as semiconductor scaling slows and artificial intelligence (AI) servers already operate near the efficiency and utilization limits of today's platforms. The practical opportunity shifts to hardware-software co-design and disciplined workload engineering: right-sized models, optimized inference,

## Implications for Technology Innovators

- Opportunities for innovation in energy sustainability exist across all horizons. Incremental enhancements to today's state of the art can provide near-term returns. Fundamental breakthroughs are needed to reach and sustain overarching energy sustainability objectives.
- Technoeconomic analyses are essential and should be done in partnership with business and market experts. Such analyses can identify market gaps that existing or future policies may be able to bridge and that may also suggest directions for engineering research.
- R&D outcomes can themselves spur policy developments that can in turn accelerate the technology push. For this reason as well, technology innovators in energy sustainability should be aware of policy trends and engage with policy makers.
- Energy technologies often demonstrate dramatic learning and experience curves. These should be incorporated in strategic planning, technology roadmapping, and policy setting.
- Innovation in energy and sustainability is a long-term undertaking in all respects—technology, market, and policy—making it even more important to approach holistically.

higher utilization, and controls that coordinate information technology equipment with cooling and power delivery.

The second and third drivers are facility infrastructure and grid integration. Higher rack power densities are accelerating the move to liquid cooling and tighter coupling between information technology choices and mechanical design. Reliability requirements also drive on-site backup generation, often diesel, though batteries and thermal storage can reduce generator runtime and provide fast response services. On the grid side, renewable generation is expanding rapidly, but connection capacity, equipment lead times, and transmission build-out are not keeping pace. Grid-enhancing technologies can add headroom, but sustained investment in wires and substations remains decisive.

Market dynamics determine how this load interacts with the rest of the system. Growth is being pulled by AI, the broader cloud economy, and ongoing demand for digital services. At the same time, the net impact depends on the backdrop of overall electricity demand growth from electrification, cooling, industrial activity, and macroeconomic conditions. The collective demand picture matters because it determines whether data centers arrive into available capacity or into an already-tight system and whether new generation and network investments are additive or forced into tradeoffs.

Policy determines whether these options translate into system-level progress. Data centers are built on fast timelines, while new transmission can take many years, so credible load forecasts, phased energization plans, and

transparent interconnection processes matter. Grid constraints could delay some of the planned global data center capacity additions if bottlenecks persist. On the market side, long-term power purchase agreements can improve the bankability of new renewables and firming resources, and grid flexibility products can reward operators for using spare server capacity, cooling load management, or on-site storage during stressed hours. Policy can reinforce alignment by incentivizing best-available efficiency, setting clear rules for backup power, and streamlining permitting for both grid upgrades and clean generation. With these elements aligned, data centers can become grid-aware anchor loads that pull investment into cleaner supply and more capable networks, rather than competing with other electrification priorities.

A second-order perspective is that data center growth can also accelerate innovation in energy sustainability. Expanded compute availability can enable broader use of AI across engineering, science, and operations, potentially increasing the pace of research and development in energy technologies, grid analytics, and system optimization. Whether these indirect benefits materialize on a meaningful scale, and on relevant timelines, remains uncertain, but the possibility reinforces why data centers should be analyzed as part of the broader technology, market, and policy nexus.

## Conclusion

Technology–market–policy alignment isn't a universal *sine qua non*. New technological developments, new business models, and new

policy initiatives, each on their own (instead of in concert), can fulfill customer needs, generate financial returns for companies, and create societal impact.

In some cases, however, and particularly in some industrial and economic sectors, the nexus is crucial. Energy sustainability is a case in point. Perhaps by its very definition, the term implies a need and desire to go beyond lowest cost, most mature, and business-as-usual solutions. Energy sustainability is a long-term objective, not the state of practice. As we've seen across the examples discussed in this article, in specific cases some elements need to be accorded higher priority than others for innovation, but progress in the field as a whole requires attention to the triad as a whole.

Hence, for technologists seeking to change the status quo, the interplay among these elements must be understood and leveraged. In "Implications for Technology Innovators," we summarize several points of guidance that we hope will be helpful for readers of this magazine.

Finally, this article has discussed the technology–market–policy nexus for energy sustainability in some detail. However, as indicated earlier, we have presented a descriptive or explanatory model, not an actionable framework for innovation. We believe the former can form the basis for the latter ... a connection that can suggest directions for further research.

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