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Diffusion of Clean Technologies: Patterns, Mechanisms, and Future Challenges*

Eugenie Dugoua† Joelle Noailly‡

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Abstract

This paper examines the patterns and mechanisms of global clean technology diffusion over the last two decades. We document four stylized facts: uneven sectoral progress favoring power and light transport; China's dominance in innovation and manufacturing; the role of modularity in driving cost declines; and limited adoption in developing economies. Through case studies of solar, electric vehicles, and hydrogen, we analyze how policy and infrastructure enable scale. Finally, we assess emerging challenges for the next phase of diffusion, including critical mineral constraints, artificial intelligence, and geopolitical fragmentation.

Keywords: Clean technology diffusion; Climate change mitigation; Renewable energy; Industrial policy; Solar photovoltaics; Electric vehicles; Hydrogen

JEL Classification: O33, Q55, O25.

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Contents

1 Introduction

Climate change is imposing mounting economic damages through extreme heat, shifting rainfall, rising seas, and disruptions to ecosystems and societies (Auffhammer 2018; Carleton et al. 2024). Averting the worst of these outcomes requires deep and sustained cuts in greenhouse gas emissions, and such reductions depend above all on the innovation and diffusion of clean technologies.

This report examines how clean technologies have spread, why adoption is uneven, and what this implies for the next phase of diffusion. We focus on mitigation technologies, with an emphasis on deployment over the last two decades rather than early scientific discovery. Three cases with global salience—solar photovoltaics, electric vehicles, and hydrogen—anchor the analysis. We highlight the mechanisms that enabled successes, the barriers that continue to constrain diffusion, and the institutional and policy responses emerging across countries. The aim is not to produce a single blueprint but to distill general lessons about how diffusion unfolds and why it matters.

The case for spreading clean technologies rests on simple cost–benefit logic. The Social Cost of Carbon (SCC) measures the economic damage from emitting one more tonne of CO_2e. Existing estimates put the mean SCC at about $185 per tonne of CO_2, with a range from $44 to $413 (5–95%) in 2020 U.S. dollars at a 2% near-term risk-free discount rate (Rennert et al. 2022). Abatement is worthwhile whenever the cost of avoiding a tonne is below this range. Many clean technologies are now cheap enough to meet this test: marginal abatement cost estimates for solar, wind, and electric vehicles are often even below the lower end of SCC estimates (Farbes et al. 2021; Gillingham and Stock 2018). This means their diffusion yields clear welfare gains, and it is not a normative goal but a matter of efficiency. For industrial technologies still at earlier stages, current costs remain above the SCC, but targeted R&D, demonstration, and innovation policies can drive costs down. In this way, fostering innovation and diffusion of clean technologies is, like in other domains, a means of improving the net welfare benefits to society.

Clean technologies have not advanced in uniform ways or at uniform speeds. Figure 1 illustrates the wide dispersion in the time from prototype to early adoption: nuclear power scaled within 20 years, while direct reduced iron took six decades. Even solar PV needed more than half a century to reach material market share. Such variation reflects differences in modularity, capital intensity, infrastructure requirements, and political economy, and cautions against one-size-fits-all narratives.

Recent experience highlights several broad trends in clean technology diffusion. Rapid cost declines have been achieved through early R&D, subsidies, feed-in tariffs, and large-scale manufacturing, accelerating movement down steep learning curves. Production and adoption have shifted toward Asia, with China's industrial strategy reshaping supply chains, lowering

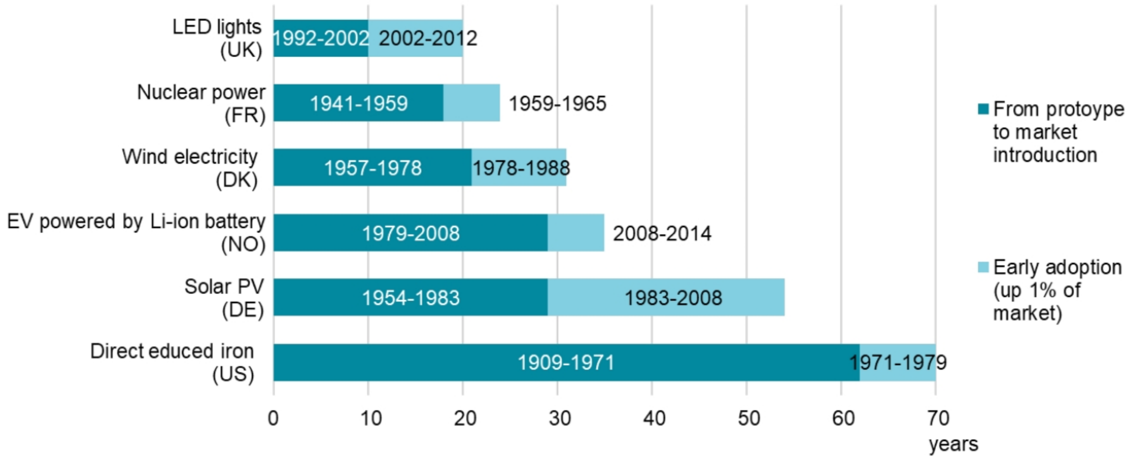


Figure 1: Clean Technology Development Timeline

Note: Reproduced from IEA (2020a, Figure 3.5, p. 76). The figure shows the time required for energy technologies to move from prototype to market introduction and early adoption, defined as reaching 1% market share. The country labels in parentheses refer to the first country to reach this threshold for the given technology. Markets are defined as follows: lighting equipment stock in buildings for LEDs; electricity generation for nuclear, wind, and PV; light-duty vehicle stock for EVs; total steel production for direct reduced iron. Development times are highly heterogeneous. Direct reduced iron (DRI), an alternative method of producing iron that bypasses the blast furnace and consumes far less fuel, took about 60 years to move from prototypes in Sweden to the first commercial-scale MIDREX plant in South Carolina, reflecting the long dominance of conventional blast furnace technology. Even recent success stories illustrate slow progress: solar PV needed about 30 years from first prototypes to commercialization, and a further 25 years before reaching 1% of electricity supply in Spain and Germany. FR = France; DK = Denmark; UK = United Kingdom; DE = Germany; NO = Norway. PV = photovoltaics; EV = electric vehicles.

prices, and enabling uptake across middle-income economies. Yet diffusion has stalled at the margins: low-income countries and hard-to-abate sectors remain far behind. The policy challenge is now twofold—mobilizing capital, infrastructure, and skills so cost declines reach the poorest adopters, and driving industrial technologies down their cost curves through targeted R&D, demonstration, and early-market creation.

The structure of the paper reflects this logic. Section 2 maps diffusion patterns and mechanisms across costs, complementary inputs, finance, skills, intellectual property, information, and political economy. Sections 3–5 provide case studies of solar, electric vehicles, and hydrogen.

2 Mapping Clean Technologies, Diffusion Patterns and Mechanisms

2.1 What Clean Tech Is Needed, and Where

The purpose of this section is to provide a concise overview of the clean technology landscape by showing where global greenhouse gas emissions originate, how they are distributed across sectors, and which technologies can reduce them. Table 1, reproduced from Dugoua and Moscona (Forthcoming), summarizes the main mitigation options, linking each sector's emissions share to the technologies available or emerging to address them and their level of maturity. The aim is not to give detailed engineering descriptions, but to provide a clear map of which sectors matter most, which technologies are already commercial, which remain in development, and how far they are from widespread diffusion. This overview sets the stage for later analysis of diffusion barriers, intellectual property, and policy tools.

Technologies are classified using the Technology Readiness Level (TRL) framework, originally developed by NASA in the 1970s and later extended by the International Energy Agency (IEA) for energy technologies. The classification used here is drawn from the IEA Clean Energy Technology Guide.[1] TRLs provide a standardized measure of technological maturity, ranging from early research to full market transformation:

- TRLs 1–3: early-stage research and laboratory proof of concept.
- TRLs 4–6: prototype development and testing under relevant conditions.
- TRLs 7–8: pilot and demonstration at scale, proving technical feasibility.
- TRL 9: first commercial applications, with competing designs still emerging.
- TRL 10: commercial and competitive deployment, but still requiring further innovation and system integration efforts ("early adoption").
- TRL 11: broad diffusion and predictable growth, with technologies widely adopted across markets.

Although the distinctions between TRLs 9, 10, and 11 may appear subtle—since all refer to technologies considered mature—they are important for understanding diffusion. Technologies with only niche deployment fall below TRL 11; TRL 11 corresponds to broad diffusion across markets.

1. The IEA TRL data tool is available at https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide

Innovation rarely proceeds linearly through these different TRL stages: feedback loops, reversals, and redesigns are common. Still, the TRL scale is valuable because it highlights the types of barriers that typically arise at different points. At low TRLs, technical and financing risks dominate; financing constraints persist at demonstration and early adoption, but supply chains, certification, and early demand also become critical; and at high levels, the main challenges concern integration into energy systems, infrastructure, and markets.

Having set out the TRL framework, we can now use it to organize the landscape of mitigation technologies. Table 1 provides a sector-by-sector map of mitigation options. For each major source of emissions—power, transport, industry, buildings, agriculture and land use, and waste—the table reports approximate global shares of greenhouse gas emissions and lists some examples of technologies available to reduce them, tagged with their current TRL. This compact taxonomy highlights three points. First, mature technologies already cover a significant share of reductions, particularly in power and buildings. Second, heavy industry and long-distance transport remain heavily dependent on options that are still at prototype, demonstration, or early adoption stages. Third, many cross-cutting enablers, such as grids, storage, hydrogen, and carbon management, are essential across multiple sectors and span a wide range of maturities.

The table is not intended to give exhaustive technical detail, but rather to show at a glance which sectors matter most, which technologies are close to full deployment, and which remain in earlier stages of development. This framing makes clear that deep decarbonization requires both rapid diffusion of mature options and sustained effort to pull lower-TRL technologies through to market. In what follows, we unpack the entries of the table in more detail, emphasizing the match between sectoral emissions and the technological pathways available to reduce them.

Power. The power sector is the largest single source of global CO_2 emissions. Mature options—solar PV, onshore wind, and hydropower—are already cost-competitive and expanding rapidly (TRL 10–11). Firm low-carbon complements include nuclear and geothermal, both commercially established but facing investment, siting, and social acceptance hurdles (TRL 10–11). Offshore wind is at mixed maturity: fixed-bottom designs are commercial (TRL 10), while floating turbines remain at prototype and demonstration stages (TRL 5–7). Ocean energy technologies are still at earlier stages (TRL 4–8). Residual fossil capacity may be decarbonized through CCUS (TRL 7–9), though costs and infrastructure remain major obstacles. The central challenge in the power sector is no longer technology cost, but system integration—grids, storage, and demand flexibility—which spans TRLs from early adoption to widespread deployment.

Table 1: Taxonomy of Mitigation Technologies and Associated Sectoral Breakdown of Global GHG Emissions.

Sector	Category/Subcategory	Global GHG emissions in 2020 (%)	Example technologies (TRL)
Power Generation **28%** Coal 20% Nat. Gas 6% Oil 1%	**Renewable**		Crystalline Si PV (10); Thin film PV (5-6); Floating offshore wind (8); Hydropower (11); Ocean salinity gradient and thermal (4-5); Small modular reactors (5); CCUS Post-combustion chemical absorption (8); CCUS supercritical CO2 cycle (5-6)
	Solar Power	–	
	Wind Power	–	
	Hydropower	–	
	Geothermal Power	–	
	Ocean Power	–	
	Other		
	Nuclear Power	–	
	Biomass Power	–	
	Fossil Power with CCUS	–	
Cross-Cutting Technologies	Energy Storage	–	Grid-forming inverter with PV or wind (7-8); Superconduct. high-voltage (7); Lithium-ion battery storage (9); Direct air capture (6–7); Direct lithium extraction from brine (7-8)
	Grid Technologies	–	
	Critical Minerals	–	
	Carbon Management	–	
	Hydrogen	–	
Buildings **7%** Residential 5% Commercial 1% Refrigerants 1%	Building Envelopes	–	Dynamic glazing (8); LED lighting: Conventional (11), Polymer (9); Induction cooking appliances (11); Air-to-air heat pumps (10); Membrane heat pumps (5);
	Lighting		
	Appliances and Equipment	–	
	Heat Pumps	–	
	Cooling		
	Data Centers and Networks		
Transport **16%**	**Road**	**12%**	Biofuels Micro-algae (3-4); Battery electric cars (9); Sustainable aviation fuel: HEFA (9-10), e-fuels (4-6); Methanol/ammonia-fuelled ships (6–7)
	Fuel Economy of Cars/Vans	–	
	Biofuels	–	
	Electric Vehicles	–	
	Trucks and Buses		
	Rail		
	Aviation	1%	
	International Shipping	2%	
Industry **31%**	Cement and Concrete	5%	Cement kiln with CCUS (4-8); Alternative materials for cement (3-9); Hydrogen direct reduced iron (4–7); Blast furnaces with CCUS (5-9); High temperature heat electrification (3)
	Chemicals and Plastics	4%	
	Pulp and Paper		
	Iron and Steel	5%	
	Aluminium		
	E-waste Recycling		
	Oil and Gas	5%	
	Cross-cutting Industry	–	
Agriculture, Land-Use and Landfills **18%**	Crops	7%	Cultured meat (5-9); plant-based meat (9)
	Livestock	6%	
	Landfills and Waste	4%	
	Land Use and Forests	1%	
	Agriculture Fuel Combustion	<1%	

Note: Reproduced from Dugoua and Moscona (Forthcoming). Largely based on the Cooperative Patent Classification. Data on the shares of global GHG emissions are from Rhodium Group and available at https://rhg.com/research/global-greenhouse-gas-emissions-2021/. Information on specific technologies and their technological readiness levels (TRL) was sourced from the IEA Clean Energy Technology Guide available at https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide.

Transport. Transport contributes roughly one-sixth of global GHG emissions. Road transport is leading the transition, with battery electric vehicles now at commercial scale (TRL 9–10), supported by progress in lithium-ion batteries and charging systems. Emerging chemistries such as sodium-ion and solid-state batteries remain at prototype to demonstration stages (TRL 5–8). Fuel cell electric vehicles are in early adoption for heavy-duty niches (TRL 8–9) but depend on hydrogen infrastructure. Aviation and shipping have fewer mature options. Sustainable aviation fuels are at early commercial scale (TRL 9–10) but constrained by feedstocks and cost, while synthetic fuels and hydrogen-based routes are at pilot and prototype stages (TRL 4–6). In shipping, biofuels, methanol, and ammonia are being tested (TRL 5–9), but large-scale adoption hinges on engines, safety standards, and global bunkering infrastructure.

Industry. Industry accounts for about one-quarter of global CO_2 emissions and is among the hardest sectors to decarbonize. Some progress can be made through efficiency improvements and electrification of low- to medium-temperature heat, which are already commercially available. But most high-temperature processes—such as those in steel, cement, and chemicals—depend on technologies that are still at pilot or demonstration stage. Options include hydrogen-based steelmaking, alternative cement binders, and electrified processes in chemicals and aluminum. Carbon capture and storage can also play a role, though it remains costly and infrastructure-intensive. Overall, deep cuts in industrial emissions hinge on advancing and scaling technologies that are not yet fully commercial.

Cross-cutting enablers. Several cross-cutting systems underpin mitigation across all sectors. Battery storage is critical both for integrating variable renewables into power systems and for electrifying transport. Lithium-ion technologies are already mature (TRL 9–10), while alternatives such as sodium-ion and metal–air chemistries are at earlier stages (TRL 6–8). Smart grids and digital controls are also commercially established (TRL 9–11), though deployment remains uneven, especially outside advanced economies. Hydrogen serves as a versatile energy carrier and industrial feedstock, with maturity spanning from established electrolysis and fossil-based routes with CCUS (TRL 8–9) to more experimental pathways such as seawater electrolysis and novel storage methods (TRL 4–6). Carbon management technologies likewise cover a wide spectrum, from established CO_2-enhanced oil recovery (TRL 11) to emerging approaches such as direct air capture and mineralization (TRL 3–7). The diversity of maturity levels highlights the importance of advancing enabling infrastructure—grids, CO_2 pipelines, storage basins, and hydrogen networks—without which sector-specific technologies cannot scale effectively.

Buildings. Buildings account for a smaller share of direct emissions than power, industry, or transport, but their role is larger once indirect emissions are considered. Direct emissions come mainly from on-site combustion for heating and cooking. Indirect emissions arise from the electricity used for lighting, appliances, and cooling, which makes buildings the single largest consumer of electricity worldwide. Efficiency measures—such as insulation, glazing, efficient lighting, and appliances—are broadly mature (TRL 9–11) and reduce both direct and indirect emissions. Heat pumps, central to decarbonizing heating, are at early adoption for most applications (TRL 8–10), with colder-climate and high-temperature variants at earlier stages (TRL 6–8). Cooling demand is rising rapidly with income and exposure to heat; efficient vapor-compression units are commercial (TRL 9–11), while solid-state and advanced designs remain prototypes (TRL 3–5). Refrigerant management and substitution are also critical and relatively mature. In this sector, the main barriers are not technical feasibility but diffusion, as adoption depends on upfront costs, building codes, and retrofit logistics.

Agriculture, land use, and waste. Agriculture, land use, and waste are often overlooked in discussions of mitigation, yet they account for a large share of global greenhouse gases and will grow in relative importance as progress accelerates in power and transport. Emissions in this sector are dominated by methane and nitrous oxide. Livestock production is a key source, through enteric fermentation in ruminants and manure management. Crop cultivation contributes large amounts of nitrous oxide from fertilizer use and soil management. Land-use change, especially deforestation, releases substantial CO_2. In waste, methane arises from the anaerobic decomposition of organic material in landfills.

A range of mitigation options exists. Alternative proteins reduce livestock emissions by shifting demand: plant-based substitutes and insect proteins are already commercial (TRL 9–11), while cultured meat, grown from animal cells in bioreactors, remains at earlier stages (TRL 5–7). Livestock feed additives like 3-NOP inhibit the enzymes that generate methane during digestion and are at early adoption (TRL 8–9), while seaweed-based supplements, which achieve similar effects, remain at demonstration (TRL 6–7). Precision agriculture technologies—such as GPS-guided machinery, sensors, and data analytics—improve fertilizer and water efficiency and are now mature (TRL 8–9). Biochar, produced by heating biomass under low oxygen, can store carbon in soils and improve fertility, and is close to commercial scale (TRL 8–9). In the waste sector, technologies to capture methane from landfills are fully mature (TRL 9–11). Overall, a broad technical toolkit is available, but adoption depends heavily on policy support, consumer behavior, and institutional capacity.

2.2 Clean Tech in the Past 20 Years: Where and How Much

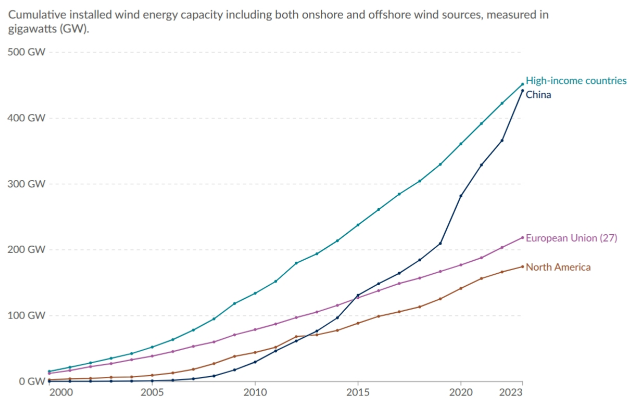
Having mapped the landscape of available mitigation technologies and their maturity levels, the question is how far these options have actually diffused. Over the past two decades, clean technology has moved from the margins to the center of the global energy system. In particular, solar photovoltaics, wind turbines, and electric vehicles have scaled from negligible levels in the early 2000s to hundreds of gigawatts of installed capacity and millions of annual sales today (Fig. 2). Innovation trends mirror this transformation: international patent families in clean technologies expanded rapidly after the mid-2000s – although they have dipped during the early 2010s (Fig. 3).

These parallel patterns of deployment and innovation frame this subsection. We organize the discussion around four stylized facts. First, China has emerged as the dominant actor in both innovation and diffusion. Second, progress has concentrated in power generation and, more recently, transport, while hard-to-abate sectors remain limited. Third, modular technologies with high learning rates—solar, wind, and batteries—have driven the fastest cost declines and diffusion. Fourth, adoption outside high-income countries remained limited until the early 2020s, though recent trends suggest this may be starting to change. The goal here is to provide a brief overview of these broad trends, which will be examined in greater detail in the case studies on solar, batteries, and hydrogen.

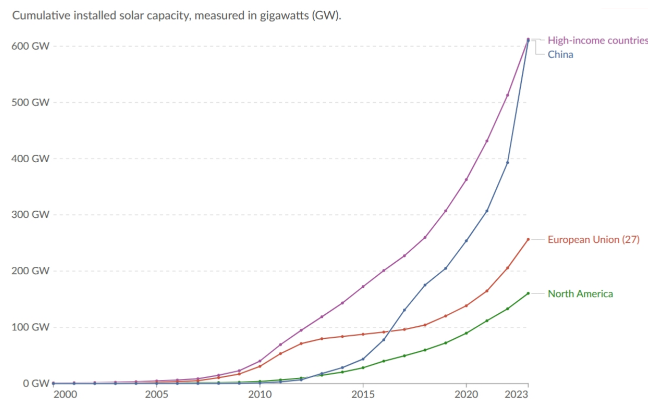
Fact 1: Sectoral focus—power first, then light transport. The clean technology transition has unfolded unevenly across sectors, with power generation leading the way. Wind power began scaling earlier, supported by strong policy commitments in pioneering countries such as Denmark, whose feed-in tariffs and industrial support measures nurtured a globally competitive wind industry. By the mid-2000s, wind capacity was already expanding rapidly. Solar photovoltaics followed with a lag: deployment remained modest until the late 2000s, after which falling module costs and widespread support through feed-in tariffs and renewable portfolio standards drove exponential growth. Together, wind and solar dominated global additions to renewable capacity in the 2010s, underpinned by learning effects and competitive auctions that locked in cost declines while reducing fiscal burdens.

Light-duty transport followed only later. Electric vehicles remained marginal until the late 2010s, when sales accelerated sharply in China, Europe, and the United States (Panel 2c). Policy mandates were central: Europe's tightening CO_2 standards and California's zero-emission vehicle program created predictable demand, which in turn encouraged automakers to commit to large-scale battery platforms. By the early 2020s, EVs accounted for double-digit shares of new car sales in major markets.

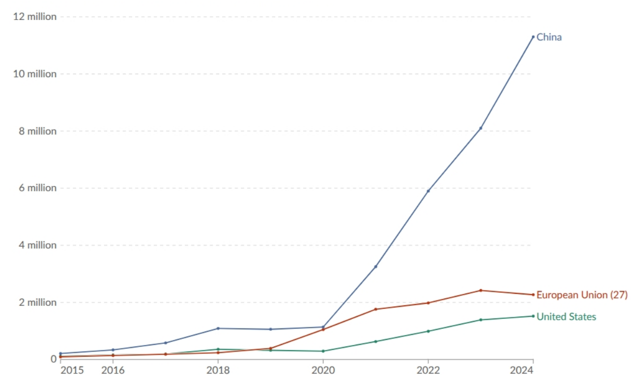
Patent data mirror these sectoral dynamics (Fig. 3). Most clean innovation over the past two decades has concentrated on electricity generation, storage, and grids, with especially strong growth in batteries and smart-grid technologies that underpin both power and transport. In contrast, innovation for hard-to-abate sectors remains small: CCS patenting, while growing, remains at roughly 100 families per year, and hydrogen activity was relatively strong in the early 2000s but declined once lithium-ion batteries became dominant in transport.



(a) Wind



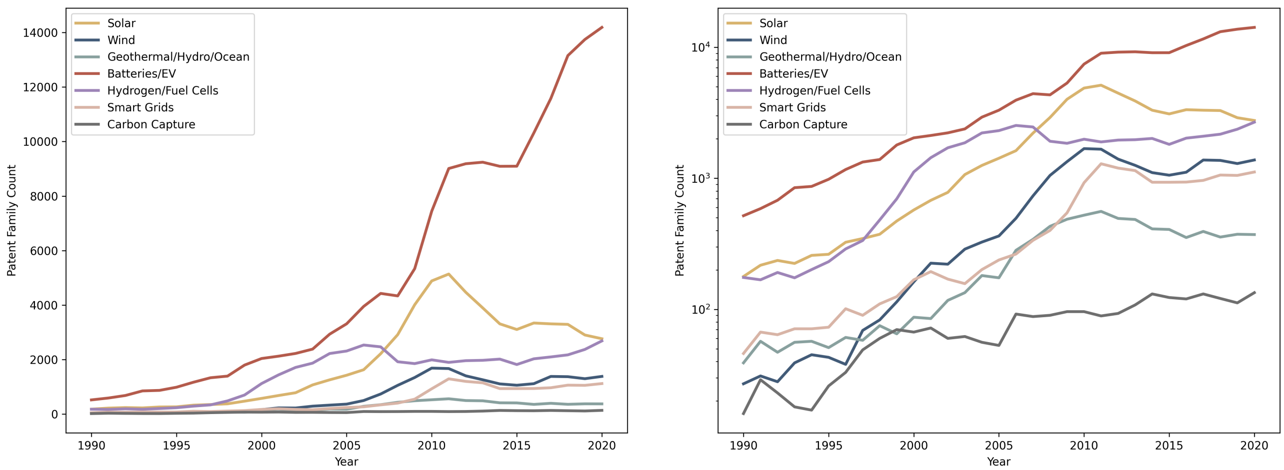
(b) Solar



(c) Electric Vehicles

Figure 2: Clean Tech Deployment

Note: Panel 2b is reproduced from IRENA (2024b), Panel 2a from IRENA (2024c), and Panel 2c uses data from the *IEA Global EV Outlook 2025*, processed and visualized by *Our World in Data*. Solar capacity includes both photovoltaic and concentrated solar power, wind capacity includes both onshore and offshore, and both are measured in gigawatts. EV sales cover fully battery-electric and plug-in hybrid cars. Together, the figures highlight the rapid worldwide scale-up of these technologies, with China being the leading market across all three.

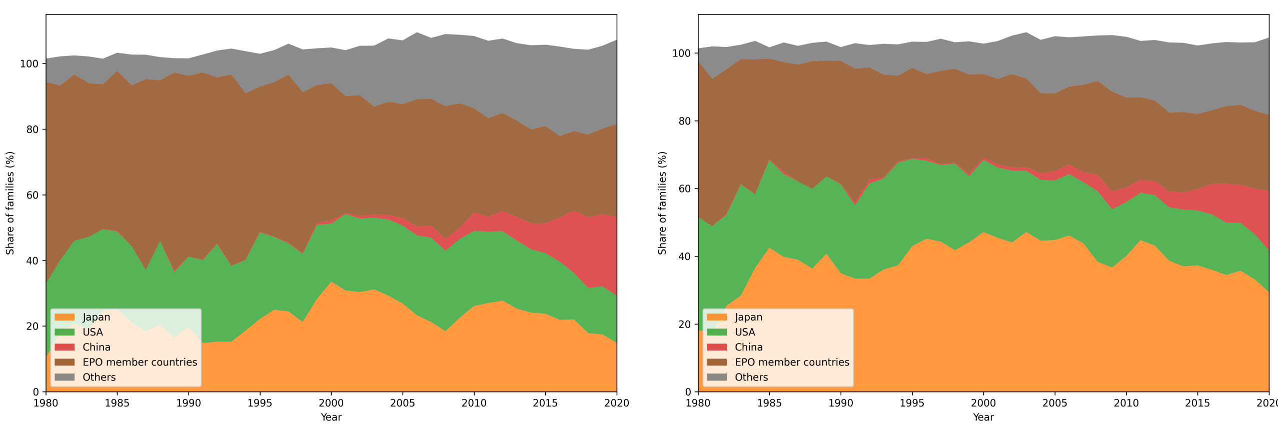


(a) Clean technologies (levels)

(b) Clean technologies (log)

Figure 3: Patenting Trends in Clean Energy Technologies

Note: Reproduced from Dugoua and Moscona (Forthcoming). Panels (a) plots annual patent family counts for clean energy technologies in levels, while panels (b) uses a log scale. These figures show *international* patent families, defined as DocDB families in PATSTAT with applications filed in at least two different countries. The year refers to the filing date of the first application in the family. The log panels highlight proportional growth, making it possible to observe the expansion of small but important categories such as carbon capture and storage (CCS), which remain limited in absolute terms. Clean patenting rises strongly after the mid-2000s, led by solar and batteries, with wind and smart grids also increasing. There is a clear drop across many clean technologies in the early 2010s.



(a) Solar international families

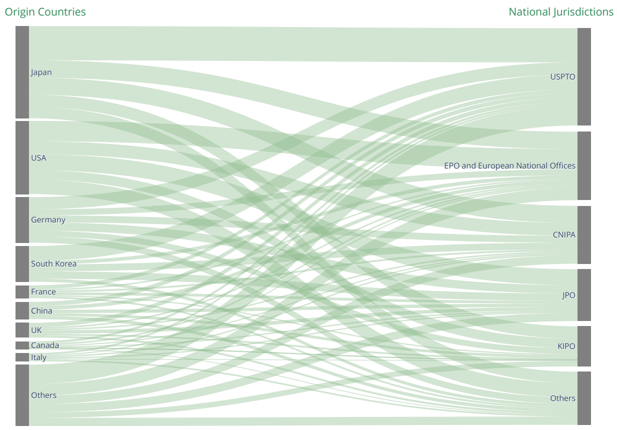
(b) Battery-EV international families

Figure 4: Key Origin Countries in Solar and EV-Batteries Families Over Time

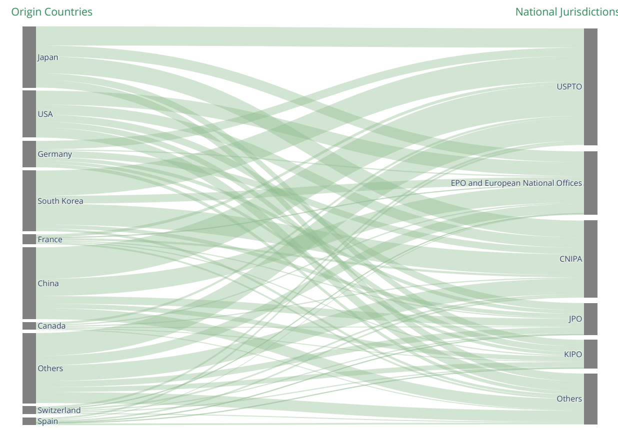
Note: The figure shows the origin countries of international patent families in solar and EV-battery technologies over time. "Origin country" is assigned hierarchically: inventor country; if missing, applicant country; if missing, the authority of the family's first filing. Years denote the earliest application within each family. The graphs cover *international* patent families (PATSTAT DocDB families with filings in at least two countries). We see that the vast majority originated with inventors in the United States, Japan, and Europe. This pattern still holds, but since 2010, Chinese inventors have claimed a growing share. For more information about patent data cleaning and processing, see Appendix A.3 in Dugoua and Moscona (Forthcoming).

We also note that in the early 2010s, clean patenting dropped sharply. A combination of

Solar Families

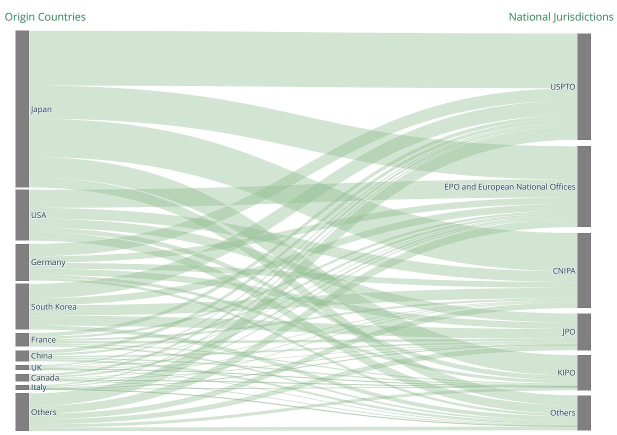


(a) 2005

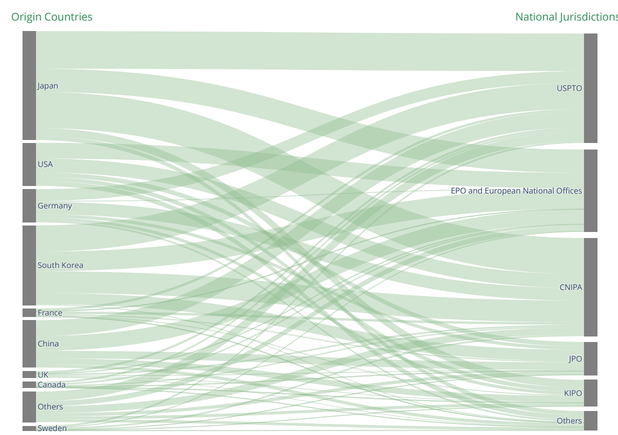


(b) 2020

EV-Batteries Families



(c) 2005



(d) 2020

Figure 5: Origin-Destination Flows of Foreign-Oriented Patent Families

Note: The figures show *foreign-oriented* patent families, defined (following WIPO) as families with inventors or applicants in one country that are filed in at least one other country, for Solar and EV-Batteries technologies. Origin is defined as explained in Fig 4. The destination is the office of the foreign filing(s). In both 2005 and 2020, the United States, Japan, and the main European countries (Germany, France, the UK) account for the bulk of foreign-oriented families, while East Asia stands out as a second major hub with Japan and South Korea highly visible. Across both technologies, the largest flows are typically Japan→USPTO, Japan→China, and US→Europe, and these remain prominent throughout the period. China was already significant in 2005, as an important destination, with CNIPA among the main authorities alongside USPTO and EPO. By 2020, its importance had grown sharply on the inventor side, making it one of the leading origins of foreign-oriented families. Together, these flows highlight the enduring dominance of the US, Japan, and Europe, the central role of East Asia, and the rapid rise of China as both a source and destination of foreign-oriented clean patenting.
For readability, European national offices and the EPO are grouped together. Note that a family with German inventors filed in France is considered foreign-oriented in this context. JPO = Japan Patent Office; EPO = European Patent Office; USPTO = United States Patent and Trademark Office; CNIPA = China National Intellectual Property Administration. For more information about patent data cleaning and processing, see Appendix A.3 in Dugoua and Moscona (Forthcoming).

factors contributed: the post-2008 financial crisis constrained investment; a boom-and-bust cycle in cleantech venture capital undermined financing; policy uncertainty increased after the failure of the Copenhagen climate negotiations; and tax credits and feed-in tariffs were curtailed in key markets such as Germany and Spain. At the same time, the shale gas revolution lowered natural gas prices, weakening incentives for renewable deployment (Dugoua and Moscona, Forthcoming).

Fact 2: The rise of China. China has become a central actor in clean technology innovation, manufacturing and deployment. Deployment data show the scale of this shift. In solar photovoltaics, China moved from negligible capacity in the early 2000s to about as much as all high-income countries together in 2023 (Fig. 2b). Wind capacity followed a similar trajectory, with China overtaking the European Union and the United States by the mid-2010s (Fig. 2a). In electric vehicles, sales accelerated spectacularly after 2020 and now exceed those of other regions by a wide margin (Fig. 2c).

Innovation trends reinforce this picture. As shown in Figure 3, international patent families in clean technologies rose strongly after the mid-2000s, led by solar and batteries, with wind and smart grids also increasing. Figure 4 shows how global shares shifted: the United States, Japan, and Europe dominated early on, but since 2010 Chinese inventors have taken a growing share, especially in solar and batteries. Cross-border flows in Fig. 5 highlight this transition. In 2005, China appeared mainly as a destination for foreign applications, while by 2020 it had become one of the leading origins of foreign-oriented families, alongside the United States, Japan, and Europe. These trends are consistent with China's rising R&D intensity and public spending on clean energy, which now rival advanced-economy levels (IEA 2022c, page 48). Overall, the growth reflects not only higher filing volumes but also a greater share of inventions targeted at international markets, captured by international and foreign-oriented families.

Several mechanisms underpin this rise. Domestic policies created large, predictable markets, first through subsidies and feed-in tariffs and later through auctions and electric-vehicle mandates. Scale manufacturing lowered costs, while intense competition among local firms led to consolidation and the emergence of global champions such as BYD in electric vehicles and CATL in batteries. These firms now dominate supply chains and compete globally on price and technology.

The result is a sharp geographic concentration of clean technology. China now dominates manufacturing and much of the upstream supply chain, from mining to refining of critical minerals, while the United States and European Union remain important but smaller hubs. China's expanding role has, in turn, reshaped global policy debates, placing industrial strategy and supply chain security at the center of clean-energy policymaking.

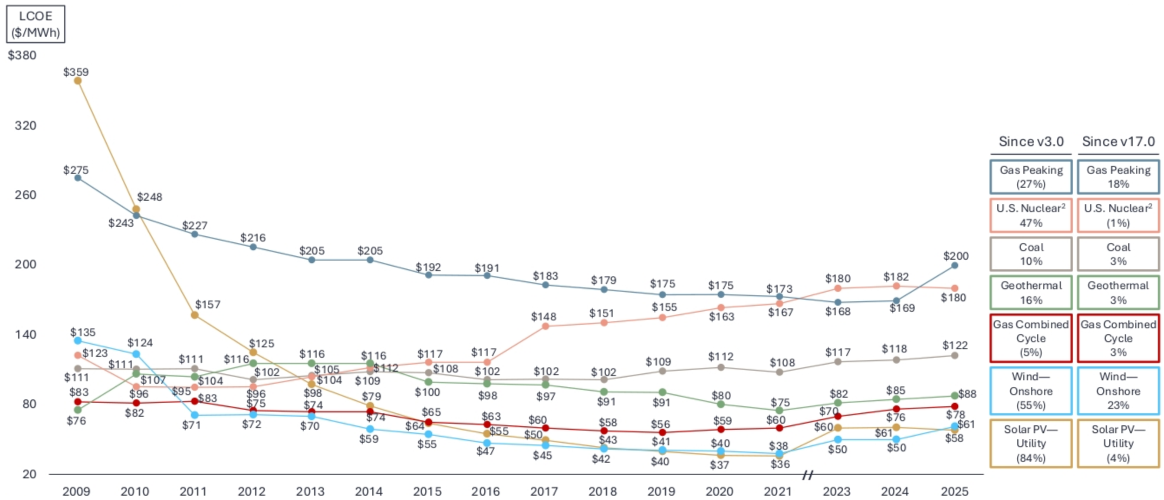


Figure 6: Levelized Cost of Electricity by Technology, 2009–2024

Note: Reproduced from Lazard (2025, pp. 14). The figure reports historical average levelized cost of electricity (LCOE) values, calculated as the midpoint between high and low estimates for each technology. It highlights the dramatic decline in renewable costs: utility-scale solar PV fell by more than 90% between 2009 and 2024, and onshore wind by around 70%. These reductions, driven by learning curves, economies of scale, and technological improvements, have made renewables broadly cost-competitive with fossil fuels. Lazard's analysis notes that these declines have begun to plateau and, in some cases, slightly reverse in recent years. For nuclear, LCOE estimates reflect Lazard's LCOE v14.0, adjusted for inflation, based on then-estimated costs of the Vogtle Plant.

Fact 3: Cost Decline and Modularity. We return in the next section to the mechanisms behind clean-technology diffusion, but it is useful to note here that the deployment of wind, solar, and EVs has been inseparable from the massive cost declines these technologies have experienced.

Cost declines in clean technologies emerge from several reinforcing mechanisms. R&D delivers fundamental improvements, learning-by-doing reduces costs as firms gain production experience, and economies of scale lower unit costs as output expands. These processes, often amplified by knowledge spillovers and growing markets, underpin the steep learning curves observed across many clean technologies. Between 2010 and 2023, module costs fell by about 90% for solar PV (IRENA 2025b), 50% for wind (U.S. Department of Energy 2023), and 90% for lithium-ion batteries (IEA 2024a), making these technologies competitive across many markets. Figure 6 illustrates the corresponding decline in the levelized cost of electricity, highlighting how rapid learning, economies of scale, and technological improvements transformed the economics of power generation.

A central feature that helps explain these steep cost declines is modularity. Modular technologies are composed of standardized components with clear interfaces, which enable mass production, parallel innovation, and flexible deployment (Baldwin and Clark 2000; Pia and Dumas 2025). This architecture accelerates iteration and diffusion: each additional output reduces costs through process refinements, supply-chain specialization, and downstream learning. By contrast, integral designs can be difficult to replicate and scale. Nuclear power illustrates this challenge: each reactor is a bespoke, capital-intensive project with long lead times. Current efforts to develop small modular reactors (SMRs) seek to introduce standardization and replication to nuclear power, precisely in order to capture the advantages of modular design.

The advantages of modularity are clear in the leading clean technologies. In solar PV, standardized panels can be combined flexibly, from individual rooftops to multi-gigawatt farms. Wind turbines advanced through modular blades and nacelles that simplify transport, installation, and maintenance. In transport, "skateboard" EV platforms and serviceable battery packs shortened development cycles and expanded product variety. Battery storage systems, inherently modular, scale through replicable units that improve both flexibility and reliability.

The prominence of modularity offers one plausible explanation for sectoral differences. Standardized, replicable designs in power generation and light transport supported mass production, rapid learning, and integration into global supply chains, which likely contributed to their faster diffusion. By contrast, integral, site-specific systems in heavy industry—such as steel, cement, or large reactors—face higher capital costs, longer project cycles, and fewer opportunities for iteration, which may help explain their slower and more uneven spread.

Fact 4: Diffusion outside high-income countries has lagged, but conditions may be shifting. Clean technology adoption has been concentrated in high-income economies and China, with middle- and low-income countries playing a much smaller role. This imbalance is beginning to shift as middle-income markets expand deployment through auctions, concessional finance, and grid investments, and as some low-income countries see early projects. Surplus manufacturing capacity in China has further lowered global solar prices, making panels more accessible in regions such as Africa (Jones 2025). Diffusion remains highly uneven, but the growing participation of middle- and low-income countries points to the possibility of a broader global expansion. The next section examines in more detail the barriers and drivers that shape these patterns.

2.3 Drivers and Barriers of Clean Tech Diffusion

In this section, we synthesize the main mechanisms behind the observed stylized facts of clean technology adoption. Table 2 organizes these mechanisms along two dimensions. Rows distinguish between cost and performance factors, complementary inputs, and political economy constraints, while columns map each mechanism to (i) its role in clean technology markets, (ii) the market failures or frictions it creates and the associated policy levers, and (iii) its implications for cross-country diffusion. By laying out these interactions systematically, the table makes clear why rapid cost declines alone are insufficient to guarantee widespread adoption, and why diffusion patterns differ sharply across technologies and income levels. The subsections that follow unpack these mechanisms in turn.

2.3.1 Cost and Performance Considerations

Cost and performance are central to clean technology diffusion because they determine competitiveness with incumbent fossil-based technologies and evolve endogenously as deployment scales.

R&D, learning-by-doing, and economies of scale. R&D investments, learning-by-doing, and economies of scale are key drivers of sustained cost reductions and performance improvements in clean technologies. As cumulative production increases, firms gain experience, refine processes, and exploit scale economies, lowering unit costs over time. Covert and Sweeney (2022), for instance, document substantial learning-by-doing in the wind turbine industry, where a doubling of manufacturing output reduces costs by 14–29%.

A caveat of very rapid learning dynamics, such as those observed in renewables, is that potential adopters may engage in 'wait-and-see' behavior, delaying investment if they anticipate further near-term cost declines or performance improvements.

These dynamics give rise to a classic knowledge externality. Because knowledge generated through R&D is only partially appropriable, innovations spill over to competitors, leading private firms to underinvest relative to the social optimum. As a result, government support—through public funding for basic research, demonstration projects, and early-stage deployment—is central to the development of clean technologies.

Historically, such support has been substantial. Following the oil shocks of the 1970s, government spending on energy R&D accounted for roughly 10–20% of total public R&D, underpinning large-scale programs that helped advance solar and wind technologies from prototypes to demonstration projects. More recently, this share has fallen to about 5% or less in most developed economies, as public R&D priorities shifted toward other areas such as health (IEA 2024b).

However, declining global costs do not imply that clean technologies are equally cheap or easy to adopt everywhere. Innovation and knowledge creation remain highly concentrated geographically, which shapes how readily cost reductions translate into local adoption.

Nearly all global R&D and patenting in clean technologies is concentrated in OECD countries. Probst et al. (2021) report that, as of 2017, inventors in Germany, Japan, and the United States accounted for more than half of global clean technology inventions. China stands out as a notable exception: while most middle-income economies remain less specialized in low-carbon technologies than high-income countries, China has rapidly closed the gap and emerged as a major innovator.

For developing countries, the effective cost of clean technology adoption depends on how easily foreign technologies can be transferred and adapted to local conditions. When adoption requires substantial 'adaptive' R&D—because technologies must be tailored to local infras-

Table 2: Drivers and Barriers of Clean Tech Diffusion

Category	Mechanism	Clean Tech Context	Market Failures and Policies	Cross-country Diffusion
Cost and Performance	**R&D, learning-by-doing, and economies of scale**	Drive cost reductions over time. Expected future price drops may discourage early adoption ("wait-and-see" behavior).	Knowledge spillovers cause underinvestment. Public support for basic research, pilots, and early deployment.	Innovation concentrated; adopters may lack absorptive capacity. Transfer via collaborative R&D, joint ventures, inventor mobility.
	Costs relative to alternatives	Compete with fossil incumbents that do not face full environmental costs.	Unpriced externalities distort investment decisions. Carbon taxes or emissions trading internalize costs.	Trade barriers raise clean tech prices, impeding adoption.
	Characteristics of demand	Demand heterogeneity matters. Electricity is homogeneous (price dominates); transport allows differentiation (Tesla's premium EVs).	Certification and eco-labeling support differentiation and address behavioral biases.	Products need local adaptation (PAYG solar, smaller EVs, micromobility). Requires local customization capacity.
Complementary Inputs	**Infrastructure**	Requires coordinated investments: EV charging networks, grid upgrades for renewables, hydrogen pipelines.	Network externalities create coordination failures. Public investment reduces risk and catalyzes adoption.	Weak state capacity limits infrastructure investment, slowing diffusion.
	Financing	High upfront costs and long paybacks. Financial institutions lack experience evaluating risks.	Credit constraints and information asymmetries limit financing. Green banks offer concessional loans and derisking.	Concessional climate finance essential in lower-income countries. Multilateral funds such as the Green Climate Fund and multilateral development banks provide low-cost capital.
	Human capital and skills	Requires trained personnel: solar installers, grid engineers, EV technicians. Maintenance gaps in developing countries.	Training programs and workforce transition policies expand skilled worker pools.	Personnel mobility and clusters support human capital development. Proximity to hubs facilitates spillovers.
	Intellectual property	Patents stimulate innovation but restrict diffusion. Global asymmetries: most patents in North, adoption needs in South.	IPRs create innovation incentives but limit access. Tools include compulsory licensing, patent pools.	IP barriers where capacity limited. CBDR principle supports relaxed enforcement for vulnerable countries.
	Knowledge and information	Adoption requires know-how about permitting, interconnection, business models. Demonstration projects build ecosystem awareness.	Knowledge spillovers underprovided. Place-based policies (clusters, hubs) facilitate information exchange.	Transfer via FDI, joint ventures, diaspora networks. Information gaps persist without local exposure.
Political Economy	**Incumbents and stranded assets**	Fossil incumbents lobby for protection, resist change. Workers in legacy sectors face job losses.	Fossil subsidies distort prices. Clean tech policies must address distributional impacts.	Weak institutions enable vested interests to block reforms. Political constraints complicate energy transitions.
	Local opposition / NIMBYism	Clean infrastructure provokes aesthetic, environmental, or safety concerns. NIMBY sentiments delay projects.	Uneven distribution of local costs and benefits. Solutions include compensation, community ownership.	NIMBY dynamics vary by land rights, governance strength, and cultural attitudes toward infrastructure.

Note: This table summarizes the main mechanisms that drive the diffusion of clean technologies. It distinguishes between channels such as learning-by-doing, spillovers, network effects, infrastructure build-out, demand creation, and institutional or policy support. Together, these mechanisms explain how innovation is translated into broader market adoption, highlighting both the reinforcing feedbacks that accelerate diffusion and the barriers that may slow it.

tructure, skills, or operating environments—costs remain high despite global price declines. Modular technologies such as solar PV, which rely primarily on standardized components and codified knowledge, are therefore easier to transfer internationally. By contrast, technologies in hard-to-abate sectors such as cement and steel typically require deeper technological capabilities, process integration, and tacit know-how before they can be deployed.

Mechanisms that facilitate knowledge transfer include collaborative R&D, joint ventures, inventor and scientist mobility, and capacity building for domestic R&D institutions.

Costs relative to alternatives. Beyond technological improvements, diffusion depends on whether clean technologies are cost-competitive with incumbent alternatives in the specific applications where they are deployed. In clean energy markets, this comparison is distorted by unpriced environmental externalities and the market power of fossil-based incumbents, which together tilt relative prices in favor of carbon-intensive technologies.

Because most emissions are not subject to carbon pricing, the social costs of pollution are not reflected in market prices, leading to systematically distorted investment and adoption decisions. Yet, even under this mispricing, several clean technologies have become highly competitive. As shown in Figure 6, the levelized costs of electricity (LCOE) from onshore wind and utility-scale solar PV are now lower than those of gas-, coal-, or nuclear-fired generation. That renewables have reached cost parity—or better—despite the absence of comprehensive carbon pricing underscores the magnitude of recent cost declines.

Corrective policies that internalize environmental externalities, such as carbon taxes or emissions trading systems, remain central to restoring efficient cost competition and accelerating clean technology adoption. At the same time, other policies can reinforce distortions. Many countries continue to subsidize fossil fuels, keeping their prices artificially low relative to clean alternatives. Trade barriers on wind and solar PV similarly raise input costs and slow diffusion by shielding domestic fossil-based generation from competition.

Demand-side Characteristics. Demand-side characteristics shape diffusion by influencing both consumers' willingness to pay for clean technologies and the scope for differentiation relative to incumbent alternatives. These effects vary systematically across sectors and across countries.

In electricity markets, demand is largely homogeneous: "clean" and "dirty" electrons are functionally identical from the user's perspective, making price the dominant determinant of adoption when consumers cannot directly observe the carbon intensity of supply. By contrast, in transport, vertical product differentiation creates scope for higher-cost clean technologies to diffuse by offering additional valued attributes, such as performance, design, or brand identity—illustrated by Tesla's early success in the premium EV segment.

In markets characterized by homogeneous demand, certification schemes and eco-labels can support differentiation by making environmental attributes salient to consumers. Such instruments also help address behavioral frictions, including present bias and inattention, which can lead to underinvestment in energy-efficient appliances even when lifetime cost savings are positive (Gillingham and Palmer 2014).

Demand heterogeneity also matters for cross-country diffusion. Clean technologies often require adaptation to local income levels, usage patterns, and constraints. In developing countries, for example, pay-as-you-go (PAYG) solar systems, smaller EVs, and electric micromobility solutions are designed to meet needs that differ from those in higher-income markets. Effective diffusion in these contexts therefore depends on the presence of local innovation systems capable of customizing technologies to user preferences and operating conditions.

2.3.2 Complementary inputs

Even when clean technologies are cost-competitive and attractive to users, diffusion can stall if complementary inputs are missing. Many clean technologies require coordinated investments in infrastructure, finance, skills, and institutions, giving rise to network externalities and coordination failures that markets alone may not resolve.

Infrastructure. The diffusion of clean technologies can be hindered by coordination failures, as widespread adoption often requires near-simultaneous investments in complementary infrastructure. EVs require a dense network of charging infrastructure before mass adoption becomes viable, yet charging providers hesitate to invest before sufficient EV uptake occurs. Maritime shipping is another example: shifting to low-carbon fuels, such as ammonia or methanol, requires redesigning ship engines and potentially building infrastructure to transport the new fuels to ports. Hydrogen also requires the building of new pipelines, and solar and wind energy can only scale if accompanied by investments in grid flexibility, storage, and transmission. These complementarities create network externalities, as the value of one investment rises only if others are made simultaneously. Left to markets alone, diffusion may stall because no single actor can capture the full social benefits of coordinated deployment. Governments can address these coordination failures by investing directly in complementary infrastructure and de-risking private investment through subsidies. Support policies targeting early infrastructure provision across municipalities in Norway have, for instance, been shown to substantially increase incentives for EV adoption (van Dijk et al. 2022). In countries with weaker state capacity or public finances, the inability to provide the necessary complementary infrastructure is even more pronounced, slowing diffusion even when the technology itself is viable.

Financing. There are many financial frictions affecting the development and diffusion of clean technologies. Explanations for these frictions are rooted in information asymmetries between lenders and borrowers. As with many emerging or unproven technologies, securing financing is difficult until viability at scale has been demonstrated. Banks and financial institutions lack experience with such projects and struggle to evaluate associated risks. The challenge, however, is especially acute for clean technologies, which are characterized by high capital intensity, long investment horizons, and policy-related risks. Policy risk and uncertainty arise as environmental regulations are often rolled back due to budgetary constraints or after elections, leading investors to delay or cancel their investment (Noailly et al. 2022). Policy designs that reduce investment risks and provide long-term stable support, such as feed-in tariffs, can improve investors' assessments towards clean tech projects.

Financing is especially scarce in bridging the 'valley of death' — the critical stages between invention and commercialization that involve demonstration plants, prototyping, and first-of-its-kind commercial facilities, all of which are essential for broader deployment. Cleantech startups are affected by limited exit opportunities, as incumbent prefer not to cannibalize their own (fossil) business (Nanda et al. 2015). R&D early-stage grants as those provided by the US Department of Energy can provide funds for startups to demonstrate the viability of prototypes (Howell 2017).

Finally, even when the technology is at commercial stage, high upfront costs may prevent consumers and small and medium firms from adopting the technology - an issue which is particularly pronounced in developing countries (Berkouwer and Dean 2022). Specific financing institutions, such as Green Banks or Multilateral Development Banks can contribute both to provide loans for clean technology adoption and to mobilize finance supporting infrastructure investments such as electricity transmission or commercial demonstration of industrial decarbonization in hard-to-abate sectors.

Human Capital and Skills. The diffusion of clean technologies depends critically on the availability of scientists, engineers, and skilled workers who contribute to both R&D and deployment. Human capital is particularly important because much of the knowledge underlying clean technologies is tacit and cannot be fully codified or transferred through blueprints alone.

A growing literature highlights the role of skilled workers and inventor mobility in facilitating technology diffusion. Kerr (2008) shows that ethnic scientific communities in the United States act as conduits for the transmission of high-tech knowledge to their countries of origin. Kerr et al. (2016) documents that inventor migration is highly concentrated, with the United States receiving a net inflow of inventors and countries such as China and India acting as major sources. Similar dynamics are evident in clean technologies. In the case of solar PV, anecdotal evidence suggests that many leaders of the Chinese PV industry were educated abroad, particularly in Australia and the United States (De La Tour et al. 2011).

These patterns imply that cross-country diffusion depends not only on access to technologies, but also on the ability to absorb and implement them locally. Policies that facilitate personnel mobility and international collaboration—through migration, knowledge exchange, or participation in global research clusters—can therefore play an important role in building human capital in adopter countries. Proximity to scientific and industrial hubs, such as clean-technology clusters, further facilitates learning and knowledge spillovers (Kerr and Robert-Nicoud 2020). Beyond mobility, public policy can also shape the supply of relevant skills by encouraging scientists to shift their fields of specialization—for example, from carbon-intensive to clean technologies—and by lowering barriers to inventor entry in clean technology domains (Dugoua and Gerarden 2025).

Beyond scientists and engineers, the diffusion of clean technologies depends on the availability of a skilled workforce capable of installing, operating, maintaining, and repairing these systems. Gaps in such operational skills can slow diffusion even when technologies are technically viable and affordable.

Empirical evidence highlights the importance of these deployment skills. In the United States, the diffusion of solar PV across municipalities accelerated only after qualified solar installers became more widely available (Fabrizio and Hawn 2013). In developing-country contexts, maintenance constraints can be binding: Hanna et al. (2016) show that, despite initial take-up of clean cookstoves by households in India, adoption declined over time due to insufficient training and maintenance investments.

Labor market data further illustrate the scale and composition of these workforce needs. Curtis and Marinescu (2022) document that solar and wind job postings in the United States have more than tripled since 2010, in parallel with growth in installed capacity. Solar employment is concentrated in sales and utilities, while wind jobs are more prevalent in installation, maintenance, and manufacturing. These patterns suggest that renewable energy deployment generates relatively high-paid jobs, often in regions exposed to job losses from fossil fuel extraction.

Expanding the supply of these skills therefore requires targeted training programs, vocational education, reskilling, and workforce transition policies. In developing countries, the challenge is not only to build such capabilities, but to do so in a way that enables leapfrogging in clean technology adoption. Attracting workers into green jobs depends critically on job quality—including wages, formality, and exposure to occupational risks—and may require complementary reforms in labor market institutions and the development of dedicated education and training systems (Vona 2023).

Intellectual Property Rights. Intellectual property rights (IPRs) play a dual role in the diffusion of clean technologies. By granting temporary monopoly rights, patents create incentives for firms to invest in costly R&D, but they also restrict access and raise adoption costs for downstream users. In the climate context, this trade-off is particularly salient: delays in diffusion translate directly into higher cumulative greenhouse gas (GHG) emissions.

The asymmetry lies less in the urgency of climate action—which is high everywhere—than in the geography of ownership and resources. Most clean-technology patents are held by entities in high-income countries, while lower- and middle-income countries face the greatest need for financial support and technology assistance to implement mitigation and adaptation at scale. This imbalance has made intellectual property a recurrent point of contention in international climate negotiations.

From an economic perspective, IPRs are often described as a "necessary evil." Knowledge is non-rival and, absent protection, can be freely imitated. Patents correct this market failure by allowing innovators to internalize returns from risky, capital-intensive R&D. Empirical evidence highlights the nature of these effects. Moscona (2021), studying U.S. plant biotechnology, finds that the introduction of patents in 1985 increased innovation and yields in affected crops, driven by expanded private investment, and generated positive spillovers into adjacent non-biological technologies. This suggests that stronger IPRs can lead to innovation gains under the right conditions.

Yet exclusivity also creates barriers. Licensing negotiations are costly, access is restricted, and adoption can be delayed. For developing countries, these challenges are compounded by limited financial resources and absorptive capacity. The solar sector illustrates the stakes: as markets have matured and competition has intensified, disputes over incremental but valuable innovations have proliferated. First Solar's recent lawsuits against rivals for alleged infringement of the "TOPCon cell" patents are emblematic of a broader rise in litigation (PV Tech 2024); observers note that such disputes reflect both the commercial significance of small efficiency gains and the growing density of "patent thickets" in mature segments of clean tech (Osborne Clarke 2021).

Concerns over restricted access are familiar from the pharmaceutical sector, where patents have at times constrained the availability of life-saving drugs in lower-income countries. However, the analogy should not be drawn too far. As Abbott (2009) emphasizes, clean technology markets differ in important respects: they tend to feature more competitors, greater substitutability across technologies, and less reliance on highly specific tacit knowledge. These features reduce—though do not eliminate—the risk that strong patent protection will operate as an absolute barrier to diffusion.

Importantly, intellectual property does not render technology transfer impossible. A variety of mechanisms can facilitate access even under strong protection regimes. Voluntary licensing agreements, joint ventures, and partnerships with local firms have often provided pathways to share both legal rights and the tacit knowledge required for effective deployment. Governments have also developed instruments to address the trade-offs inherent in IPRs. Compulsory licensing enables states, under defined conditions, to authorize the use of a patented invention without the consent of the holder, while patent pools and commons allow multiple rights holders to aggregate or voluntarily share patents, reducing transaction costs and promoting interoperability. These approaches underscore that the effects of intellectual property are not predetermined but depend on how rights are managed and governed.

These policy tools also operate within a broader governance context. Under the UNFCCC, the principle of Common But Differentiated Responsibilities (CBDR) recognizes that while all countries share an obligation to address climate change, the poorest and most climate-vulnerable countries face distinct constraints. Applied to intellectual property, CBDR could be seen as providing a normative basis for relaxing strict enforcement of IPRs in such contexts, supporting arguments that equity and fairness require greater flexibility in access to essential technologies. Seen in this light, international climate law reinforces the idea that the impact of IPRs on diffusion is not fixed but mediated by political choices about responsibility and burden-sharing.

Experiments with voluntary initiatives show both the promise and the limitations of these alternative models. The Eco-Patent Commons, launched as a collective effort to make environmentally beneficial patents freely available, illustrates the challenges. Despite its symbolic appeal, the initiative had little measurable effect: ambiguous licensing terms, limited outreach, and weak alignment with user needs undermined its impact (Contreras et al. 2018, 2019).

Patent pledges have also attracted attention as an alternative to traditional exclusionary practices, but their practical impact on diffusion remains uncertain. Tesla's 2014 announcement that it would not initiate lawsuits against good-faith users of its EV patents is the most prominent example. While hailed as a bold move to accelerate market growth, scholars debate whether such pledges represent genuine commitments, strategic branding, or attempts to position one's own technology as the dominant standard (Contreras 2015; Shi et al. 2023). Tesla's behavior underscores the complexity: even as it released parts of its patent portfolio, the company has continued to guard its most valuable process innovations—such as advanced battery manufacturing—through trade secrets. Its lawsuit against Matthews International over alleged misappropriation of dry-electrode production know-how, and the subsequent filing of competing patents, highlights how critical tacit knowledge is to competitive advantage, and how little of it is captured by formal patent disclosure (Energy Global 2024).

Adoption-Stage Knowledge and Information. Beyond formal R&D and human capital, the diffusion of clean technologies is shaped by the spatial concentration of knowledge and information at the adoption stage. Knowledge spillovers are non-rival and underprovided, and they often diffuse through geographic proximity.

Being located near operational projects, supplier networks, and pools of skilled labor makes it easier for firms and institutions to access tacit know-how. Co-location from R&D and demonstration to production and deployment allows ideas, practices, and expertise to circulate more readily across actors. Empirical evidence links innovation ecosystems and industrial clusters to higher research productivity and commercialization (Guzman et al. 2024), as well as to lower entry and information costs and stronger start-up employment (Delgado et al. 2010).

Spatial concentration can also help overcome coordination failures. When firms, investors, and regulators operate in close proximity, it becomes easier to align standards, synchronize investment timelines, and build trust. This reduces financing frictions and amplifies spillovers, supporting faster diffusion. Territorial differences therefore matter: higher labor mobility and more integrated markets in the United States have tended to accelerate adoption, while institutional fragmentation and regulatory barriers have slowed diffusion in parts of Europe (Crescenzi et al. 2007).

2.3.3 Vested Interests and Political Economy

Incumbents and Stranded Assets. The diffusion of clean technologies does not occur in a political vacuum. Because they displace entrenched industries, they generate both winners and losers, shaping the incentives of powerful actors to either support or resist change. Fossil fuel incumbents have strong incentives to defend existing revenue streams and protect sunk capital. Utilities, coal producers, and oil and gas majors have historically lobbied against carbon pricing, emissions standards, and subsidy removal (Skovgaard and Asselt 2018).

Beyond direct lobbying, incumbents have financed campaigns to sow doubt about climate science and to exaggerate risks of clean energy technologies (Dunlap and McCright 2011; Kleinman Center for Energy Policy 2023). Stranded asset concerns further reinforce resistance: coal plants, pipelines, and refineries can lose value abruptly if policy or market conditions shift. Employment in fossil-intensive regions is also highly exposed, and worker dislocation can translate into political opposition. Managing these distributional consequences is therefore central to sustaining policy momentum.

Persistent fossil fuel subsidies illustrate the distortionary effect of vested interests. Despite global commitments to phase them out, subsidies exceeded USD 1 trillion in 2023, shielding consumers and producers from price signals that would otherwise accelerate clean technology adoption (OECD 2024). Their endurance reflects the political difficulty of reform, since subsidies are often popular and closely tied to affordability.

A related challenge arises with clean energy subsidies. Because technologies like rooftop solar and EVs are typically purchased by higher-income households, early subsidy programs disproportionately benefited the well-off. Policy design must therefore anticipate distributional consequences. The Inflation Reduction Act in the United States addressed this by linking EV tax credits to income and vehicle price thresholds.

Political economy barriers are particularly strong where institutions are weak. In many resource-rich countries, state-owned utilities and fossil fuel enterprises yield significant influence over decision-making, resisting reforms that threaten established rents. Where corruption and regulatory capture are prevalent, clean energy support policies are often delayed or diluted. By contrast, stronger governance and civil society oversight are associated with earlier fossil subsidy reform and faster adoption of enabling policies for clean technologies (Rentschler and Bazilian 2017). These contrasts highlight that global diffusion depends not only on falling technology costs but also on institutional capacity to manage vested interests.

Local Opposition and NIMBYism. Social acceptance is a key determinant of the speed at which clean technologies diffuse. Even when technologies are cost-effective and technically mature, local opposition can delay or block deployment. Nuclear power, carbon capture and storage (CCS), as well as wind and solar projects have all faced resistance from nearby communities, giving rise to "Not In My Backyard" (NIMBY) dynamics. Such opposition increases permitting delays and project costs, slowing diffusion.

Wind power illustrates these mechanisms clearly. Wind turbines generate local externalities, including noise, shadow flicker[2], and landscape disruption, which are borne by nearby residents while climate benefits are global. Concerns about property values are therefore central. Synthesizing results across a range of empirical studies, Parsons and Heintzelman (2022) estimate a mean net effect of wind power projects on property values of about -5% within 1 km, declining to -1.2% at distances of 3–4 km.

Local opposition, however, rarely reflects a single concern. Susskind et al. (2022) show that resistance to utility-scale renewable projects in the United States arises from overlapping factors, including environmental impacts, property value concerns, perceived health and safety risks, limited public participation, and failures to respect Tribal rights. Land-use conflicts may also involve religious, cultural, recreational, or productivity considerations—for example, concerns that large solar farms may affect soil quality or agricultural yields.

NIMBY dynamics are not confined to high-income countries. Evidence from emerging and developing economies, including India (Lakhanpal 2019) and Mexico (Martinez 2020), points to similar patterns, though their intensity varies with land tenure systems, cultural attitudes toward infrastructure, and the strength of local governance. In settings with communal or customary land rights, land acquisition can be particularly contentious.

Policy responses aimed at mitigating NIMBY opposition include compensation schemes,

2. Repetitive blinking shadows caused by rotating turbine blades.

community ownership models, and participatory planning processes that increase local acceptance (IRENA 2025a). Permitting and zoning regulations can also shape outcomes by governing siting decisions and minimum setback distances for wind turbines and solar installations.

2.3.4 Conclusion

Taken together, the mechanisms discussed in this section highlight that clean technology diffusion is shaped by more than technological progress alone. Cost reductions and performance improvements interact with demand characteristics, complementary inputs, and political economy constraints, generating multiple market failures and coordination problems that can slow adoption. As summarized in Table 2, these frictions vary across technologies and countries, helping to explain the observed heterogeneity in diffusion paths.

2.4 Looking Ahead: Challenges and Risks for the Next Phase of Diffusion

This section looks beyond early adoption to the issues that could shape clean tech diffusion over the next decade. As technologies like EVs scale, new constraints are emerging—some technical, others political or systemic. We focus on three important trends: growing pressure on critical mineral supply chains, the rise of AI as both enabler and competitor, and a more uncertain geopolitical and policy environment.

2.4.1 Critical Minerals: A Growing Constraint

The diffusion of clean energy technologies increasingly depends on the availability of critical minerals, raising concerns about material supply constraints and making access to specific inputs a potential bottleneck for large-scale deployment. Renewable energy technologies such as wind and solar power rely on substantial quantities of critical resources, including rare-earth elements for permanent magnets and silicon metal for the production of solar PV modules. Electric vehicle batteries depend heavily on lithium, manganese, and cobalt, while large volumes of copper and aluminum are required for electricity transmission and distribution infrastructure (IEA 2021b).

Disruptions in the supply chain of critical minerals could slow down the adoption of clean technologies, particularly if supply cannot ramp up at the required speed and scale to meet the demand. Supply risks are mostly induced by geopolitical factors, as both the extraction and processing of critical materials tend to be concentrated in a small number of countries, with a particular dominance of China in many markets. Overall, geopolitical challenges raise the risk of disruption from export controls, trade conflicts, or political instability, leading to increased price volatility. In March 2022, nickel prices surged by 270% over three trading days in response to Russia's invasion of Ukraine, prompting the London Metal Exchange to suspend trading (Oliver Wyman 2023).

Rising prices for critical mineral inputs risk offsetting the cost reductions achieved in clean technologies over the past decade, potentially slowing diffusion by undermining affordability. This concern is particularly salient for batteries. While cathode materials—such as cobalt, nickel, and manganese—accounted for less than 5% of battery pack costs around 2015, they now represent roughly 20% of total costs. It remains an open question whether these increases reflect short-term price volatility or signal more persistent supply constraints.

To mitigate the risks of future supply disruptions, several countries have started to implement policies to diversify critical minerals supply chains. In November 2023 the EU has reached an agreement on the EU Critical Raw Mineral Act which aims to increase the domestic capacity of extraction in the EU to cover at least 10% of the EU's annual consumption of critical minerals, to increase processing capacity to cover 40% of EU annual consumption, and to increase its recycling capacity to cover at least 25% of the EU's annual consumption.

In the US, the Inflation Reduction Act provided tax deductions to electric car and battery manufacturers on the condition that they use a large share of critical materials that are sourced from the US or a country sharing a trade agreement with the US. Nonetheless, these attempts to reshore and diversify mineral supply chains could also fuel trade tensions, retaliatory measures, and lead to a potential fragmentation of global markets. Another promising option to mitigate mineral supply risks is to encourage technological innovation reducing the mineral intensity of components for the energy transition (substitution, material efficiency, recycling, extending the lifetime of products) – see Dugoua and Joëlle (2025) for a detailed overview of the role of innovation for critical minerals supply chain.

2.4.2 Artificial intelligence: Opportunity and Trade-Offs

Artificial intelligence (AI) has emerged as both an enabler of clean technology diffusion and a potential source of new pressures on energy systems and supply chains. It can accelerate the pace of innovation and improve efficiency across the clean energy value chain. AI speeds up materials discovery, including the search for novel battery chemistries through machine learning and autonomous laboratory platforms (Chen et al. 2024; Dave et al. 2022; IEA 2025a; Yik et al. 2025). In manufacturing, AI tools improve process control, reducing waste and raising quality. Applied to energy storage, AI supports advanced battery management systems that extend battery lifespans and improve performance (Metzger et al. 2023; Severson et al. 2019). In power systems, AI facilitates more efficient grid integration of variable renewables and enables coordinated charging strategies for electric vehicles, reducing system costs and balancing challenges (IEA 2020b, 2025d).

At the same time, the rapid rise of AI generates substantial new demand for electricity and infrastructure. Data centers consume large amounts of energy and require reliable high-capacity grids. Moreover, AI hardware competes for some of the same critical inputs as clean technologies, such as copper and advanced semiconductors (IEA 2025a). This overlap raises the risk that AI expansion could crowd out clean tech deployment by straining limited supply chains. Yet it could also crowd in investment by anchoring new renewable generation, accelerating grid upgrades, and lowering financing costs for clean electricity projects.

The net effect will likely be context-specific. In some countries, AI expansion may exacerbate resource constraints and slow clean technology deployment. In others, it may reinforce incentives to scale low-carbon power and modernize infrastructure. The direction of this balance is still an open question and will likely depend on policy frameworks, industrial capabilities, and the speed of complementary investments in clean energy.

2.4.3 Political and Geopolitical Headwinds

The diffusion of clean technologies is increasingly constrained by political and geopolitical frictions. Fragmented trade, contested standards, and volatile domestic politics raise costs and slow scale-up, with the sharpest effects in smaller and poorer markets. Clean tech deployment in the past benefited from open trade, cross-border investment, and global R&D networks, but that footing is weakening. Trade tensions, investment screening, export controls, sanctions, and local-content rules increasingly shape supply chains. Standards are diverging, and data regimes are tightening. Critical mineral markets face export restrictions and logistics shocks. These frictions increase capital and coordination costs, reduce learning spillovers, and delay technology transfer. Smaller buyers face longer queues and higher prices, widening the adoption gap.

Domestic political uncertainty adds another layer of risk (Noailly et al. 2022). Rollbacks or delays to measures such as ICE phase-out timelines, EV subsidies, renewable support, and building standards create stop-and-go cycles. Policy instability raises the cost of capital, deters local manufacturing, and discourages grid and storage investments that require credible long-term signals. Tools to strengthen credibility include predictable multi-year trajectories, automatic adjustment rules, independent regulators, long-term contracts such as PPAs and CfDs, and stability clauses. Complementary measures—targeted consumer support, place-based transition programs, and streamlined permitting—can reduce backlash and make commitments harder to unwind.

The balance of these headwinds will likely vary by sector and country. Jurisdictions that preserve openness where possible and strengthen domestic credibility are more likely to diffuse clean technologies faster and at lower cost.

2.4.4 Summary: What This Means for Diffusion

Future diffusion will hinge less on breakthroughs than on managing systemic risks. Mineral scarcity, AI expansion, and political headwinds can raise costs and fragment markets, but innovation, diversification, and credible policy can offset them. The balance is uncertain: in some contexts, these pressures may slow adoption, in others, they may catalyze new investment and coordination. Whether clean technologies keep scaling at the speed required will depend on how effectively institutions provide stability, openness, and resilience.

3 Case Study: Solar Energy

This section reviews the various stages of solar photovoltaic (PV) technology diffusion, from initial scientific discovery to global deployment. The first patents in solar PV emerged from technology-push R&D programs following the oil crises of the 1970s and 1980s. In the 2000s, a new wave of supportive demand-pull environmental policies, among which in particular the German feed-in tariffs, played a decisive role in enabling large economies of scale, leading to substantial cost reductions. Subsequently, China managed to move up the global value chain and played a central role in diffusing affordable solar PV worldwide. Despite remarkable progress, solar PV still faces persistent challenges in closing the final adoption gap.

3.1 Technology-Push and Demand-Pull Policies Led to Major Cost Declines

The major scientific breakthrough in solar energy occurred in 1954 at Bell Labs, where researchers developed the first practical silicon-based photovoltaic cell. Initially, these cells were prohibitively expensive and restricted to niche applications, most notably in powering satellites during the space race. Substantial cost declines over the following decades resulted from a combination of technology-push and demand-pull policies.

The oil crises of the 1970s, during which global oil prices more than doubled, created an urgent need to conserve energy and identify alternatives to oil. In response, the US government launched a large-scale technology-push program for solar PV. Between 1974 and 1981, federal authorities invested approximately $1.7 billion in R&D, creating new institutions such as the Department of Energy and the Solar Energy Research Institute (SERI). Public procurement programs, including the "Block Buy" scheme, further supported market formation by guaranteeing demand for solar modules. During the 1980s, however, declining oil prices combined with President Reagan's cuts in federal funding reduced incentives for alternative energy. Nonetheless, the decade-long investment in PV R&D nurtured an emerging solar industry and generated significant technological breakthroughs, with solar PV module costs falling by a factor of five between 1974 and 1981 (Nemet 2025).

As the US lost interest in solar energy, innovation moved elsewhere, particularly to Japan and Germany. Japan entered the solar PV sector in the 1970s with the Sunshine Project, which sought to reduce dependence on oil imports through large R&D investments. This program fostered the development of thin-film PV technologies that initially found commercial use in consumer electronics (e.g., Sharp's first solar-powered calculator was developed in 1980). Unlike in the US, Japanese R&D funding remained relatively stable even after oil prices declined, ensuring continuity in expertise and industrial capacity. From the 1990s onwards, Japan began developing a solar industry beyond consumer electronics. A landmark policy was introduced in 1994, when the government launched the Rooftop Subsidy Program, offering rebates for household solar installations. The program proved extremely popular and by 2000 had made Japan the largest PV market worldwide. However, political opposition from electric utilities and the nuclear industry curtailed support, leading to the program's termination in 2005.

Next to these early R&D programs in the US and Japan, Germany's aggressive demand-pull policy as part of the Renewable Energy Sources Act (EEG), which introduced feed-in tariffs (FiTs) in 2000, is the leading policy that transformed the global PV landscape. The FiT guaranteed fixed payments for renewable energy fed into the electricity grid, providing long-term certainty for investors. For several years, there were no limits on the tax deductions available for investments in solar and wind power. Despite its high cost, the German program successfully accelerated the scaling of the solar industry and has been widely characterized as a 'gift to the world' (Nemet 2025). The expansion of PV markets in Germany enabled massive economies of scale and encouraged firms to finance technological innovations and expand production capacity. As a result, the price of solar modules fell from 9 $/W in 1983 to 0.5 $/W in 2015 (Gerarden 2023; Gillingham and Stock 2018). Moreover, Germany's FiT catalyzed global learning-by-doing and technological spillovers. Empirical evidence from Gerarden (2023) quantifies that between 2010 and 2015, 88% of solar adoption attributable to German-induced innovation occurred outside Germany. Following Germany's lead, other European countries adopted feed-in tariffs. Yet, the financial crisis of 2009–2010 imposed severe fiscal constraints, leading to the scaling back of subsidy programs across Europe. In the years that followed, a growing number of countries shifted toward auction-based support mechanisms for solar PV, as a way to allocate subsidies more cost-effectively.

3.2 China's Rise in the Solar PV Value Chain and Global Deployment

The next important stage in the global diffusion of solar PV is the rise of China in the solar PV value chain, leading to an expansion of solar PV manufacturing. Today, China fully dominates the global solar PV industry, having successfully built a competitive domestic sector through a strategy of technology acquisition, vertical integration, and policy support.

The rapid expansion of PV markets in Germany and Japan created significant export opportunities for Chinese firms. Initially, Chinese companies entered the market by importing production equipment and focusing on module assembly. The entry of China into cell and module production was facilitated by relatively low trade and technological barriers in downstream production, where turnkey manufacturing lines could be imported and operated with limited prior experience. By 2007, China had become the world's largest PV producer, accounting for 35% of global cell and module production, although its participation in upstream segments such as polysilicon remained limited, producing only 2.5% of the world's silicon (De La Tour et al. 2011).

Over time, Chinese firms further advanced into polysilicon, ingot, and wafer production, building technological capabilities in upstream segments. This transition was facilitated by the recruitment of foreign-educated talent, R&D collaborations with international partners, and the attraction of foreign direct investment (FDI) (Zhang and Gallagher 2016). By 2009, China captured roughly one-third of global solar PV FDI flows, mainly through the establishment of joint-ventures with western firms. Licensing played only a minor role in knowledge acquisition and intellectual property rights have not impeded the rise of the Chinese solar industry. Instead, the emergence of production clusters reinforced local learning networks and helped consolidate China's industrial leadership. (De La Tour et al. 2011). Chinese firms continued to pursue aggressive strategies of vertical integration and international acquisitions, such as Suntech's purchase of MSK in Japan.

The global financial crisis of 2008–2009, combined with tariff measures against Chinese exports from the Obama Administration, posed a serious threat to the Chinese solar industry. In response, the Chinese government introduced strong domestic support programs, notably the Building Integrated PV subsidy and the Golden Sun initiative, both launched in 2009 (Banares-Sanchez et al. 2024). These measures created a robust domestic market that reinforced economies of scale and drove further cost reductions. Figure 8a plots the significant acceleration of China's solar PV deployment after 2012, driven by high local demand under these support programs. As of 2024, China has reached over 1 TW of cumulative capacity in solar PV, accounting for almost half of the world's PV capacity (IEA 2025e).

The rapid expansion of the Chinese solar industry has played a pivotal role in the worldwide diffusion of solar energy. First, mass production for the Chinese market contributed to accelerating learning-by-doing and economies of scale, leading to significant cost declines in solar PV prices as cumulative capacity increased, as depicted in Figure 7. The speed and extent of scale economies were greatly facilitated by the modular design of solar PV in manufacturing, which makes solar cells affordable even at a small scale (e.g, 100 W) by contrast to other energy technologies (e.g., coal or nuclear power plants, the minimum scale is in the range of hundreds of millions of watts) (Nemet 2025).

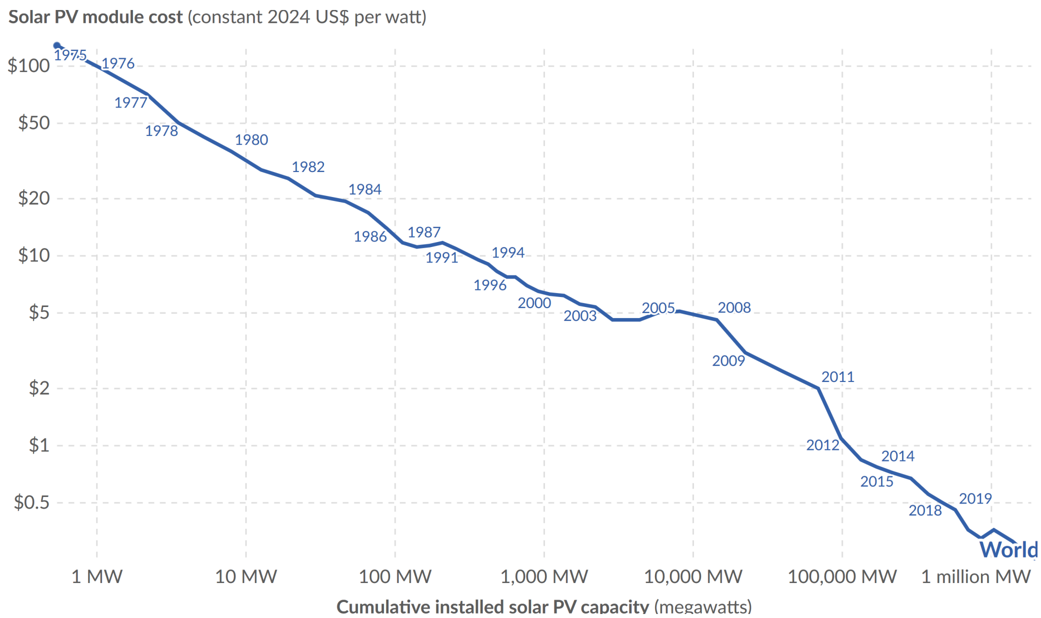


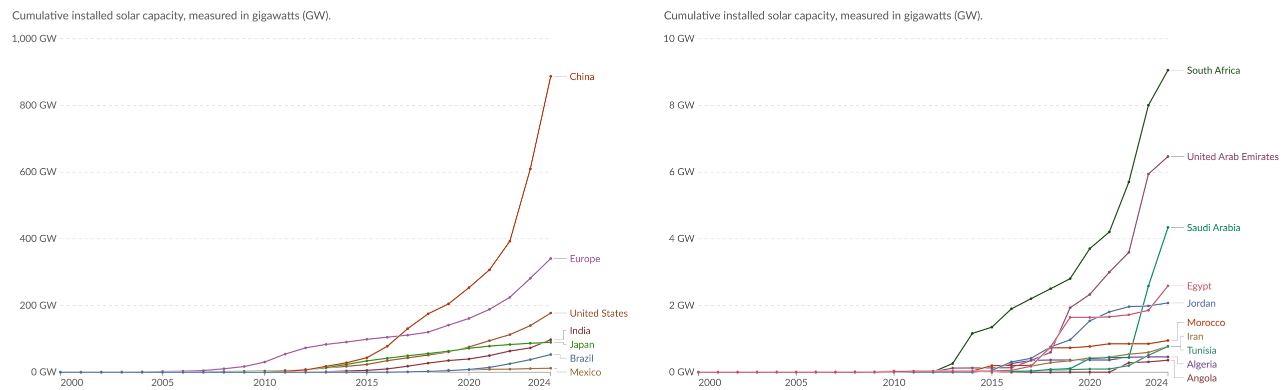
Figure 7: Solar PV panel prices vs. cumulative capacity

Note: Reproduced from Our World in Data (https://ourworldindata.org/grapher/solar-pv-prices-vs-cumulative-capacity). Solar module costs are from OWID et al. (2025), incorporating earlier series from Nemet (2009) and Farmer and Lafond (2016), and are expressed in constant 2024 US$/W. Deployment data refer to installed PV capacity from IRENA (2024b), accessed via Our World in Data. The learning curve shows the decline in module prices from over $100/W in 1975 to below $0.5/W in 2024, plotted against cumulative global capacity. Each doubling of deployment has driven significant cost reductions, underscoring the role of learning-by-doing and economies of scale in modular clean technologies.

Second, China became a massive exporter of cheap solar modules, helping thereby other parts of the world to expand their installed capacity as illustrated in Figure 8a. As of 2024, there are now 27 countries in which the cumulative installed capacity in solar PV contributes to more than 10% of the country's electricity consumption (IEA 2025e).

Today, China faces substantial overcapacity across all segments of the PV value chain, producing more than twice its domestic share of global PV demand. Unable to absorb this excess output, China continues to export a significant portion of solar PV products -—accounting for up to 7% of its trade surplus during 2017–2022 —- to other parts of the world (IEA 2022b). Confronted with import tariffs in the US and Europe, China redirected its solar exports toward emerging economies, including Southeast Asia, Latin America, and the Middle East, which by 2018 collectively absorbed nearly one quarter of Chinese solar exports (Jackson et al. 2021). More recently, reports indicate sharp growth in Chinese PV shipments to African countries, particularly South Africa and Nigeria, but also Sierra Leone and Chad, the latter two countries importing nearly half of their total current electricity capacity.[3] The International Energy Agency further highlights sizable inflows into Pakistan and Saudi Arabia, noting that while modules in Pakistan have been installed, in other cases it remains uncertain whether all

3. See https://www.nytimes.com/2025/08/26/climate/africa-china-solar-panels.html



(a) Selected Countries

(b) Middle East and Africa

Figure 8: Installed Solar PV Capacity around the world over time

Note: Data from IRENA (2024b). Panel (a) shows the exponential growth in solar capacity across major regions from 2000–2024, with China's dramatic expansion after 2012 driving global deployment. Panel (b) highlights recent capacity additions in the Middle East and Africa, demonstrating how falling costs have enabled solar diffusion beyond traditional markets. The figures illustrate how Chinese manufacturing scale helped democratize access to solar technology worldwide.

imported units are being deployed (IEA 2025e).

3.3 Barriers, Trade-offs and Challenges

Despite impressive global diffusion, several barriers and trade-offs continue to constrain the large-scale deployment of solar PV.

3.3.1 Grid Integration and Infrastructure

An important bottleneck to solar diffusion is the availability of complementary technologies and infrastructure, in particular to ensure the reliability of the electricity grid.

Just like wind energy, electricity produced from solar PV fluctuates depending on weather conditions and the time of day. The intermittent nature of solar energy creates imbalances between supply (mostly during the day) and demand (mostly at nighttime), leading to potential grid instability and forced cut-off (curtailment) of some generators. In addition, solar generation is often distributed across many small generating units distant from urban centers, which need to be connected to the grid. Hence, many complementary investments in high voltage transmission lines, transmission networks (i.e. improving interconnections with other regions), grid stability equipment (i.e. voltage control equipment, advanced inverters), net metering systems (e.g. when prosumer policies allow consumers to inject the surplus of energy into that network), improved distribution network (e.g. smart grids, sensors) are required to manage fluctuating supply and demand locally. Failure to invest fast enough in grid infrastructure impedes the efficient integration of solar PV systems. In addition to grid investments, another way to address the intermittency of solar power is through storage solutions, such as lithium-ion batteries or large-scale seasonal storage. The pace at which storage costs decline due to economies of scale will play a key role in accelerating the adoption of systems that integrate solar power with batteries. In China, for instance, mandatory coupling of storage with solar has led to record volume. Finally, a last type of complementary inputs relates to human capital. Fabrizio and Hawn (2013) shows that the diffusion of solar PV increased substantially more after a critical complementary input – qualified installers – became available. Along with programs that reward solar PV adoptions, it is critical to fund training programs in specific human capital skills and complementary products and services.

In developing countries, the lack of complementary infrastructure to accommodate renewables into the electricity grid is particularly challenging. With a growing population getting access to energy-using goods, demand for electricity across the developing world is projected to rise sharply in the coming decades, and choices of energy infrastructures in developing countries today will have major implications for both economic development and global climate change (Wolfram et al. 2012). At the same time, there is hope that the developing world could 'leapfrog' to renewable energy systems – just like with mobile technology – and benefit from the deployment of cheap solar PV to sustain its development goals, in particular with the diffusion of mini-grid and off-grid energy systems coupled with solar. This view, however, must be nuanced as mini-grid and off-grid systems may not be sufficient to meet the growing electricity needs of households without complementary investments. Lee et al. (2016) show, for instance, that once basic needs are fulfilled, households aspire to high-wattage appliances (refrigerators, television) that cannot be accommodated with home solar systems – unless when possibly coupled with sufficient investments in batteries. Yet, meeting the electricity needs of schools, hospitals, businesses, and industries will generally require grid connections. Hence, complementary investments—such as transmission and distribution upgrades—will be essential to integrate solar energy into the grid and facilitate economic development in developing countries.

3.3.2 Financing Constraints

Past support policies for solar in developed economies have been successful in achieving important cost declines. As such, market failures linked to the knowledge and environmental externalities are less relevant given that learning-by-doing has led the costs of generating electricity from solar below the costs of fossil energy. Yet, other factors contribute to raising the costs of solar PV and to hamper diffusion.

First, trade restrictions in particular from the US since 2014 and Europe over the 2013-2018 period have led to rising costs of importing solar PV, leading to reduced solar adoption. In 2014, the Obama Administration imposed anti-dumping and countervailing duties on Chinese solar cells and modules. Chinese firms responded to US import tariffs by shifting production to other countries, in particular Vietnam and Malaysia. Yet, in 2018, the Trump administration implemented broader tariffs on all global PV imports regardless of origin, which are still in place today. There is evidence that following the 2014 US tariffs, prices for solar PV in the US increased by about 10% relative to other markets, and by 20% following the 2018 tariffs, leading to reduced adoption of solar panels in the US (Gerarden et al. 2025).

Second, on the producer side, even in the absence of trade tariffs and despite low LCOE costs, there are still important financial risks of investing in solar PV projects, as those are typically highly capital-intensive and financed via project finance.[4] After the financial crisis and the end of generous feed-in tariff policies, solar and other renewable energy projects witnessed a drop in investment. More recently, increases in interest rates and inflation have also caused the cancellation of multiple solar projects. One major obstacle to investments in solar projects is the financial risk implied by the volatility and short hedging horizons of electricity prices (Neuhoff et al. 2022). Due to the intermittency of renewable energy production, electricity prices are more volatile than oil and gas. In addition, electricity forward contracts are implemented with retail consumers usually for a period of 1-3 years, and investors can only hedge on relatively short-term horizons. Yet, solar projects need 15–20 years of stable revenues to match their investment horizon. New policies, in the form of 'contracts for differences' (CfDs) (i.e., the government (investor) pays back the difference if the market price is lower (higher)), sliding or fixed premiums, can help to lower future financing costs of solar projects (Neuhoff et al. 2022). In addition, innovative financial tools, such as green banks, green bonds, and sustainability-linked loans, can help attract private investments for solar projects and broaden the pool of capital available. Multilateral development banks and other international financial institutions can provide low-cost, long-term financing for solar projects and help mitigate country risks.

On the consumer side, credit constraints can affect the ability of consumers to install solar PV. In developed economies, even if the costs of solar system hardware (modules, inverters) have fallen, there remain important 'soft' costs hampering the deployment of solar PV. O'Shaughnessy et al. (2019) show that soft costs – such as installation labor, permitting costs, financing costs, and customer acquisition – for small-scale solar systems remain high in the US, up to 70% of the price of a typical solar installation. Online platforms that match buyers and sellers can substantially ease access to price quotes, intensify competition, and lower solar prices (Dorsey 2024). Given the high upfront costs that consumers have to pay to install solar PV, new business models can facilitate adoption. Solar leases, where consumers pay a fixed monthly fee instead of purchasing the system, have gained popularity in some markets. In developing countries, pay-as-you-go (PAYG) schemes represent one of the few ways to make solar energy more affordable, as they allow households to pay in small installments over time.

4. By contrast to fossil power plants, which tend to be financed via the balance sheet of utilities.

However, in contexts of extreme poverty, such as rural Rwanda, Grimm et al. (2020) show that demand for off-grid solar kits remains well below market potential, even when credit-based PAYG options are available. This underscores the need for additional subsidies to bring down costs and ensure access to solar energy for the poorest households.

3.3.3 Supply Chain Risks

As mentioned in Section 3.2, China nowadays dominates the supply chain in all the manufacturing stages of solar PV (polysilicon, ingots, wafers, cells, and modules). The heavy concentration of solar supply chains in China raises concerns about vulnerability to geopolitical and domestic shocks. First, future energy systems based on solar PV will require critical minerals to meet demand for electrification and batteries (in particular, lithium, copper, and tellurium - a by-product of copper). Yet, extraction and especially processing and refining of these minerals tend to be equally concentrated in China. Supply shocks, e.g., export restrictions but also climate risks affecting mines, could hamper the availability of these minerals, impacting the costs of solar technology (Nijsse et al. 2023). Second, ongoing trade wars, combined with growing scrutiny over labor and environmental standards, risk undermining consumer confidence in solar PV. Allegations of forced labor in China's Xinjiang region and weak environmental regulations highlight the potential reputational risks associated with the sector's cost competitiveness. Third, diversifying the solar supply chain remains difficult when overcapacity from China is inundating the market, making it currently unprofitable for many countries to develop local manufacturing, even despite import tariffs and active manufacturing support policies (IEA 2025e). The modular nature of solar PV means that panels are effectively "plug-and-play," requiring limited local engineering expertise, as the technology can be readily adapted to different contexts without extensive innovation. As a result, cost competitiveness tends to outweigh incentives for developing local manufacturing or building advanced technological capabilities. Most of the Chinese activities in developing countries have remained focused on downstream deployment rather than upstream R&D collaboration with little transfer of technological capabilities (Jackson et al. 2021).

3.3.4 Other Challenges

Finally, vested interests and political resistance remain significant obstacles. Fossil-fuel subsidies and regional employment concerns continue to hinder diffusion. A rapid solar transition may put at risk the jobs of up to 13 million people worldwide working in fossil fuel industries and dependent industries. Equity issues will arise when some communities are severely affected (Nijsse et al. 2023).

At last, environmental and land-use impacts of large solar farms further complicate deployment, especially in densely populated regions where local opposition is expressed through

"Not In My Backyard" movements (Susskind et al. 2022). Most reasons cited for opposing large solar farms are visual impact, financial impacts on property values, and potential impact on wildlife, agriculture, or soil quality. Yet, reductions in property values are only modest for houses located in the vicinity of solar farms, in contrast to wind parks where impacts are more important. Nonetheless, when allocating permits for solar farms, planning decision-makers seem to be particularly responsive to local factors, especially in wealthier areas, leading to inefficiencies in the deployment of solar power (Jarvis 2025).

4 Case Study: Electric Vehicles

Global deployment of electric vehicles has accelerated sharply in the past few years. According to the IEA (IEA 2025c), in 2024, more than 17 million electric cars[5] were sold worldwide, accounting for over one in five new cars. This lifted the global stock to around 58 million vehicles, or about 4.5% of the passenger fleet. Electrification is also beginning to extend beyond passenger cars, with electric trucks approaching 2% of global sales.

The spread of adoption, however, has been highly uneven across countries. Figure 9 illustrates that Norway was the clear early leader: diffusion accelerated already before 2015 and reached close to 90% of new sales after 2020. By contrast, most other countries saw little movement until around 2020, at which point adoption began to rise quickly in Nordic and other European countries as well as in China. In the United States, increases have been more modest but still significant. Japan stands out as a laggard: despite being among the first to introduce EV models, its market share remains comparatively low.

Panel B of Figure 9 highlights another dimension of this heterogeneity by showing the time between the introduction of the first EV model in a country and the year when EVs reached 0.5% of the car stock. Many models were first introduced early (around 2010–2012), but in most countries the technology did not diffuse rapidly—Norway being the exception. By contrast, a number of middle-income countries, such as Thailand and Indonesia, only saw their first models appear toward 2020, but they reached the 0.5% threshold within just a few years. This contrast underscores the diverse trajectories of EV diffusion across income groups and regions.

4.1 How We Got Here: Policy and Market Drivers

The rapid growth of electric vehicles did not occur spontaneously. Diffusion has been shaped by a combination of deliberate policy interventions and evolving market dynamics. On the policy side, governments have deployed purchase subsidies, tax incentives, fuel economy standards, and mandates that created early demand and helped overcome cost disadvantages. On the

5. Including fully battery-electric and plug-in hybrids.

market side, expanding model availability, declining battery costs, and economies of scale encouraged manufacturers to invest and consumers to adopt. Together, these forces explain why EV uptake accelerated after 2020 and why adoption patterns differ so markedly across countries.

4.1.1 Norway: Consistent Incentives and Taxation

Norway illustrates how a stable package of demand-side measures can drive rapid uptake. The government combined high taxes on petrol and diesel cars with generous exemptions for EVs, producing the world's highest market share (IEA 2023a; Nolan 2025). Crucially, this policy mix remained consistent across governments, and the absence of a domestic automaker lobby removed opposition to high fuel taxes.

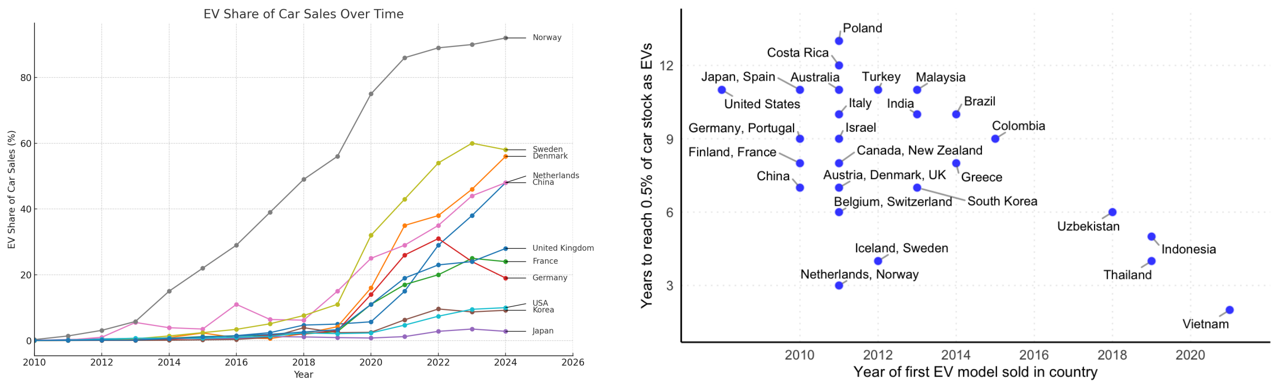
The roll-out focused squarely on consumer adoption rather than building a domestic industry. Long-standing exemptions from value-added tax (VAT) and registration taxes created a strong cost advantage for EVs, reinforced by CO_2-based taxation of internal combustion cars. Complementary measures such as reduced tolls, free or discounted parking, selective bus-lane access, and municipal procurement further boosted demand. Early investments in nationwide fast-charging infrastructure and the country's low-carbon power system reduced range and emissions concerns.

As EV adoption expanded, incentives were gradually phased down—for example, reintroducing VAT above certain price thresholds and normalizing tolls—while avoiding retroactive changes that could undermine credibility. The result is near-universal adoption: by 2024, EVs accounted for more than 90% of new car sales and about one-third of the vehicle stock.

4.1.2 China: Industrial Strategy and Scale

China's electric vehicle expansion is the clearest example of how coordinated industrial policy can transform a sector. Since the early 2010s, national and local governments combined consumer subsidies, purchase-tax exemptions, and public procurement with non-price measures such as license-plate advantages in major cities. At the same time, public investment expanded charging networks, while industrial plans supported battery production through credit, land, and permitting. These instruments were later consolidated into a dual-credit system linking support to vehicle efficiency and range. Subsidies were gradually reduced as volumes expanded and costs fell, but by then scale and learning effects had already driven a decline of more than 90% in EV battery costs between 2010 and 2020 (IEA 2023a).

Industrial ambitions broadened in the mid-2010s with initiatives such as *Made in China 2025* and the 14th Five-Year Plan, which mobilized large financial resources for R&D, promoted vertical integration from raw materials to final products, and fostered consolidation of domestic



(a) Share of EV in Car Sales Over Time

(b) Introduction Year vs. Time to 0.5% of fleet

Figure 9: EV Diffusion

Note: Panel 9a uses data from the IEA's Global EV Data Explorer (https://www.iea.org/data-and-statistics/data-tools/global-ev-data-explorer). Panel 9b is based on the introduction years manually collected and verified by the authors. Panel 9a shows the wide variation in EV market shares, with Norway nearing universal adoption by 2024 while many other markets remained below 20%. Panel 9b highlights how, although most countries introduced EV models around 2010–2012, the time to reach meaningful adoption (0.5% of fleet) differed sharply—from Norway's rapid 2–3 years to more than a decade elsewhere. This heterogeneity illustrates that policy frameworks and market conditions, rather than technology availability alone, are decisive in shaping the speed of EV diffusion. Countries with consistent incentives and supportive policies achieved faster adoption regardless of when they started.

champions (Aglietta et al. 2021; IEA 2024c; Institute for Security and Development Policy 2018; Wübbeke et al. 2016). The result is the world's largest EV market and globally competitive firms such as BYD and CATL at the technology frontier (Aranca 2025; UN Environment and German Development Institute 2017).

On the firm side, Chinese producers now dominate both EVs and batteries. Domestic brands supply over four-fifths of EVs, led by BYD with its large integrated manufacturing base and the Blade Battery platform (IEA 2025d). Battery manufacturing has advanced in parallel. CATL alone accounts for nearly 40% of global demand (SNE Research 2024), and the sector as a whole has expanded rapidly on the back of state-backed finance and intense domestic competition.

These achievements also carry global repercussions. China's production capacity now exceeds domestic demand, fueling intense price competition and prompting concerns of overcapacity. Average transaction prices fell by about 10% in early 2024 as firms fought for market share, while the United States, European Union, and Canada responded with tariffs of up to 100% on Chinese EVs, citing unfair subsidies (Aranca 2025). In parallel, China's dominance in critical mineral refining—over 60% of lithium and more than three-quarters of cobalt, much of it imported from Chile, Australia, and the Democratic Republic of Congo—creates additional dependencies and risks for global supply chains.

4.1.3 California and the United States: Policy Heterogeneity

The United States illustrates both the opportunities and limits of EV diffusion in large and heterogeneous markets. California has been the clear leader, pairing ambitious targets with a consistent policy mix. State-level rebates, often income-tested to support low- and middle-income households, complement the Zero-Emission Vehicle (ZEV) mandate and the Low-Carbon Fuel Standard, which creates additional value for electricity used in transport (IEA 2023a). Measures such as HOV-lane access, utility make-ready investments (i.e., utility-funded upgrades to local electricity infrastructure that facilitate charger installation), and support for public fast-charging further reduced adoption barriers. At the same time, high retail electricity prices and limited access to home charging, especially in multi-unit dwellings, have eroded the operating-cost advantage of EVs (Rapson and Muehlegger 2023).

Longstanding measures such as HOV-lane access, utility make-ready investments (i.e., utility-funded upgrades to local electricity infrastructure that facilitate charger installation), and support for public fast-charging further reduced adoption barriers.

At the federal level, the Inflation Reduction Act (IRA) introduced revised tax credits of up to $7,500 per vehicle, conditioned on domestic assembly and critical-mineral sourcing. Unlike earlier credits, the new design allows for near point-of-sale delivery, increasing visibility and uptake. Evidence indicates high pass-through to consumers, with event studies estimating $1.87 in consumer benefits per federal dollar relative to pre-IRA policy. Still, the cost per additional EV remains high at around $32,000, reflecting large transfers to inframarginal buyers and persistent supply constraints (Allcott et al. 2024).

4.1.4 Contributions of Industrial Policies and Innovation

The global rise of electric vehicles reflects the cumulative effects of sustained policy support and technological learning, rather than aspirational targets alone. Using a new global dataset on industrial policies, Barwick et al. (2024) show that by 2022 nearly half of all automobile-related policy measures explicitly targeted electric vehicle technologies, up from almost none in 2008. What mattered most were concrete instruments—consumer subsidies, tax exemptions, procurement programs, and support for battery and charging infrastructure—rather than headline sales targets. Such measures created early demand, de-risked private investment, and steered firm-level R&D (Barwick et al. 2024).

These policies left clear marks on innovation. Cross-country econometric evidence indicates that a one-standard-deviation increase in cumulative EV-targeted industrial policies is associated with roughly a 4% increase in new EV patent applications. At the firm level, an additional 10% in financial incentives to automakers and battery suppliers led to about a 4% increase in EV-related innovations (Barwick et al. 2024).

At the same time, policy-driven deployment reinforced powerful learning dynamics. Average battery pack costs fell by more than 90% between 2010 and 2020, with structural estimates suggesting a learning rate of about 7.5%—each doubling of cumulative production lowered costs by that amount. Crucially, consumer subsidies amplified this process: by accelerating adoption, they induced faster cost declines and generated spillovers across countries (Barwick et al. 2025).

Market composition further shaped diffusion. The number of EV models worldwide rose quickly and reached 500 in 2022, broadening consumer choice (IEA 2023a). But preferences diverged by region: North American and European consumers favored larger vehicles with bigger battery packs, while Chinese buyers adopted smaller, lower-cost models. Chinese firms such as BYD, NIO, and Geely have since leveraged domestic scale to expand abroad (Aranca 2025).

4.2 The Road Ahead: Prospects and Barriers for Broader Diffusion

Having traced how electric vehicles reached their current scale, the question now is how far and how fast diffusion can continue. Projections suggest continued growth, with EVs expected to account for an increasing share of global car sales over the next decade. The decisive issue is not whether the technology works, but whether the remaining obstacles can be addressed in ways that sustain broad-based and equitable adoption.

Four sets of barriers stand out. First, cost and performance gaps remain: battery prices have fallen steeply but are still critical to competitiveness, and mineral supply chains pose risks to further declines. Second, infrastructure is uneven, with major disparities in charging availability and in the ability of electricity grids to accommodate growing demand. Third, financing and equity challenges persist, as higher upfront costs and limited access to credit slow uptake among lower-income households. Finally, political, cultural, and industrial factors—from incumbent resistance to polarized consumer attitudes—continue to shape markets. The following subsections examine each of these barriers in turn and outline strategies to overcome them.

4.2.1 Cost and Performance

Even after years of rapid cost declines, electric vehicles remain more expensive than conventional cars in most markets. In 2024, battery electric cars on average cost around 20% more than comparable internal-combustion models in Germany and nearly 30% more in the United States. By contrast, two-thirds of EVs sold in China were already cheaper than their gasoline equivalents (IEA 2025c).

Figure 10 compares the levelized cost of driving (LCOD) across vehicle and fuel pathways.

The LCOD is the average cost per mile over a vehicle's lifetime, combining purchase price, energy costs, and maintenance. Competitiveness varies strongly by battery size and range. Smaller EVs are already cheaper to operate than gasoline or hybrid cars, while 400-mile models remain more expensive. NREL projects that rapid cost declines will bring even these large EVs to parity with internal combustion vehicles within the next few years. Fuel cell vehicles remain higher-cost options overall, though they may retain a role in heavy-duty segments (IEA 2023a).

For consumers, range is the critical performance factor. Longer range offers confidence for daily driving and long trips but requires larger batteries, which raise cost and weight. This trade-off explains why short-range EVs are already competitive while long-range models still carry a price premium—albeit one expected to narrow quickly. Range is also tied to charging availability, which is addressed in the next subsection. In practice, longer recharge times and gaps in charging networks continue to sustain "range anxiety," slowing adoption in many markets (NREL 2024; Rapson and Muehlegger 2023).

Finally, upstream supply chains pose growing risks to further cost declines. China refines more than 60% of global lithium and over three quarters of cobalt, relying heavily on ore imports from Chile, Australia, and the Democratic Republic of Congo (IEA 2025b). This concentration exposes EV production to geopolitical, environmental, and market shocks (Aranca 2025). Mineral markets have already shown how volatility can erase cost gains: in March 2022 nickel prices surged more than fourfold within three trading days, and cathode inputs have risen from under 5% of battery pack costs around 2015 to about 20%, temporarily reversing the decade-long fall in battery prices (Kim 2022). Average pack prices fell again in 2024—by roughly 30% in China and 10–15% in Europe and the United States—but volatility in lithium, nickel, and cobalt and persistent supply-chain bottlenecks could stall further reductions (IEA 2025b). Diversifying sources, scaling recycling, and expanding lower-critical-mineral chemistries such as lithium-iron-phosphate and sodium-ion remain the main strategies to mitigate these risks.

4.2.2 Infrastructure

Charging infrastructure is a critical bottleneck for EV diffusion. As shown in Figure 11, the global stock of public charging points expanded from under 1 million in 2018 to more than 5 million in 2024. Most of this growth has been in slow chargers, though fast and ultra-fast options are increasing rapidly. China accounts for the majority of worldwide deployment, underscoring its leadership in infrastructure build-out. In countries such as the United States and the United Kingdom, growth has not kept pace with the expanding vehicle fleet. Ultra-fast chargers (>150 kW) are becoming more common, growing by about 50% in 2024, but they still account for only around 10% of public fast chargers worldwide. According to IEA estimates, public charging capacity would need to expand nearly ninefold by 2030 to accommodate EV sales consistent with current policy targets (IEA 2025c).

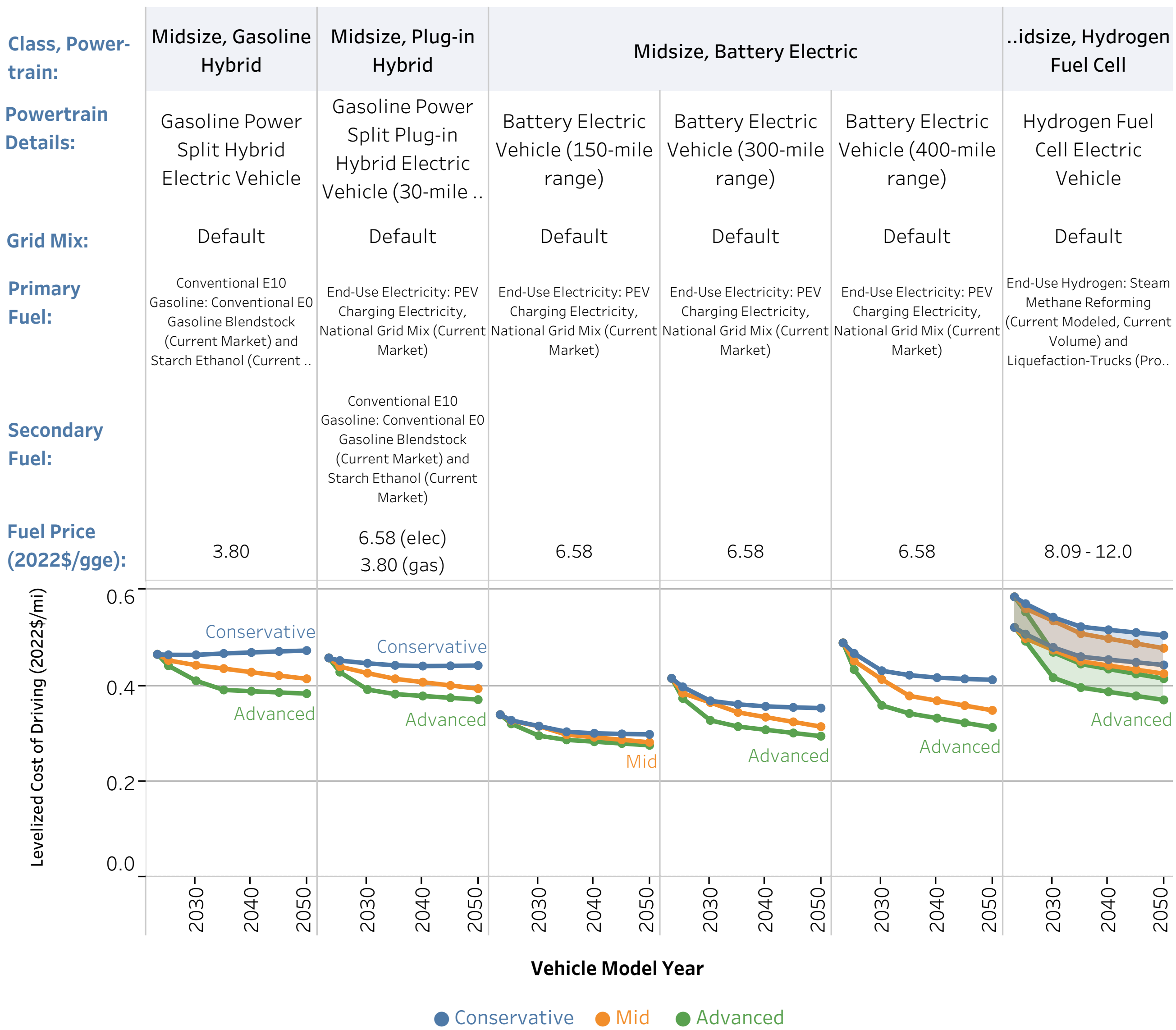


Figure 10: Levelized Cost of Driving (LCOD) Analysis: Technology Pathways for Transportation Decarbonization

Note: Reproduced from the National Renewable Energy Laboratory's Annual Technology Baseline for Transportation (NREL 2024). The figure reports the levelized cost of driving across different vehicle technologies and fuel pathways, including battery electric vehicles, fuel cell electric vehicles, alternative fuels, and conventional internal combustion engine vehicles. By standardizing costs per mile driven, the comparison illustrates the relative economic competitiveness of decarbonization options in the transport sector.

Figure 12 places this expansion in context by relating vehicle stocks to the number of charging points for different countries. Since 2016, Norway has dramatically reduced the EV-to-charger ratio from around 25 to nearly 1, while the U.S. and U.K. remain above 30 EVs per point in 2024. Cross-country comparison shows that markets with denser charging networks also have higher EV shares, highlighting the central role of infrastructure in EV adoption. Norway's success reflects not only generous incentives but also sustained investment in public charging.

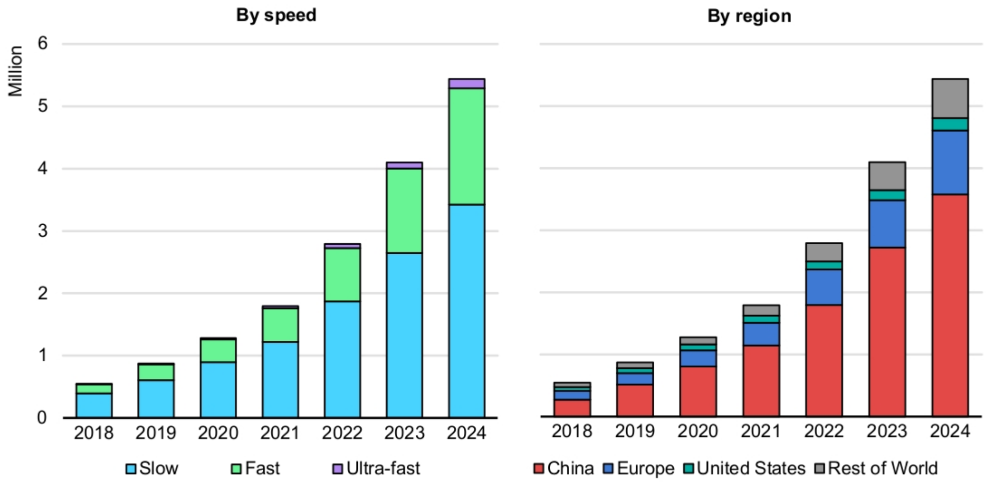


Figure 11: Global Stock of Public Charging Points, 2018-2024

Note: Reproduced from IEA (2025d, p. 100). This figure illustrates the rapid expansion of public charging infrastructure, with global charging points growing from under 1 million in 2018 to over 5 million by 2024. The left panel shows the dominance of slow charging infrastructure, though fast and ultra-fast charging segments are growing rapidly. The right panel reveals China's commanding position in charging infrastructure deployment, accounting for the majority of global charging points. This infrastructure expansion has been critical in addressing range anxiety and supporting EV adoption, particularly in markets with high EV penetration rates. The speed categorization (slow $\leq$22 kW, fast 22-150 kW, ultra-fast $\geq$150 kW) reflects different use cases, with slow chargers typically for home and workplace charging, while fast and ultra-fast chargers enable long-distance travel.

Access to private charging remains uneven. Many urban households, particularly those in multi-unit dwellings, lack the option to install home charging. Workplace access is similarly limited. Expanding fast-charging corridors along highways and incentivizing installation in apartment blocks and workplaces can alleviate these barriers.

The rise of EVs also affects electricity systems. Higher peak demand will require upgrades in grid capacity and management. Smart charging and vehicle-to-grid (V2G) technologies offer partial solutions, but their effectiveness depends on supportive regulation, market design, and technical standards. Utilities will need to engage in proactive planning to maintain reliability as EV penetration rises (IEA 2024c).

Conversely, the performance of electricity systems affects the economics of EVs. Even when subsidies are available, fuel-cost savings vary sharply by region. High electricity tariffs in some areas, such as California, erode the advantage of lower per-mile costs despite elevated gasoline prices (Rapson and Muehlegger 2023). Financing mechanisms will need to account for these differences to ensure that operating cost benefits are widely realized.

Finally, new business models may also complement conventional networks. In China, for instance, NIO had deployed more than 2,000 battery-swapping stations by 2024, offering a rapid alternative to plug-in charging (NIO 2023). Early experiments with wireless and dynamic on-road charging are underway in several countries, though these remain at a pilot stage (Alorifi et al. 2025).

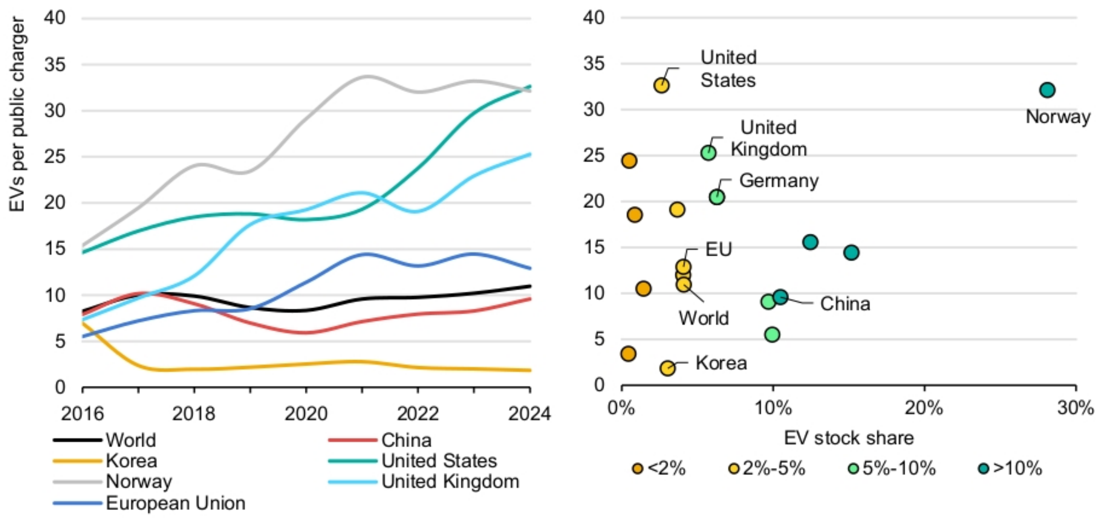


Figure 12: Electric Vehicles per Public Charging Point, 2016-2024

Note: Reproduced from IEA (2025d, p. 101). The left panel shows the evolution of the ratio of electric light-duty vehicles to public charging points across major markets from 2016-2024. Notable patterns include Norway's dramatic improvement in charging infrastructure density (ratio declining from around 25 to about 1), while the United States and the United Kingdom show concerning trends with ratios above 30 EVs per charging point by 2024. The right panel correlates this infrastructure adequacy with EV market penetration in 2024, revealing that markets with lower EV-to-charger ratios (better infrastructure density) generally achieve higher EV market shares. This relationship underscores the critical importance of charging infrastructure in enabling EV adoption, with Norway's success partly attributable to its comprehensive charging network alongside strong policy support.

4.2.3 Financing and Equity

Affordability remains one of the most persistent barriers to broad-based EV adoption. While lifetime costs are often favorable, the purchase price of battery-electric cars in Europe and the United States remains 10–50% higher than for comparable internal-combustion models, dampening uptake outside high-income households (IEA 2025d). Even when the total cost of ownership turns positive within a few years, consumers must still finance the higher upfront cost, and access to credit is not evenly distributed. Loan rates and availability are typically less favorable for subprime borrowers, creating another barrier for lower-income groups. Innovative instruments such as zero-interest loans, on-bill financing tied to utility accounts, or co-investment by public green banks could help overcome these gaps by reducing capital costs and risk.

Distributional concerns are also evident in existing subsidy schemes. In the United States, more than 80% of EV tax credits accrued to the top income quintile, while the bottom three quintiles together received less than 3% (Borenstein and Davis 2025). Program design matters: California has capped rebates by household income, and a 2024 reform allowed the federal tax credit to be delivered as a point-of-sale rebate rather than retrospectively, improving liquidity for buyers. Leasing has further broadened access, since leased vehicles are exempt from some domestic-content restrictions, and by 2024 nearly half of U.S. EVs were leased, up from less than a quarter three years earlier (IEA 2025d). Used EV markets provide another channel: in early 2024, more than half of used EVs in the United States were priced below USD 30,000, eligible for a USD 4,000 federal credit, while several EU countries subsidize second-hand purchases (IEA 2024c). These secondary and leasing markets can lower entry costs and diffuse benefits beyond high-income early adopters.

4.2.4 Incumbents, Politics, and Trade

Beyond cost and infrastructure, political and industrial dynamics also shape the diffusion of electric vehicles. In the United States, adoption remains highly polarized: about half of all new EVs registered between 2012 and 2023 were concentrated in the 10% most Democratic counties, and one-third in the top 5% (Davis et al. 2025). This correlation persists even after controlling for income, population density, and gasoline prices, underscoring the role of ideological preferences as a barrier to widespread diffusion.

Industrial policy and trade tensions add further complexity. The Inflation Reduction Act ties federal EV tax credits to domestic assembly and critical-mineral sourcing, generating only about $1.02 of benefit per dollar spent compared with a no-credit scenario (Allcott et al. 2024) and provoking objections from trading partners (Shepardson 2022). Meanwhile, the United States, European Union, and Canada have imposed tariffs on Chinese EVs—some as high as 100%—citing unfair subsidies and geopolitical concerns. Such measures may slow global diffusion by fragmenting markets and raising costs (Aranca 2025). Incumbent automakers also influence outcomes. Retooling factories and supply chains for EV production is costly, and firms may resist or lobby against stringent zero-emission mandates (Shepardson 2019).

Finally, global overcapacity is beginning to distort markets. Aggressive expansion in China has pushed production beyond domestic demand, triggering intense price competition. In early 2024, average EV transaction prices fell by about 10% as Tesla and BYD cut prices to protect market share. While this benefits consumers in the short run, prolonged price wars could erode profitability and discourage investment in further innovation (Aranca 2025).

5 Case Study: Hydrogen

Hydrogen is a versatile energy carrier and industrial feedstock with potential applications across several hard-to-abate sectors. It can replace coal in steel-making, provide high-temperature heat for cement and chemicals, act as a feedstock in refining and fertilizer production, and serve as a zero-carbon fuel for long-distance transport such as shipping, aviation, and heavy trucks. It can also offer seasonal storage for power systems with large shares of variable renewables, linking electricity to heat, industry, and transport. These multiple end-uses explain why clean hydrogen is often described as a linchpin of deep decarbonization strategies.

Yet adoption remains nascent. Today, more than 99% of global hydrogen is produced from unabated fossil fuels ("grey" hydrogen), while low-carbon "blue" and renewable "green" pathways are still at demonstration or early-commercialization scale (IEA 2024d). This limited diffusion reflects a persistent green premium—the higher production cost of low-carbon hydrogen relative to grey hydrogen—which remains large in the absence of strong carbon pricing or subsidies. This cost gap, compounded by scarce demand-side incentives, inadequate transport and storage infrastructure, and regulatory uncertainty, has slowed diffusion. The following sections first assess how far each hydrogen production pathway has diffused (or not), then unpack the interlocking economic, policy, and coordination barriers that hinder wider adoption. This sets the stage for a deeper exploration of regional "hydrogen hubs" as a deliberate policy response to catalyze investment, pool demand, and accelerate technological learning.

Table 4: Comparative Overview of Hydrogen Production Pathways

Pathway (Color)	**Primary Technology**	**Feedstock**	**Key Byproducts**	**CO_2 Intensity (kg/kg)**	**LCOH Range (USD/kg)**	**Technology Readiness**	**Key Advantages**	**Key Disadvantages**
Grey	Steam Methane Reforming (SMR)	Natural gas, steam	Carbon dioxide (CO_2)	$\sim$10	1.50–2.50	Mature	Lowest cost, established technology	High carbon emissions
Blue	SMR + Carbon Capture, Utilization & Storage	Natural gas, steam	Captured CO_2	3.5–4.0	2.00–4.70	Near-commercial	Lower emissions than grey, uses existing infrastructure	CCS cost & complexity, capture inefficiency, upstream methane leaks
Green (Alkaline)	Alkaline Water Electrolysis (AWE)	Water, renewable electricity	Oxygen (O_2)	$\sim$0	3.50–12.00	Mature	Zero emissions, mature technology	Higher cost, less flexible than PEM
Green (PEM)	Proton Exchange Membrane Electrolysis	Water, renewable electricity	Oxygen (O_2)	$\sim$0	3.50–12.00	Commercial	Zero emissions, rapid response to variable renewables	Higher cost, critical mineral dependency (iridium)
Turquoise	Methane Pyrolysis	Natural gas	Solid carbon	Variable (low)	Pre-commercial	Demonstration	Low emissions, valuable solid carbon byproduct	Technology not yet proven at scale
White	Geological hydrogen extraction	Subsurface accumulations (natural hydrogen)	Co-produced gases (N_2, He, CH_4)	Not yet established	Not yet established	Exploration/pilot	Potentially very low emissions; no reforming or electrolysis required	Resource uncertainty; unknown reservoir extent and recharge; limited field data; regulatory gaps; co-produced gas handling

Note: Authors' compilation based on Acar and Dincer (2025), BloombergNEF (2023), Hydrogen Council and McKinsey & Company (2025), Iberdrola (2024), IEA (2024d), IRENA (2024a), and National Grid (2023). The table compares hydrogen production pathways by technology maturity, cost, and emissions intensity. Grey hydrogen dominates current production due to low costs ($1.50–2.50/kg) but generates high emissions (10 kg CO_2/kg). Clean alternatives like green hydrogen face significant cost premiums ($3.50–12.00/kg) that limit commercial viability, while emerging pathways like turquoise and white hydrogen remain at early demonstration stages. The stark cost differentials highlight why over 95% of global hydrogen production still relies on unabated fossil fuels despite growing policy support for clean alternatives.

5.1 Status of Diffusion by Hydrogen Colour

Hydrogen is often described in terms of a "rainbow" of production pathways—grey, blue, green, turquoise, pink/purple, and white. Each differs in feedstock, process, cost, and lifecycle emissions. Table 4 summarizes these pathways and their advantages and disadvantages.

Today, production remains dominated by unabated fossil fuels. More than 99% of the supply is grey hydrogen from steam methane reforming and coal gasification. This route is cheap at about \$1.0–3.0/kg but carbon-intensive, releasing 10–19 tCO_2 per tonne of hydrogen and driving over 900 Mt of CO_2 emissions in 2022 (IEA 2023b, 2024d).

Blue hydrogen, which adds carbon capture and storage (CCUS) to fossil-based production routes, remains at an early stage of deployment. Depending on configuration, technology readiness spans roughly TRL 4–6. Emissions can be reduced to 1–4 kg CO_2e/kg H_2 if capture rates are high and upstream methane leakage is controlled. Project announcements suggest up to 10 Mt of capacity by 2030, yet only 0.6 Mt has reached final investment decision (IEA 2023b). With costs of \$1.5–3.6/kg still exceeding those of grey hydrogen, deployment also depends on access to policy support. However, eligibility for instruments such as the U.S. 45V tax credit requires lifecycle emissions below 4 kg CO_2e/kg H_2, a threshold that many blue hydrogen configurations may struggle to meet without very high capture rates and tightly controlled upstream methane leakage (IEA 2023b; Navarrete 2025).

Green hydrogen, produced via electrolysis powered by low-emissions electricity, is technically mature for alkaline and PEM systems (TRL 9) but still at low volumes and high cost. Emerging variants such as wastewater (TRL 4) and seawater electrolysis (TRL 5) remain at the prototype and demonstration stage. Global electrolyzer capacity doubled in 2023 to 1.2 GW, led by China, with announced project pipelines exceeding 500 GW by 2030. China accounts for more than 40% of projects reaching final investment decision and hosts about 60% of global electrolyzer manufacturing capacity (IEA 2024d). Yet only around 20 GW has secured financing, and current costs of \$3–11/kg constrain uptake.

Other hydrogen pathways remain experimental. Turquoise hydrogen from methane pyrolysis, nuclear-based electrolysis (pink and purple), and naturally occurring white hydrogen are confined to pilot projects or early exploration, though interest in geological hydrogen is growing (IEA 2023b).

Demand remains narrowly concentrated, reflecting supply constraints. Refining and ammonia still absorb more than four-fifths of consumption, with low-emissions hydrogen providing under 1% of refinery demand (IEA 2023b). Transport use is marginal: by mid-2024 the global fuel-cell vehicle fleet reached about 70,000, concentrated in Chinese trucks and Korean passenger cars, yet transport remains under 0.1% of demand (IEA 2024d). Aviation and shipping are at pilot scale, though orders for methanol- and ammonia-fueled ships show momentum (IEA 2024d). Power generation use is below 500 MW globally, mostly co-firing in Asia. Demonstrations in Japan and Korea prove turbine feasibility and seasonal storage potential, but commercial scale-up is limited (IEA 2024d).

5.2 Barriers to Diffusion

Clean hydrogen has attracted growing political attention, yet actual deployment remains limited. Progress is held back by a set of interlocking barriers that affect both supply and demand. This section briefly reviews the most important obstacles before turning to how governments are attempting to address them through the creation of hydrogen hubs.

Cost is the primary constraint on clean hydrogen diffusion. Renewable and other low-carbon hydrogen remain several times more expensive than grey hydrogen, creating a persistent "green premium." The gap is driven by three main factors: (i) electricity prices and electrolyzer utilization, (ii) capital intensity and stack durability, and (iii) midstream costs for compression, storage, and transport. Electricity is the dominant cost component, but recent evidence also points to higher-than-expected electrolyzer costs. While falling renewable power costs improve the long-term outlook, the post-2022 decline in natural gas prices has reduced grey and blue hydrogen costs, widening the gap in the near term. Overcoming this premium will require more than subsidies alone. It calls for sustained R&D to improve efficiency, durability, and catalyst design; demonstration programs to bring emerging pathways such as methane pyrolysis and nuclear electrolysis to market; and scale-up of manufacturing and system integration to capture learning effects and economies of scale.

Infrastructure is another binding constraint. Dedicated pipelines, storage facilities, and port infrastructure are scarce. Of the 56 countries with hydrogen strategies, 43 identify infrastructure as the most critical barrier (Iacob et al. 2025). Limited midstream capacity constrains scale-up, and the lack of common technical standards hampers cross-border trade. CO_2 transport and storage could lower blue hydrogen costs, but such investments are proceeding slowly (IEA 2024d). Options to move hydrogen indirectly—as ammonia, methanol, or liquid organic carriers—require large-scale facilities and raise environmental and safety concerns (IRENA 2024a).

On the demand side, market creation has lagged. For much of the past decade, policy support has emphasized subsidizing supply rather than guaranteeing off-take. Developers consistently cite the absence of demand support as a top barrier: without long-term visibility on buyers, projects struggle to reach financial close (IEA 2022a). Globally, of the 34 Mt of potential clean hydrogen demand that could emerge by 2030, only about 8 Mt has a viable business case under current policies (Hydrogen Council and McKinsey & Company 2025). A survey of 56 national hydrogen road-maps finds that, after high capital costs, demand uncertainty is the most frequently cited obstacle (Iacob et al. 2025).

Regulatory and institutional factors add to the difficulty. Permitting, safety standards, and eligibility rules for incentives such as tax credits remain unclear in many jurisdictions (IEA 2024d). U.S. stakeholders rank regulatory uncertainty as the most important barrier to market formation. Internationally, the absence of a harmonized system for certifying hydrogen's carbon intensity risks market fragmentation. The IRA has provided welcome certainty for hydrogen by finalizing the 45V tax credit (U.S. Department of the Treasury 2025). Rules issued in 2025 clarify emissions accounting, eligible power sources, and credit values of up to $3/kg; projects that begin construction before 2028 can secure ten years of support, giving investors a predictable horizon (U.S. Department of Energy 2025a). While questions remain over DOE hub funding, 45V guidance removes major regulatory ambiguity and offers a stable basis for development (Reuters 2025).

A final barrier is the failure to coordinate supply and demand. Producers hesitate to invest in large-scale facilities without secure off-take agreements, potential users hold back without a reliable and affordable supply, and infrastructure developers delay projects without guaranteed volumes. This mutual waiting game stalls investment and slows diffusion. Breaking the deadlock requires mechanisms that align incentives across the value chain: standardized long-term contracts, demand aggregation and anchor procurement, open-access pipelines and storage, and public risk-sharing through price guarantees or concessional finance. Governments are pursuing hydrogen hubs precisely to address these coordination failures by co-locating producers, consumers, and infrastructure, thereby pooling risk, synchronizing investment, and enabling scale-up.

5.3 Hydrogen Hubs as a Strategic Response

Hydrogen hubs have emerged as a prominent policy idea, though more in theory than in demonstrated practice. The concept is that co-locating production facilities, midstream infrastructure, and end-users within a single region could accelerate deployment. By synchronizing investment timelines and sharing assets, hubs are expected to help projects move from pilots to commercial scale. In this framing, the hub serves as a coordination device—reducing first-mover risk and providing a setting for technological learning.

The potential benefits are usually described in four channels. First, hubs might coordinate producers, infrastructure developers, and off-takers on capacity, timing, and technical standards. Second, they could lower costs through shared pipelines, storage, terminals, and, where relevant, CO_2 transport. Third, they aim to generate credible demand signals by securing anchor off-takers and diversifying applications, thereby improving revenue certainty. Fourth, large demonstrations within hubs could provide operational data, advance safety and certification practices, and inform regulatory frameworks.

In principle, these channels map onto well-known market failures. Coordination failures could be eased as investment across producers, infrastructure operators, and end-users is synchronized; some programs explicitly require diversity of applications and geographic spread to avoid the chicken-and-egg dilemma. Learning externalities might be addressed as first movers generate and disseminate operational know-how and sustainability frameworks. Financing barriers could be mitigated through public co-funding and shared infrastructure that lowers the green premium and crowds in private capital. Finally, hubs are sometimes expected to deliver broader social and economic benefits, with value-chain studies pointing to potential gains in employment, industrial diversification, and social inclusion—especially if developing countries are integrated into emerging supply chains.

Whether hubs will deliver on these promises remains uncertain. They could provide an effective way to overcome coordination failures, or they could become costly experiments with limited spillovers. Outcomes will hinge on design, implementation, and local context.

United States. In 2023 the United States launched the Regional Clean Hydrogen Hubs program, providing up to $7 billion in federal funding to establish a network of large-scale hydrogen projects across the country (U.S. Department of Energy 2025b). Table 5 summarizes the initiative. The U.S. portfolio was deliberately diversified: seven hubs were selected and together they cover a mix of production pathways—renewable-based "green" hydrogen, natural gas with carbon capture ("blue"), or nuclear-based ("pink")—and are linked to priority end-uses such as heavy-duty transport, fertilizer production, refining, steel-making, and power generation.

The hubs are intended to demonstrate diverse technologies, create early demand in hard-to-abate sectors, and build the infrastructure needed for transport, storage, and use. By concentrating activity in regional clusters, the program aims to reduce costs, attract private investment, and accelerate learning. Estimates suggest the hubs could generate hundreds of thousands of jobs while catalyzing tens of billions of dollars in additional investment. The initiative marks the first coordinated federal effort to build a nationwide hydrogen ecosystem and to position the United States as a leader in clean hydrogen production and use (U.S. Department of Energy 2025b).

European Union. The EU has positioned "Hydrogen Valleys" as a flagship instrument to accelerate deployment by clustering production, storage, distribution, and end-use across regions or cross-border areas. Supported through the Clean Hydrogen Partnership, Important Projects of Common European Interest (IPCEIs), and cohesion funds, these initiatives integrate multiple sectors—industry, mobility, and power—and create shared infrastructure and standards. Under the REPowerEU plan, financial support was significantly scaled up, with the explicit goal of doubling the number of operational Hydrogen Valleys by 2025. In doing so, the EU seeks not only to de-risk early investments but also to foster replicable models that can be transferred across Member States and to partner countries (Clean Hydrogen Joint Undertaking 2024; European Commission 2022).

Emerging Market Regions (Asia–Pacific, MENA, Latin America). In many emerging regions, hydrogen hubs are being designed first and foremost with export markets and energy-security objectives in mind, capitalizing on abundant renewable resources and proximity to major shipping routes. In the Middle East, Oman, Saudi Arabia, and the United Arab Emirates are developing large-scale projects that convert renewable hydrogen into ammonia for long-distance trade, while also positioning themselves as future suppliers to Europe and Asia (IEA 2021a). In Latin America, Chile has established hydrogen clusters in Patagonia and Antofagasta and is developing port-linked hubs such as Pecém and Porto do Açu in Brazil, combining export ambitions with industrial decarbonization goals (IEA 2024d). In the Asia–Pacific, Australia has designated multiple hydrogen hubs—including Pilbara, Gladstone, and Bell Bay—that integrate large wind and solar resources with ammonia and synthetic-fuel production, primarily targeting overseas markets but also laying the groundwork for domestic industrial use (IEA 2021a).

Conclusion. The central question is whether hubs will prove effective in addressing the barriers outlined above. In principle, they are designed to reduce production costs through shared infrastructure, create credible demand signals via anchor off-takers, accelerate the build-out of pipelines and storage, and provide greater regulatory clarity through demonstration and certification. Yet at this stage, the evidence base is thin. Most hubs are still at the announcement or early implementation stage, and it is too soon to know whether these mechanisms will work in practice or at scale. Critical perspectives also point to risks. Heavy reliance on blue hydrogen could prolong fossil fuel dependence, and complex eligibility criteria for subsidies such as tax credits may raise transaction costs and slow investment. There are also concerns about distributional outcomes: whether local communities will see meaningful benefits, and whether hubs in resource-rich developing countries will capture value or mainly serve export markets.

These uncertainties highlight the need for systematic evaluation as hubs move from concept to operation. Careful design will be essential: engaging communities, ensuring transparent emissions accounting, and aligning projects with long-term decarbonization goals. Comparative evidence across regions will be particularly valuable for assessing whether hubs deliver on their promise or simply repackage existing barriers in a new form.

Table 5: Overview of U.S. Regional Clean Hydrogen Hubs

Hub Name (Acronym)	Key States	Federal Funding (Up to)	Primary Production Pathways	Key Target End-Uses
Appalachian (ARCH2)	WV, OH, PA	$925 Million	Blue (Natural Gas + CCS)	Industry, Power Generation
California (ARCHES)	CA	$1.2 Billion	Green (Renewables, Biomass)	Heavy-Duty Transport, Ports, Industry
Gulf Coast (HyVelocity)	TX, LA	$1.2 Billion	Blue (Natural Gas + CCS), Green (Renewables)	Industry (Refining, Petrochemicals), Marine Fuel
Heartland (HH2H)	ND, SD, MN	$925 Million	Blue (Natural Gas + CCS), Green (Renewables)	Agriculture (Fertilizer), Power Generation
Mid-Atlantic (MACH2)	PA, DE, NJ	$750 Million	Green (Renewables), Pink (Nuclear), Orange (Biogas)	Industry, Heavy-Duty Transport
Midwest (MachH2)	IL, IN, MI	$1 Billion	Green (Renewables), Pink (Nuclear), Blue (Natural Gas + CCS)	Industry (Steel, Glass), Power, Transport
Pacific Northwest (PNWH2)	WA, OR, MT	$1 Billion	Green (Hydropower)	Heavy-Duty Transport, Agriculture

Note: Source: State participation and funding details from the U.S. Department of Energy and the U.S. Hydrogen Alliance (U.S. Department of Energy 2025b; US Hydrogen Alliance 2023), job creation estimates from the Clean Air Task Force (Clean Air Task Force 2025). The hubs are designed to accelerate commercial-scale deployment of clean hydrogen, decarbonize heavy industry and transportation, and deliver significant economic benefits through good-paying jobs and improved energy security.

6 Conclusion

This paper reviewed how clean technologies have spread, why adoption has been uneven, and what this implies for the next phase of diffusion. Four stylized facts stand out. Deployment has been rapid in power and light transport, but remains limited in hard-to-abate sectors. China has become the central actor in both innovation and deployment. Modularity has been decisive in driving cost declines and scaling. Adoption outside high-income economies has begun only recently, though the potential is large.

The case studies of solar, electric vehicles, and hydrogen illustrate the common mechanisms. Early R&D and targeted demand-pull policies in lead markets initiated diffusion. China's industrial strategy then scaled production, delivering steep cost reductions. Complementary inputs—grids, charging infrastructure, finance, and skills—were critical to sustain adoption. Political economy headwinds slowed but did not prevent progress where credible policy frameworks were in place.

Looking ahead, we also emphasize the pressing challenges that will shape the next phase of clean technology diffusion. Beyond the urgent task of accelerating adoption across developing countries, several risks are emerging. Heightened vulnerabilities in the supply of critical minerals raise new concerns about costs and affordability, while uncertainty around the transformative — and potentially disruptive — impacts of artificial intelligence introduces both opportunities and risks for clean innovation and deployment. At the same time, geopolitical tensions are redefining the global landscape and could redirect the trajectory of clean technology diffusion in unforeseen ways.

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