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24-5 Powering the clean energy innovation system

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ABSTRACT

This paper focuses on the innovation angle in green industrial policy design. The innovation system, delivering new and improved technology solutions for the clean energy transition, can be the cornerstone of a successful transition that reconciles decarbonization, competitive value creation and jobs, and strategic autonomy on a global scale. This, however, requires the innovation system to be properly directed. This paper first lays out the principles of a policy design that properly steers the innovation system. It then documents the current performance on clean energy innovations and clean energy policymaking globally, with focus on the Inflation Reduction Act (IRA) and the Net-Zero Industry Act (NZIA) trends in clean tech policymaking in the United States and European Union, respectively. The evidence shows that the innovation system is not at full potential, and there is still ample room to improve the current clean energy policymaking and international policy coordination.

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INTRODUCTION

Shifting economies from fossil fuel–based to green energy represents one of the most significant socioeconomic transformations in history. The green transformation brings socioeconomic opportunities and challenges. While phasing out fossil fuel–based products, activities, and jobs, new green products, activities, and jobs are being created. Clean energy is key to fostering a deep decarbonization process. The International Energy Agency (IEA) estimates that if countries worldwide fully implement their announced energy and climate 2030 pledges, the global market for key mass-manufactured clean energy technologies will have tripled in size. Clean energy manufacturing jobs would more than double from 6 million today to nearly 14 million by 2030 (IEA 2023a). Recognizing the opportunities and challenges of the transition from dirty to clean energy, all major economies have ventured into clean energy industrial policy and are competing for their share of the global economic opportunities from clean energy, reconciling their decarbonization and socioeconomic transformation objectives.[1]

The COVID-19 outbreak dramatically exposed economies to their vulnerabilities, introducing a call for policies ensuring the resilience and security of supply of inputs considered strategic. The war in Ukraine and the “weaponization” of Russian gas and Chinese minerals exacerbated concerns about supply security, particularly for energy, especially in Europe.[2] All major economies are now combining their climate and clean energy industrial policies with efforts to ensure the security of energy supply and strategic autonomy in clean energy value chains. In the absence of global policy coordination, this sets in motion a train of mutually reinforcing reactive pressures to further the strategic autonomy angle in countries’ clean energy industrial policies.[3]

Countries are still figuring out how to reconcile the multidimensional objectives of a green industrial policy, particularly when these dimensions counteract each other. What are the best ways to combine decarbonization with economic growth, jobs, and world competitiveness, and all this with resilience and security of supply? What is the socioeconomically best way to achieve decarbonization and resilience? How and how far to go in moving toward supply resilience and security , and what are the costs in moving away from decarbonization and economic efficiency? How far to move away from a horizontal policy approach shaping framework conditions to ensure open

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[1] For example, in March 2020 the newly established European Commission under Ursula von der Leyen, with climate goals firmly anchored in its Green Deal and Fit for 55 package, presented its New Industrial Strategy for Europe, centered around the twinning of its green and digital transitions. China’s latest Five-Year-Plan (2021–25) has clean energy high on its radar. And the United States, with its Inflation Reduction Act (IRA) adopted in August 2022, introduced a massive package of support for clean tech technology deployment.

[2] The European Union in May 2022 launched its REPowerEU plan to transition faster to clean energy, diversify its energy supplies, and save energy to improve its “strategic autonomy” in energy.

[3] The US IRA is a clear articulation of this, particularly its local content requirement stipulations, which outlined Europe’s response in March 2023 with its Net-Zero Industry Act (NZIA). While the concept of “open strategic autonomy” was already presented in the 2020 New Industrial Strategy for Europe, this had mostly China as a “systemic rival” on the radar (EC 2020). The NZIA takes its “strategic autonomy” in clean energy a few steps further, reacting to the deepened geopolitical risks.

markets, such as a strong competition policy and open trade? How far to go toward a vertical approach to picking technologies and projects deemed strategic to secure supply?

This paper focuses on the innovation angle in green industrial policy design.[4] I argue that the innovation system must be at full capacity to deliver new and improved technology solutions for the clean energy transition. In the context of broad, urgent, paradigmatic changes for economies, innovations can be the cornerstone of a successful transition that reconciles decarbonization, competitive value creation and jobs, and strategic autonomy on a global scale. This, however, requires the innovation system to be properly directed. This paper first lays out the principles of a policy design that properly steers the innovation system. I then document the current performance on clean energy innovations and clean energy policymaking globally and zoom in on the recent Inflation Reduction Act (IRA) and Net-Zero Industry Act (NZIA) trends in clean tech policymaking in the United States and European Union, respectively. The paper concludes with an assessment of current clean energy innovation policymaking and recommendations.

INNOVATIONS FOR CLEAN ENERGY

This section lays out the principles for an industrial policy that has innovation as its cornerstone to deliver new and improved technologies for a successful clean energy transition that reconciles decarbonization, competitive value creation and jobs, and security of supply.

Fallacies about Innovations for Clean Energy

Before making the case for innovation as a cornerstone of clean energy industrial policy, three fallacies need to be put in perspective. The first comes from the degrowth proponents, who claim that, even with new solutions, economies will overshoot ecological limits, perpetuating unsustainable lifestyles and social injustice. They reject “the convenience of technological optimism” (e.g., Boucher et al. 2014) and instead focus on a cultural shift that changes consumption patterns rather than finding cleaner means of production. The fallacy in this perspective is seeing both options as alternative pathways, as complements. Behavioral change will be needed to shape the successful uptake of new clean solutions while at the same time new innovative solutions can help make behavioral changes easier, less costly, and more likely to be adopted.

A second fallacy often heard is that the necessary technologies already exist and it’s not necessary to invest in further developing technologies and searching for new ones. The IEA (2020a) models what it would take to reduce emissions to meet a net zero target by 2050. It considers as mature technologies nuclear, hydropower, wind, and solar; technologies in early adoption still requiring substantial further development are heat pumps, electrolysis, and next-generation wind and solar. Other technologies are further from market readiness, still in the demonstration stage or only in the lab or prototypes. Carbon capture,

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[4] This paper focuses on innovations for clean energy for climate change. But the innovation system is also powerful for providing other new mitigation solutions for climate change (such as new materials for packaging), as well as new solutions for adaptation.

for example, is mostly in the demonstration stage, particularly when stored; when used, many applications are still in prototype. Direct air capture (DAC), whether stored or used, is in the prototype stage. And then there are technologies outside the scope of the IEA modeling, because they are rough ideas in the concept stage or not even there yet. In the IEA's 2020 assessment mature technologies accounted for only 25 percent of the required reductions for the Net-Zero Emissions (NZE) by 2050 Scenario (IEA 2020a). In its updated analyses, the IEA (2023a) reported substantial progress in clean energy innovation over the past two years, such as on battery chemistries, but mostly a stronger market momentum for mature technologies such as solar photovoltaics, such that the share of emissions reductions in 2050 from technologies still under development was "only" 35 percent. Despite this progress, the innovation job is not done and technologies in need of research and development will be essential to achieve NZE targets. These include, for example, DAC designs, algae-based biofuels, electric aircraft designs, and solar geoengineering. Examples of technologies facing scale-up challenges include hydrogen-based synthetic fuels; carbon capture, utilization, and storage for hydrogen production; cement or steelmaking; and hydrogen-based steel production (IEA 2020a). Also, the production of near-zero materials in hard-to-abate sectors (e.g., cement, steel) still needs considerable research and development. And then there are the yet-to-be-generated ideas that may be the future technology breakthroughs. They will certainly be needed if the global temperature increases and its effects approach critical tipping points. Overall, it is fair to say that thinking we already have what it takes is a clear fallacy.

The third fallacy is that the innovation system will do its job within its current format and that it's fine to simply wait for it to produce new and/or improved cleaner technologies. Unfortunately, the response to the environmental crisis cannot rely on waiting for cleaner technologies to come about but instead requires designing government interventions that will tackle the various market failures at different points of the technological change pipeline. Policy push is needed not just to accelerate innovation in the general sense, relying on standard undirected innovation policy tools, but also matters to guide the direction of technological change: clean technologies must improve, not just in absolute terms, but relative to dirtier ones (Acemoglu et al. 2012).

Innovation Capacity for Reaching Competitive and Resilient Clean Energy Supply

Innovation capacity is needed to reach climate change targets. At the same time, innovative investments are the cornerstone of a green industrial policy targeting competitive value creation and jobs. Clean energy offerings originating from new technology-based innovations are more likely to support competitive positions on world markets and hence long-run sustainable jobs, as these offerings originate from unique, not-easy-to-replicate innovative capacities whose returns can be appropriated through legal or strategic protection mechanisms. Innovations can also play a critical role in building resilient clean energy positions, alleviating future bottlenecks for clean technology supply chains. Examples of such innovations include new production methods or designs that reduce or avoid the use of materials critical in current value chains, and developing new cost-effective alternative materials (e.g., bioplastics)[5] or new modular production technologies that can easily switch between material needs. Another important line of clean tech innovations for resilience involves improving the reuse and recycling of critical materials.

Technology Sovereignty

When relying on new or improved clean energy solutions that offer resilience, the innovation system itself needs to be resilient. New constellations of international technological leadership will emerge, which may lead to new dependencies. The problem of technology dependency is of particular importance for systemically relevant technologies that are of importance to a broad spectrum of use (so-called key or foundational technologies). These include digital technologies (e.g., chips, quantum computing, AI) as well as other key technologies for materials and life sciences (like synthetic biology).

Technological sovereignty is, on the one hand, about the degree to which one can master a certain technology in its application and use, and, on the other, about the degree to which it is available or accessible (Cantner 2023). When the best technology is not available domestically and has to acquired elsewhere, the degree of technological sovereignty results from the quality of one's absorptive capabilities (mastery) and the conditions for acquiring the technology (availability). With formal and informal mechanisms in place for the diffusion of technological know-how over time (such as the patent system), the critical condition for technological sovereignty is more likely to be absorptive capability rather than availability.

Measures against the use of foreign superior technologies and in support of reshoring and domestically building R&D capacities might ensure that technologies and goods are developed and produced domestically. However, the potential long-run efficiency gains from such support measures need to be traded with the short-run inefficiencies from forgoing the advantages of qualitatively better technologies available elsewhere. The more mature and established an envisioned technology is on the international level, the higher these short-run inefficiencies and the lower the dynamic efficiency gains that can be envisioned by going for local deployment. Support for further developing absorptive capacities of the best available frontier technologies may be a better policy avenue to build technology resilience.

Making the Innovation System Work for Green Industries

The innovation system can be a powerful force to reach the multidimensionality of clean energy industrial policy objectives, delivering new and improved solutions for decarbonization, competitiveness, and security of supply. But the system needs to be supported and steered in the right direction.

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[5] Alternative chemistries for making electric vehicle batteries are an important example of such material substitution. An important goal of battery innovation efforts is to diversify designs to reduce reliance on lithium, the critical mineral that is least substitutable with current technologies and the one facing the largest potential shortfall in supply in upcoming years based on planned projects.

This section sketches the specifics of clean technologies for innovation policymaking, outlining the principles of a green innovation–based industrial policy and how it should guide the innovation system. Following are some key principles for such a policy, using insights from the *new industrial policy perspective* advocated by Dani Rodrik (2014). He takes a multidimensional, multiinstrument, multiactor perspective, viewing industrial policymaking as a process of institutionalized public-private collaboration and dialogue rather than a top-down approach of allocating funds to a few winners.

Involvement of Private and Civil Society

Central to a green innovation policy is for public entities to mobilize the innovation capacity at both public research entities and private firms to develop and deploy new solutions, through public private partnerships. To properly mobilize the private sector in such partnerships, a balanced set of sticks and carrots is needed to incentivize the sharing of resources, risks, and information while avoiding rent-seeking. In view of the broad challenges faced, these public-private partnerships will have to cover a larger set of scientific and technology areas and private sector areas than in other areas of innovation and industrial policy. Because climate change is a big transformative change, the transition will also require the involvement of civil society, more than in other areas of innovation and industrial policy.

Mixing and Coordinating Innovation Policy Instruments and Environmental Policy Instruments

Topping up classic market failures and knowledge externalities with environmental externalities represents a significant challenge for green innovation policy, particularly as these externalities may have complex reinforcing interactions. To tackle this multidimensional market failures, a mix of policy instruments has to be used, extending beyond the classical tools for innovation policy (like subsidies or tax credits). A green innovation policy mix should be developed in coordination with the policy instruments used by climate policy and innovation policy more generally.

Carbon pricing and environmental regulations are particularly important instruments to complement the classic subsidies or grants in the policy toolbox. If the price of carbon remains too low to drive low-carbon technology innovation, a green innovation subsidy policy will be in second-best mode. Results from calibration exercises using a macroeconomic endogenous growth model with directed technical changes show how high the optimal carbon price or subsidies would have to be when used in isolation relative to its optimal level when used in combination: the carbon price would have to be about 15 times bigger during the first 5 years, and subsidies would have to be on average 115 times higher in the first 10 years (Aghion, Hémous, and Veugelers 2009).

More Directionality

Environment-directed innovation policy cannot be neutral. It cannot rely solely on new projects arisen purely bottom-up. It needs to select clean technologies for extra support to address the additional environmental externalities hampering clean tech market potential. Clean technologies are also found to have higher knowledge externalities, particularly as they are typically still in early stages and have broader applications (e.g., Dechezleprêtre, Martin, and Mohnen 2014; Martin and Verhoeven 2023). In addition, clean technologies face challenges from incumbent dirty technologies. A policy push for clean technologies is necessary to counter the locking-in of fossil fuel–based technologies and their path dependencies (Aghion, Boulanger, and Cohen 2011; Aghion et al. 2016, 2019). Locking in unsustainable pathways, delaying the transition, will further increase the costs of mitigating the climate crisis, as a function of time.

Favoring clean technologies requires identifying which are clean and whether and how to choose among clean technologies and projects, picking winners. Choices among clean technologies and projects (e.g., hydrogen or batteries) be guided by the general principle of divergence between expected social and private returns and should also take into account externalities of any choice on other nonselected clean technologies. All this calls for a good mix between vertical and horizontal instruments, bottom-up and top-down selection, and limiting support in time and ensuring competition with a level playing field (Aghion, Boulanger, and Cohen 2011).

Related is the choice of technologies based on their readiness level, i.e., support for research versus development versus deployment. The urgency of the climate change challenges may tend to favor higher readiness levels. The choice should take into account the relative intensity of market failures in the maturity of the technologies considered, trading off knowledge spillovers, path dependency, learning by doing, and network externalities. Ignoring earlier-stage R&D, with typically higher knowledge spillovers and still high learning by doing opportunities to exploit, runs the risk of missing out on next-generation or completely new clean energy technologies that may be the next breakthroughs. Carolyn Fischer, Louis Preonas, and Richard Newell (2017) model the optimal distribution of public spending between R&D support and deployment under various scenarios. They find that only extremely high learning costs or network externalities warrant stronger support for deployment from a decarbonization target perspective over R&D.[6]

Risk Taking

Uncertainty about future climate and technology scenarios underlines the importance of learning and information sharing, and thus experimentation, risk taking, self-discovery on the market, and industry-research-policy collaborations to share risks and information. At the same time, the urgency calls for policy action despite the high risks. The size and complexity of the climate change challenge do not allow precautionary principles and pursuit of only low-risk "known" solutions. Policy must not shy away from taking risks to support radically new ideas. Even if these ideas are high-risk, and require the establishment of new networks, they may yield crucial high-gain breakthroughs

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[6] They find that the optimal ratio of deployment spending to R&D spending does not exceed 1 for wind energy in almost all scenarios, while it exceeds 1 for solar energy, but not by much (Fischer et al. 2017).

and should not be missed. To manage the high risks of such an approach, a portfolio approach needs to be taken, allowing some initiatives to fail along the way.

Policy Governance Challenges

Green innovation policy faces a larger risk for government failures than is usually the case. A first challenge is the information problem in a highly uncertain environment. As a green innovation policy requires a more directed approach toward clean technologies (as explained above), it relies on the government having the information capacity to correctly direct support to winning technologies and projects. The new industrial policy approach calls for a policy governance system that allows for experimentation, fast learning, interim milestones, and information sharing among all partners to manage the information problem dynamically.

Another governance challenge has to do with the need for a long-time horizon for green policymaking. While the incentives of politicians are typically to look for short-term successes, a long-time horizon for policy objectives, paths, and milestones is needed to incentivize long-term clean tech private investment and societal transitions.

In addition, coordination among the many different types of stakeholders, policy governance areas, instruments, and projects will require a strong operational governance for a successful green innovation policy. Stronger governance is also needed to monitor and evaluate progress on green industrial policy targets. This requires a highly competent and empowered governance body, which is sufficiently “politically independent” or detached from political pressures, yet accountable for its achievements with a set of clear and realistic milestones (Tagliapietra and Veugelers 2020).

With strong governance as a necessary condition for successful green industrial policy, how realistic one considers the feasibility of addressing the governance challenge will sort proponents from sceptics of green innovation–based policy.

PERFORMANCE ON CLEAN ENERGY INNOVATIONS SO FAR

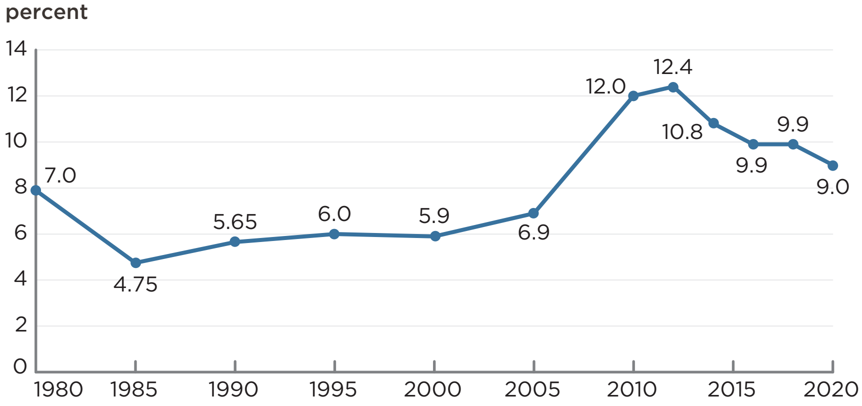
Having sketched both the potential for innovation as a driver of a clean energy industrial policy with resilience and the contours of how policy should steer innovation to reach this potential, this section reviews performance thus far on clean tech innovations. A matching of this performance with current clean energy innovation policymaking and the principles for such policymaking as sketched above will inform recommendations for moving forward.

Patent Applications for Low-Carbon Technologies

Patents are a common measure used to trace new inventive ideas. Low-carbon patenting worldwide was on the rise until 2011, but since then has seen a downward trend (figure 1). On average, they represented less than 10 percent of all patents worldwide in 2017–20, down from 13 percent in 2010–13. While total patenting grew at an average pace of 4.6 percent per year since 2011, low-carbon patents increased at an average rate of only 0.3 percent per year

Figure 1

Trends in green patenting: Low-carbon inventions as a share of inventions in all technology areas, 1980–2020



Note: Data refer to families of patent applications filed under the Patent Cooperation Treaty (PCT), by earliest filing date. Low-carbon patents are identified using the "Y02" classification code developed by the European Patent Office and applied to all patents filed globally. The categories included are climate change mitigation technologies related to buildings (Y02B), in information and communication technologies (Y02D), in the production or processing of goods (Y02P), in transportation (Y02T) and in wastewater treatment or waste management (Y02W); reduction of greenhouse gas emissions related to energy generation, transmission or distribution (Y02E); and capture, storage, sequestration or disposal of greenhouse gases (Y02C).

Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, November 2022. Reproduced with permission of the OECD; permission conveyed through Copyright Clearance Center, Inc.

(and decreased more than 5 percent in 2014–15) (OECD 2023). The decrease in low-carbon patenting affects nearly all technologies and is thus not technology specific (OECD 2023). Possible reasons for the decline in green innovations are declining fossil fuel prices (related to the shale gas revolution), low carbon prices, and increasing technological maturity for the most important clean technologies, such as hybrid and electric vehicles and renewables (Probst et al. 2021). The only technologies escaping this trend are energy storage (batteries), witnessing important new recent inventions, and hydrogen and fuel cells (OECD 2023).

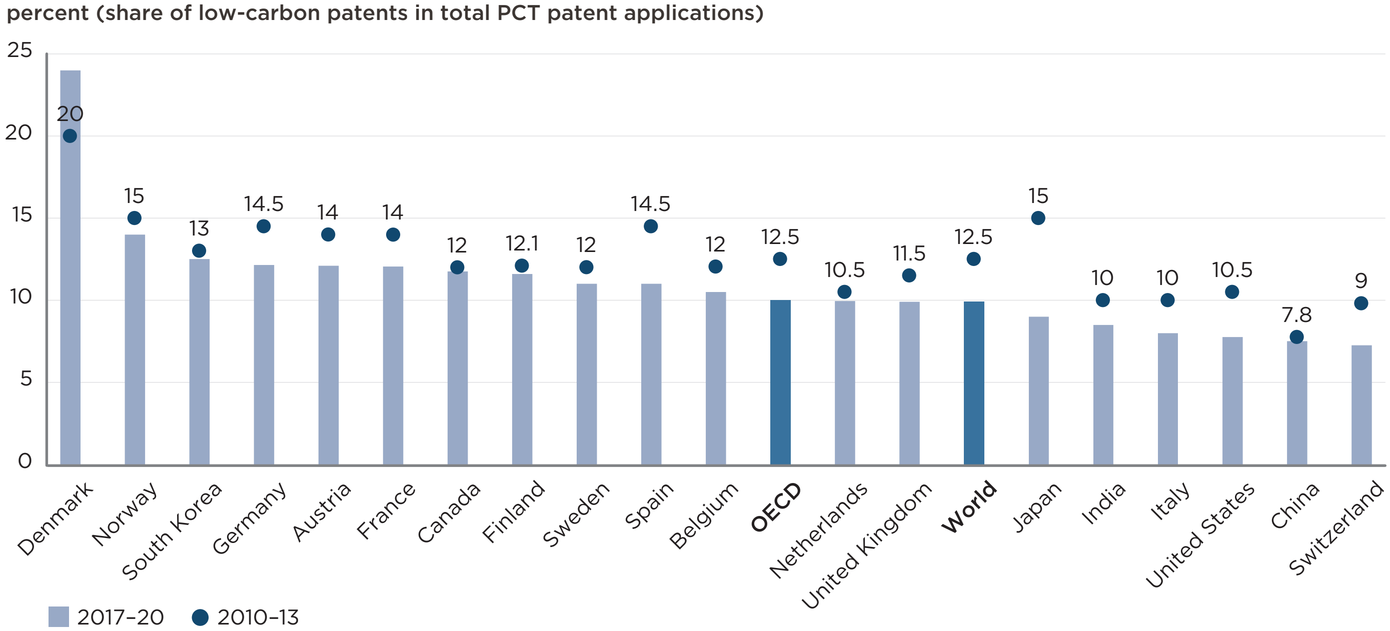
Looking at individual countries (figure 2), most of those in Europe—e.g., Denmark, Norway, Germany, Austria, France, Sweden, Finland, Spain, and Belgium—display a higher share of their total patents in low-carbon technologies than the world average, although, with the exception of Denmark, all have seen a drop in this share since 2013. Even so, their share in low-carbon technologies remains above the world average.

This contrasts with the United States. In absolute terms, the United States may be an important clean patent country, factoring in its strong innovation ecosystems, but it does not specialize in low-carbon technologies: These represent only 7 percent of all its patents, down from 11 percent in 2010–13—lower than the averages for either the world or Organization for Economic Cooperation and Development (OECD) and much lower than most European countries.

In Asia, Korea and Japan specialize in low-carbon technologies, but Japan has seen a significant decline more recently, from 15 percent to less than 10 percent. China has seen a fast rise in low-carbon patents (figure 3), albeit slower than

Figure 2

Trends in country specialization in low-carbon patenting, 2010–20



Note: Data refer to patent applications filed under the Patent Cooperation Treaty (PCT), by filing date; for selected country, according to the inventor's residence using fractional count.

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its rise in other technology areas. With 7.5 percent of its patents in low-carbon technologies (figure 2), it does not specialize in low-carbon. Unlike most of the other countries, Korea and China do not show a drop in their share of low-carbon technologies more recently but maintain a very stable position.

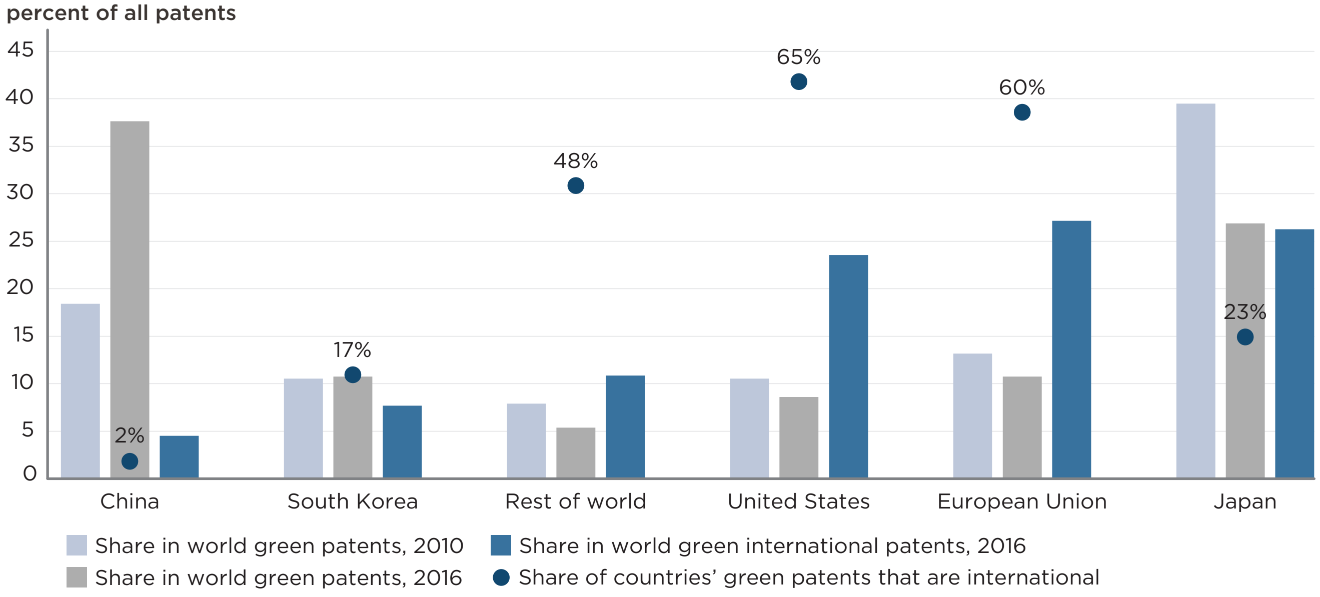
I can also look at whether patents have been applied for not only at home but also in at least one other geographic area. Such international applications reflect the higher value of the invention, as patent protection is typically applied for in other markets only for high-quality inventions. The scope of international coverage of patent protection is also an indicator of the geographic spread of the new technology's use, as patent protection is sought in markets where the applicant has plans to commercialize the technology. Figure 3 shows the share of patents applied for internationally.

China's low-carbon patenting performance is far less impressive when looking at international patents: it is lowest among the considered countries on this indicator (figure 3). This is partly a reflection of the importance of the Chinese market for Chinese green inventors, but also partly of the low attractiveness/quality of these inventions for other markets. The countries/regions with the highest share of green patents sought internationally are the United States, European Union, and Japan (figure 3).

The United States has the highest share of clean patents sought internationally. For US green inventors, other markets are important, certainly in the considered period when US green policy was still in low gear (see section

Figure 3

International patenting in low-carbon technologies, selected jurisdictions, 2010 and 2016



Note: International patents are applications filed in at least in two patent authorities.
Source: Author's calculations based on Grassano et al. (2020).

4). When looking in more detail at the most frequent destinations for foreign IP protection, the biggest foreign market for US green inventors to seek IP protection is the European Union.

And for EU green inventors, the United States is the major foreign market for IP protection. China is on the radar for US and, somewhat less, EU green inventors, but Korea and Japan are particularly active in seeking protection in the Chinese market for their green inventions. For Chinese green inventors, to the extent that they apply abroad, it is primarily for the US market. Overall China is the largest destination for foreign green IP protection, closely followed by the United States, with Europe in third place (Grassano et al. 2020).

Nicola Grassano and colleagues (2020) further illustrate global interconnectedness by looking at the information on international coapplications. These data illustrate the highly globally interconnected coproduction of green inventions, with a particularly strong EU-US node: 38 percent of all US international coinventions are with the European Union, making it the largest US partner in green patents. And the United States, with 29 percent, is the European Union's largest international coapplicant partner. China accounts for a much smaller but nevertheless important share of US international coapplications, 14 percent, but only 6 percent of EU international coapplications. For China, most (63 percent) of its international green coinventions are with neighboring Asian countries. For the European Union, on par with its US connection are substantial intra-EU connections: EU member states generate one third of their green coinventions through intra-EU connections (Grassano et al. 2020), illustrating the importance of the EU single market for developing innovative ecosystem in clean tech.

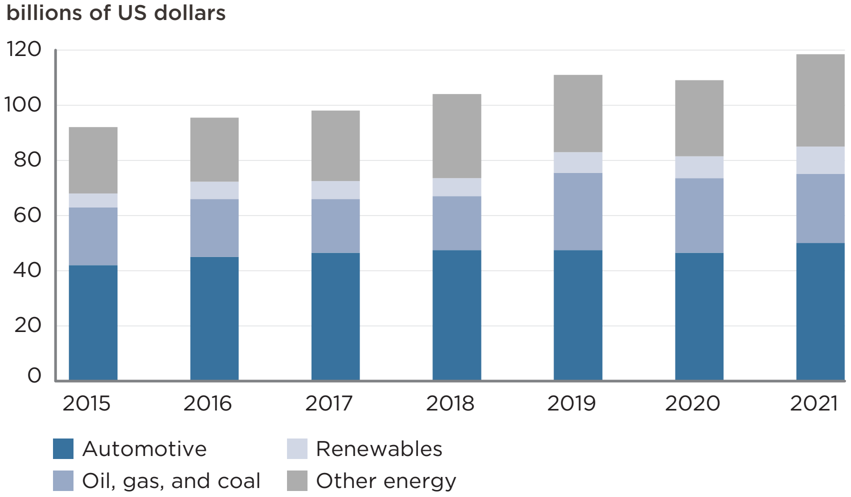
Although most green patents are in the corporate sector, the share of green patent applications by or together with public research organizations is larger for green inventions than in general, reflecting the (on average) still early stage of green technologies. Also, the extent to which green patents rely on scientific publications as prior art for their inventions is much higher than for dirty combustion patents, particularly for emerging clean tech technologies, such as hydrogen (OECD 2023).

Corporate Energy R&D Investments

Corporate expenditures for energy R&D, as reported by the IEA (2023b), show a steady but small rise over time (figure 4). Most of this spending is in the automotive sector, which combines investments in clean, dirty, and hybrid technologies, which unfortunately cannot be disentangled. Renewables are somewhat increasing in relative importance but are still quite small. Coal, oil, and gas remain important. Overall, this suggests only a weak transition to clean energy in corporate energy R&D and illustrates the dirty path dependence risk, as mentioned in section 2.

To identify the R&D investing firms for green R&D, I use the 2022 European Commission Joint Research Center Scoreboard of the largest 2,500 R&D spending companies worldwide (Grasssano et al. 2022). The scoreboard includes a sector dedicated to "alternative energy," with 8 out of the 2,500 spenders (table 1). Together the R&D expenditures of these dedicated clean energy companies represented 0.2 percent of all R&D spent in 2021 by the 2500 companies. This might seem small, but it represents about one quarter of all scoreboard R&D spent by *oil and gas* companies and 44 percent of all R&D spent by *utilities* companies. Furthermore, R&D expenditures by dedicated clean energy companies are fast growing. Europe is well represented in this sector. The two largest companies in terms of R&D are European, with Siemens Energy (Germany) ranking 141 in the scoreboard and Vestas Wind Systems (Denmark) at

Figure 4
Corporate energy R&D by technology, 2015–21



Source: Based on IEA (2023b). License: CC BY 4.0.

Table 1

2022 scoreboard for "alternative energy" companies

Rank in World R&D Scoreboard 2021 (out of 2,500 companies)	Company	Country	Technology	R&D, 2021 (millions of euros)	R&D one-year growth (percent)	R&D to sales (percent)	Capex to sales (percent)
141	Siemens Energy	Germany	Clean energy	1343	14	4.72	3.47
405	Vestas Wind Systems	Denmark	Wind	444	34	2.85	3.05
834	Solaredge Technologies	US	Clean energy services	191	33	11.03	7.60
1015	Sungrow Power Supply	China	Solar	153	46	4.59	6.94
1346	Orano	France	Nuclear	108	4	2.29	12.53
1584	First Solar	US	Solar	88	6	3.39	18.48
1763	SMA Solar Technology	Germany	Solar	77	8	7.83	1.79
2166	Nordex	Germany	Wind	58	23	1.07	3.12

Source: Author's calculations based on Grassano et al. (2022).

405. China has only one, in solar energy, but it is the fastest-growing company of the eight. The United States has two companies in the scoreboard: SolarEdge (a young company, born in Israel), ranked 834, and First Solar, ranked 1584.

Looking at the car manufacturing sector, the scoreboard includes both the large incumbent car manufacturers and dedicated electric vehicle (EV) producers. Unfortunately, it only has R&D information at the consolidated firm level, so it is not possible to identify how much the large incumbent car manufacturers are spending on R&D for clean versus dirty or hybrid technologies.[7] The largest dedicated EV companies in the world are US Tesla and three Chinese companies (BYD, Guangzhou Automobile, and Nio) (figure 5). The share of their R&D relative to the sector in 2021 is dwarfed by that of the incumbent car manufacturers. The biggest R&D spender among EV firms is Tesla, which, with its €2.3 billion in 2021, ranks only 18 in the R&D scoreboard for automotives, representing 1.7 percent of this sector R&D. Together the three largest Chinese EV producers account for 2 percent of sector R&D.

Overall it is fair to say that the evidence supports the power of the innovation system in delivering clean tech, but below its potential. Underperforming compared to other areas, including dirty technologies, it should and can

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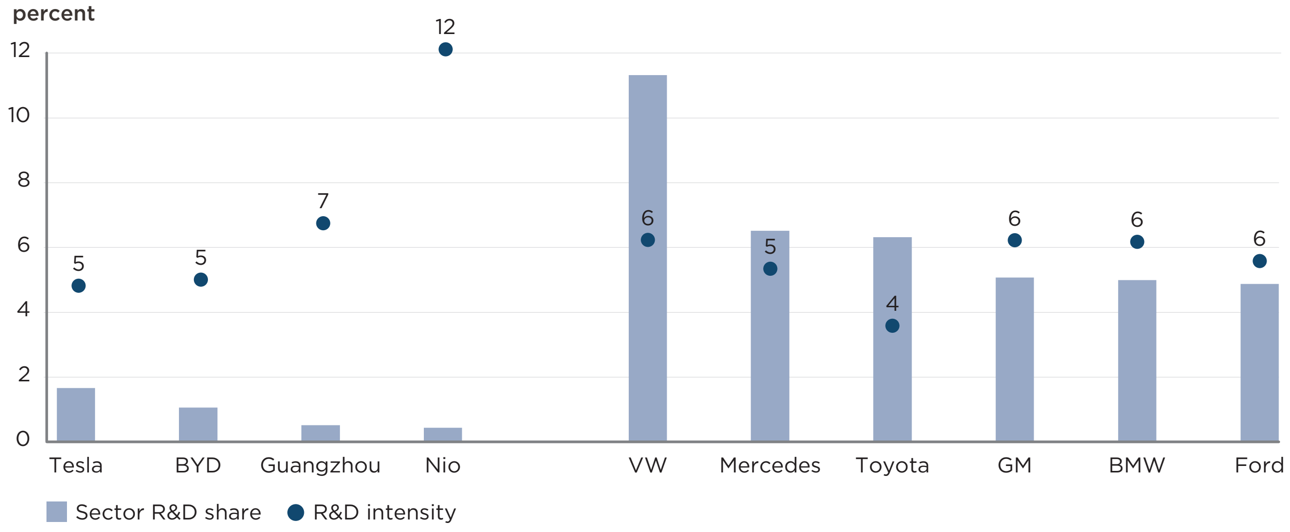
[7] Although it is not possible to disentangle clean versus dirty R&D spending for the incumbents, the scoreboard matched the patent data for the ranked firms and, using the green classification of patents, showed that about 13% of all patents from incumbent automobile firms were green. Assuming that their R&D spending for clean mobility is proportional to their green patenting, this would leave the overwhelming majority of their total R&D spending on nonclean spending. Nevertheless, this would still leave €7 billion in clean R&D from the top six (VW, GM, Toyota, Mercedes, Ford, BMW).

Figure 5

International automotive R&D spending, selected major manufacturers of electric and internal combustion vehicles



Source: Author's calculations based on Grassano et al. (2022).

do more and faster. Particularly disturbing is the recent decline in clean tech patenting, a decline that may be related to deficiencies in green policy deployment. The strong, relatively stable position of EU countries and the relative underperformance of the US innovation system may also be related to differences in green innovation policy choices.

To check the hypothesis that deficient clean innovation policies are keeping clean tech innovation performance below potential, the next section looks at the clean energy policies being deployed.

DEPLOYMENT OF CLEAN ENERGY POLICIES SO FAR

As noted in section 2, green innovation policy requires a mix of policy instruments, most notably combining carbon pricing, regulations, and targets and public financing for R&D and deployment of clean tech. The OECD has developed an Environmental Policy Stringency (EPS) indicator (Kruse et al. 2022) that monitors these (since 1990) and makes it possible to discern countries' progress in policy efforts to support climate-related innovation.

Environmental Policy Stringency Rankings

The EPS tracks (i) market-based policies (carbon pricing, e.g. taxes, certificates), (ii) nonmarket-based policies (e.g., emission targets, performance standards), and (iii) technology support policies.[8] Figure 6 shows the trend in EPS between 1990 and 2020 in the OECD.

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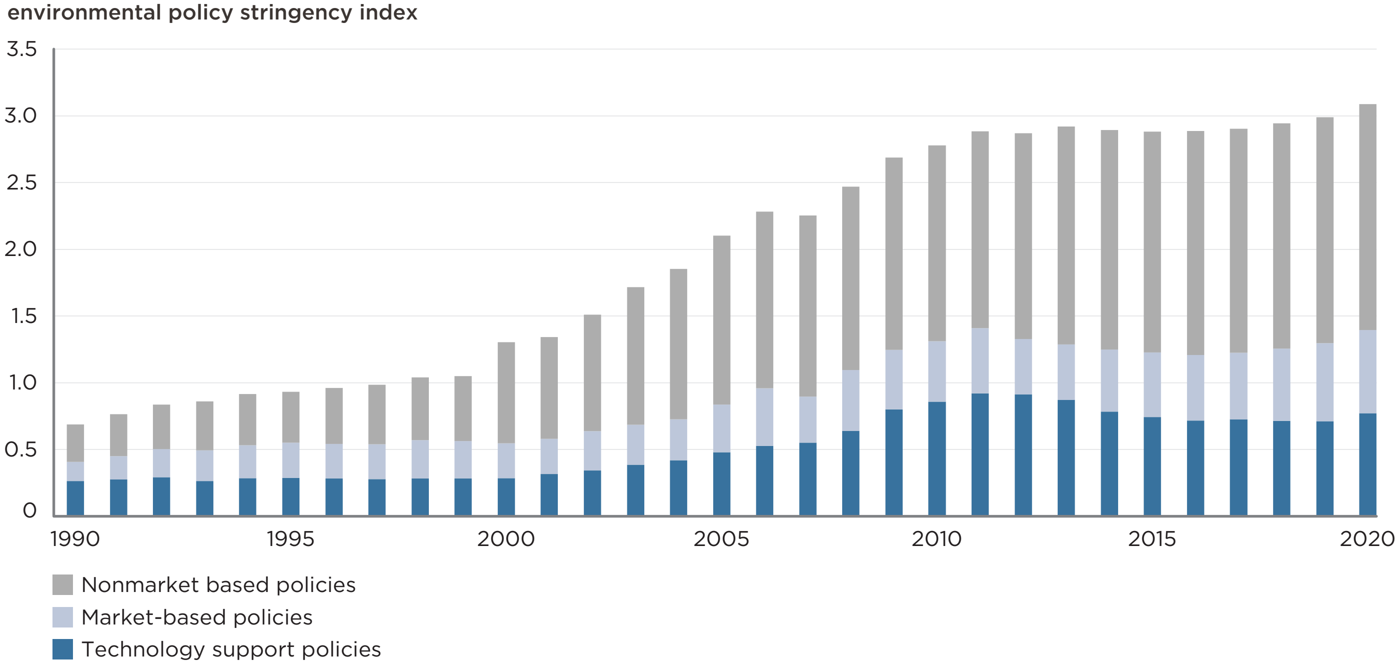
[8] The revised current version of the EPS covers climate change and air pollution policies, for which data are most comprehensively available. The index does not cover other important environmental domains such as water, biodiversity, or waste management, lacking data comparable across countries and time.

Figure 6

Trend in environmental policy stringency, OECD average, 1990–2020



0 = no stringency; 6 = highest degree of stringency.
Note: Yearly averages of OECD countries except Colombia, Costa Rica, Latvia, and Lithuania as data were not available.
Source: Kruse et al. (2022).

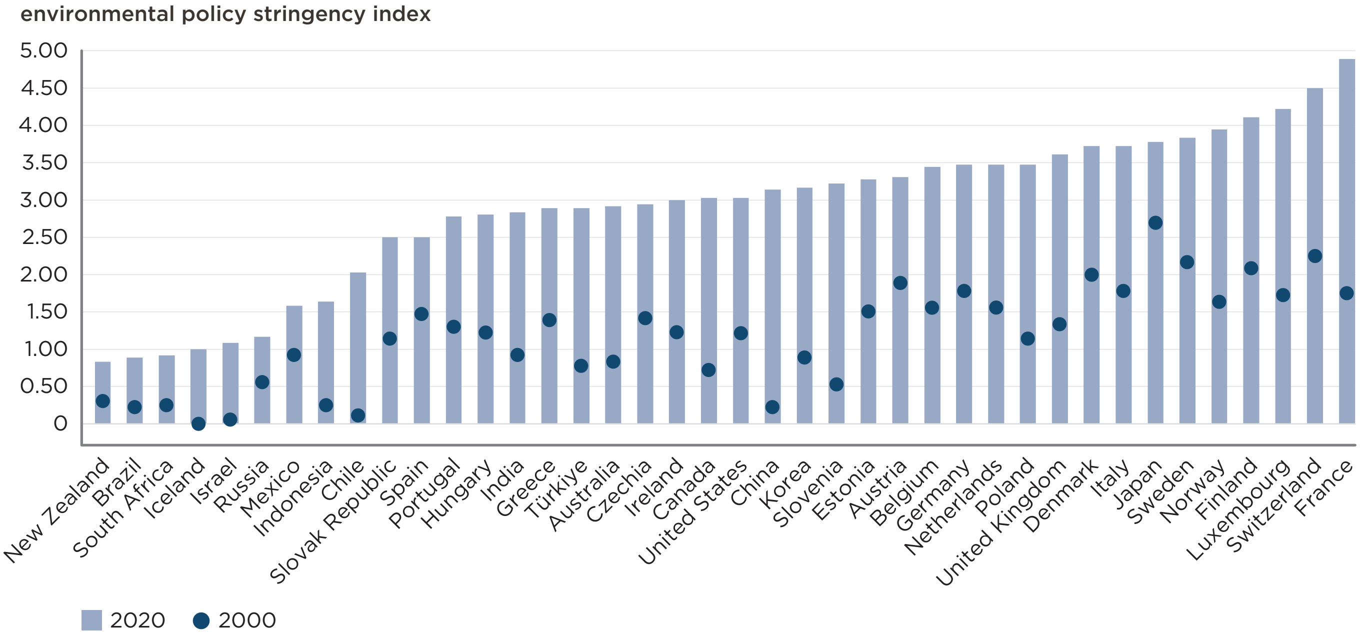
It shows clearly how the apparent slowdown or stagnation in low-carbon inventions, documented in section 3, corresponds to a recent leveling off of climate policy measures across OECD countries, and particularly technology support policies (OECD 2023). After two decades of continuous growth, the stringency of climate policy has more or less stabilized since 2011, in both market and nonmarket policies. But most notable is the reduction in the level of policy support for technology (–10 percent), following a strong increase from 2000 to 2011. This decline is driven by a drop in the level of the two main components of the technology support subindicator of the EPS index: public R&D expenditures for low-carbon technologies and subsidies for renewable energy adoption (OECD 2023).

The timing of the decrease in the level of technology support policies corresponds markedly to the slowdown in global low-carbon patenting shown in figures 1 and 2. Although market- and non-market-based instruments could also support innovation, they are less efficient when not combined with R&D subsidies, as argued in section 2. This suggests that current policymaking is deficient in its deployment of a sufficiently mixed set of instruments and calls for inclusion of technology-support policies in this mix.

The levels and trends in EPS scoring show a significant heterogeneity across countries (figure 7). Although all countries have a higher EPS score in 2020 compared to 2000, there are important differences. The countries with the most stringent environmental policies in 2020—mostly in Europe (France, Switzerland,

Figure 7

Environmental policy stringency by country, 2000 and 2020



0 = no stringency; 6 = highest degree of stringency

Source: Kruse et al. (2022).

Scandinavia) as well as Japan—have EPS scores that are four times higher than those of countries at the bottom and twice the scores of even some European countries (e.g., Spain, Portugal, and Hungary). The United States, at about 3, is in the middle of the pack. China showed one of the greatest increases in EPS scoring, moving from a bottom position in 2000 to surpass the United States in 2020. Japan lost the leading position it had in 2000, overtaken by faster-improving European countries.

There are three major policy instruments for clean tech innovation.

Carbon Pricing

The European Union with its emissions trading system (ETS) has the highest carbon price, covering about half of its emissions, and this will increase with its Phase 4 revision (2021–30) (figure 8, top panel). China's carbon pricing is at much lower levels and with much less coverage. Unlike the EU ETS, China's ETS is based on emission intensities, such that the overall cap (as well as company allowances) adjusts upward with production. The United States has no carbon pricing scheme, although some states have cap and trade systems.

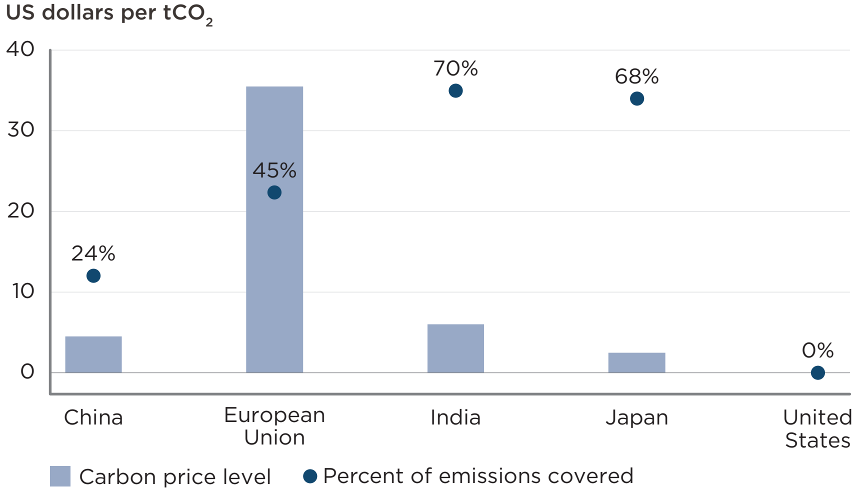
Deployment Targets

Looking at deployment targets (figure 8, bottom panel), again the United States is lagging. The Clean Power Plan, announced by President Obama in 2015, set the first-ever limits on carbon pollution from US power plants. It faced successful court challenges. The Trump administration withdrew the United States from

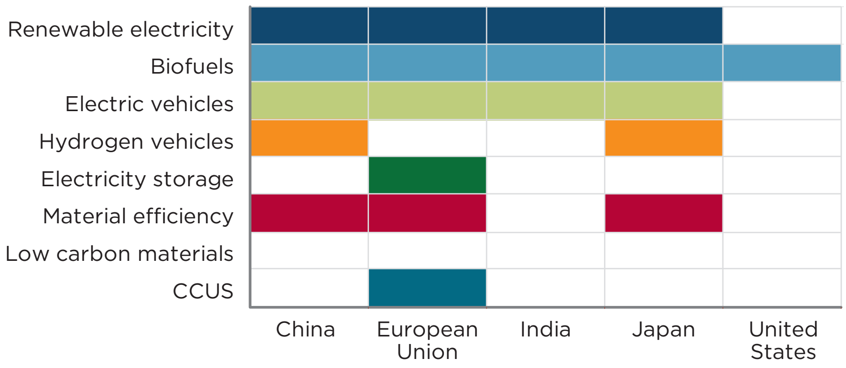
Figure 8

Carbon pricing and green technology deployment targets, selected jurisdictions

a. Explicit carbon pricing, 2020



b. Stated and legislated deployment targets, 2020



	China	European Union	India	Japan	United States
Renewable electricity	■	■	■	■	
Biofuels	■	■	■	■	■
Electric vehicles	■	■	■	■	
Hydrogen vehicles	■			■	
Electricity storage		■			
Material efficiency	■	■		■	
Low carbon materials					
CCUS		■			

CCUS = carbon capture utilization and storage.

Notes: Excludes subnational or EU member state policies, which increases the market-pull incentives for innovation in some regions. Carbon pricing includes explicit climate change-related pricing policies; it does not include other general energy taxes (which effectively price carbon). Targets included set an objective for future deployment in a given technology application and explicitly support the technology referenced in the legend.

Source: Based on IEA (2020b). License: CC BY 4.0.

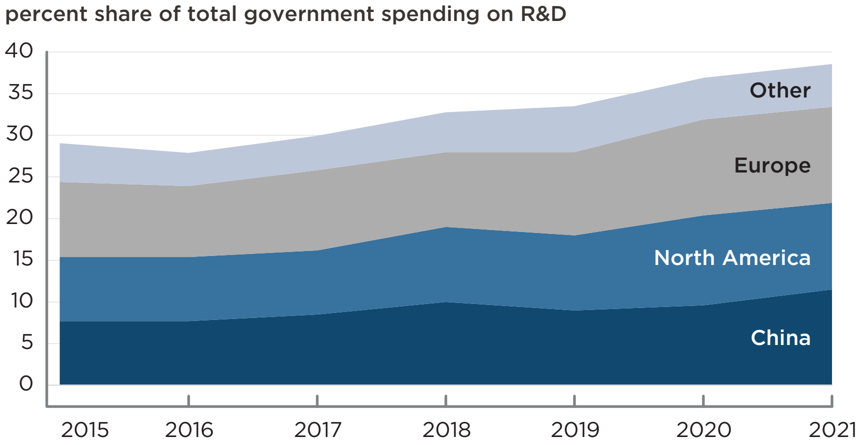
the Paris Agreement, but the country rejoined in February 2021 under Biden. The European Union and China are the most active in stating and legislating deployment targets. The areas most covered by targets are biofuels, renewable electricity, and electric vehicles.

Public Spending on Energy R&D

The trend over time is one of initial decline in public energy R&D spending after a boost in the late 1970s, following the oil shock. At its peak, it still represented less than 0.1 percent of total government spending in research, development, and demonstration (RD&D) in major economies (IEA 2023b). Since the end

Figure 9

Trends in government spending on energy research and development (R&D), by area, 1974–2020



Source: IEA (2023b). License: CC BY 4.0.

of the 1990s it has been on a growth path, but a very slow one. As a share of overall GDP, it has remained fairly constant in major economies since 2012. As a share of total government's R&D spending, it has floated around 0.04 percent since 2010 (IEA 2023b). The decline in public R&D is particularly prominent for nuclear energy.

Looking at the recent trends in public funding for energy-related R&D in different countries/regions, the European Union and China have been increasing theirs over time, albeit slowly (figure 9). Both spend more than North America.

As discussed in section 2, important questions for policy are not only how much to spend on clean energy in general but (i) how to select which clean technologies to support and (ii) how much to spend on research and development of new or early-stage clean technologies versus support for the deployment of commercially ready clean technologies. Ignoring the earlier-stage R&D, with typically higher knowledge spillovers and still high learning-by-doing opportunities to exploit, runs the risk of missing out on next-generation or completely new clean energy technologies that may yield the next breakthroughs. Only high learning costs or network externalities would warrant greater support for deployment, from a decarbonization target perspective, over R&D (Fischer, Preonas, and Newell 2017).

Unfortunately, there is no systematic tracking of either policy support by stage of technology readiness or the state of innovation performance by stage of readiness. Nevertheless, more casual evidence suggests that countries have so far put a strong emphasis on deployment policies compared with direct R&D support (OECD 2023). As an illustration, subsidies for electric vehicles are a popular instrument for supporting deployment. In the renewable electricity domain, these subsidies typically take the form of feed-in tariffs and auctions. For example, in 2018 European countries spent €4.6 billion to support R&D for renewables (wind and solar power), compared to €78.4 billion for deployment of wind and solar technologies (OECD 2023). Although the latter support has been instrumental in inducing important cost reductions for solar panels, the proportion relative to R&D support (150 times) is extremely high and hard to reconcile with the optimal proportion results from Fischer et al. (2017). Even for green hydrogen, a technology far from market maturity, Emile Cammeraat, Antoine Dechezleprêtre, and Guy Lalanne (2022) find support focused on deployment, although R&D and large-scale demonstration projects are critical to bring down the cost of electrolyzers. All this is consistent with a bias of politicians in favor of deployment over R&D support, where the market failure case is strong but the returns are risky and longer-term.

RECENT TRENDS IN CLEAN ENERGY PUBLIC FUNDING: THE US IRA AND THE EU NZIA

The evidence as of 2020 suggests that the major economies are still far from green industrial policy deployment to power the innovation system sufficiently and quickly. Yet since 2020 there have been some important shifts in green industrial policymaking, most notably in the United States. This section looks at these shifts in the United States and the following reactions in the European Union,[9] and whether they can be seen as game changers for an innovation-based green industry policy.

US public clean energy RD&D support has traditionally been lackluster, but more recently federal climate policy took a more ambitious turn. For FY 2023, the Department of Energy (DOE) saw its budget increase by 10 percent compared to FY 2021, with about $9.3 billion for energy R&D (Chong 2023). New is DOE's Office of Clean Energy Demonstration, which will address the need for more public-private partnerships for clean tech demonstration projects, as discussed above, but will have to prove its merits with a small budget.[10] The IRA was mostly meant for the deployment of clean technologies with high technology readiness levels, not for R&D support.

Although the recent increases in US public funding for clean energy RD&D surely help to redress a historically low level of support, they are part of an unbalanced mix of policy instruments that lacks a carbon price and has a smaller scope and depth of deployment targets, thus reducing the efficiency of the funding to reach its decarbonization targets. In terms of directionality, the choice of funded clean tech areas and the selection of specific projects may not seem overly restrictive. But it is not clear what criteria and process for the selection of programs and projects are used to avoid the influence of ad hoc political and local preferences rather than addressing the decarbonization targets and redressing market failures in clean energy.

Integration and coordination of the new measures with the existing funding programs, the fit within the policy mix of regulations, and coordination with different policy governance institutions and between federal and state policy levels remain huge challenges. These challenges are for John Podesta, chair of the Interagency National Climate Task Force and senior advisor to the president for Clean Energy Innovation and Implementation, who has been assigned to oversee implementation of the IRA's clean energy and climate provisions.

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[9] For further discussion of these recent trends, see the papers by Gourinchas, Schwerhoff, and Spilimbergo (2024) and Bown and Clausing (2024).

[10] Its FY2023 budget is $89 million.

In summary, the US clean energy industrial policy may be enjoying a new boost, but it is still unconvincing in terms of deploying a sufficiently balanced set of policy objectives and instruments as well as a sufficiently diversified portfolio of supported technologies in various stages of technology readiness to fully leverage US innovation strengths for clean energy.

Compared to the United States, European countries can be considered front-runners in green policymaking. Yet Europe's green industrial policy landscape is highly complex, displaying a multitude of green industrial policy initiatives, covering various policy competences and different geographical layers (regional, national, and EU-level).[11] These initiatives are generally not coordinated—and may even conflict. This represents a major issue, because the presence of significant differences in green industrial policies across countries fragments the EU single market, jeopardizing the power of its scale. Nevertheless, the European Union has in place a wide range of policy tools for green industrial policy, ranging from its ETS, common targets, standards, and regulations to public funding for green research, development, and deployment. Most of the public funding for R&D in the European Union runs through member states, but actual EU R&D funding programs (the 7-year Framework Programs)—although they represent only 7 percent of EU public R&D spending in the EU—are important complements and leverage for member states' R&D funding. These programs typically cover only R&D, not efforts beyond early-stage prototyping and demonstration. The 2021–27 Framework Program, Horizon Europe, has around €15.1 billion earmarked for climate, energy, and mobility projects.

Another EU instrument, beyond the Framework Program, is the Innovation Fund, which is financed from ETS revenues and leverages private financing for large deployment projects. Relatively new components of the EU green innovation policy toolbox are its Knowledge and Innovation Communities (KICs), European alliances (i.e., the European Battery Alliance and the European Clean Hydrogen Alliance), the Important Projects of Common European Interest (IPCEI), and missions, putting into practice an institutionalized process of collaboration between the public sector and the private sector and civil society at European scale.

The US adoption of the IRA, particularly its local content requirements, raised the pressure in the European Union to enhance its strategic autonomy and economic competitiveness objectives in its green policymaking. In response, the European Commission put forward its Net-Zero Industry Act,[12] together with a proposal for a Critical Raw Materials Act (EC 2023).[13] As there is very little EU-level funding associated with the NZIA,[14] public incentives to spur the needed

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[11] A deeper discussion of EU green industrial policy is provided in Tagliapietra, Trasi, and Veugelers (2023).

[12] For a discussion of what should be the EU response to the US IRA, see Kleimann et al. (2023).

[13] For a critical assessment, see Le Mouel and Poitiers (2023).

[14] In June 2023 the Commission proposed a repackaging of existing EU funds (the most important beneficiary for clean tech projects, the Innovation Fund, received an extra €5 billion) under a Strategic Technologies for Europe Platform (STEP), introducing an "EU quality label for sovereignty projects" and a "sovereignty portal" for accessing funding opportunities under STEP. For clean technologies STEP will focus on the NZIA technologies and support the rapid development and deployment of homegrown clean energy technologies.

private investments in this space currently come from national state aid, putting the member states in a central position for EU Temporary Crisis and Transition Framework state aid.[15]

The NZIA, very much in line with the IRA, adopts a top-down approach in which policymakers cherry-pick clean technologies and, within these, specific projects to be considered as strategic for the transition to net zero emissions and favorable treatment. While the criteria for selecting technologies in the NZIA, as in the IRA, may not be overly restrictive, they do preclude certain options, such as nuclear, recycling, and energy efficiency. NZIA projects, as in the IRA, will have to be ready for (early) adoption. These represent a break with the past EU policy approach, where support was focused on earlier stages, mostly research, early-stage development, and prototyping. With its exclusive focus on the deployment of already developed technologies, following the US IRA, the NZIA risks an imbalance in support for R&D versus deployment.

Rather than playing to its initial green innovation (policy) strengths, the NZIA follows the US IRA with a stronger focus on deployment rather than R&D and an implementation of sovereignty by emphasizing local production. With its focus on local deployment to ensure strategic autonomy, like the IRA, the NZIA misses out on alternative innovation-based strategies for ensuring strategic autonomy, and it reneges on its “open” dimension of strategic autonomy approach to clean energy industrial policy. Targeting domestic manufacturing as the sole mechanism to ensure strategic autonomy (and this in the NZIA with a 40 percent headline target for domestic production for all strategic technologies) will likely not be the most efficient and effective mechanism to achieve security of supply together with global competitiveness for the European Union and the targeted decarbonization.

The NZIA, by focusing almost exclusively on the promotion of individual national projects, seems to disconnect from the approach of establishing EU-wide public-private ecosystem networks, like its alliances, IPCEIs, KICs, and missions. Diverting from an EU-coordinated approach is an important downside of the act because only by exploiting a home market at the EU scale and fostering synergies and collaborations within the union, can Europe establish itself in the global clean tech manufacturing race.

In summary, although the European Union and its member states have been deploying a mix of green innovation policy instruments, combining carbon pricing, targets, and regulations with public support for R&D and early deployment, and despite new initiatives like alliances, IPCEIs, KICs, and missions supporting ecosystems encompassing all players operating in a clean tech value chain, there is still a long way to go for an effective EU green industrial policy, as outlined in the section 3. The EU green industrial policy strategy appears to be an ill-coordinated collection of energy, climate, innovation, and social policy initiatives rather than a truly coherent green industrial policy framework. The

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[15] This recent revision of state aid essentially allows EU member states to provide very sizable amounts of aid for NZIA investments. Also new is support allowed for operating expenditures, increasing the room for support for mature technologies. And finally “matching aid” is allowed: provision of either the amount of support the beneficiary may receive for an equivalent investment in an alternative location, or the amount needed to incentivize the company to locate the investment in the European Union. Particularly the latter is a reaction to the IRA and runs the risk of instigating subsidy races.

NZIA only adds further fragmentation to the various programs and policy levels rather than enforcing stronger coherence and exploiting the larger EU scale. It will be critical to develop a stronger green industrial EU policy governance to address the key challenge of coordinating different stakeholders, policy competences, and instruments. The European Union should take an example from the US whole-of-governance approach and should appoint an EU coordinating body to ensure effective political direction of the overall process.

THE WAY FORWARD FOR AN INNOVATION-BASED GREEN INDUSTRIAL POLICY

Countries are still figuring out how to reconcile the multidimensional objectives of a clean tech industrial policy with efforts to combine decarbonization with economic growth, jobs, and the creation of world competitive clean tech value chains, all while ensuring resilience and security of supply.

This paper presents the case for an innovation system at full capacity to master this multidimensionality. Clean tech innovations can be the cornerstone of a successful transition that can reconcile decarbonization, competitive value creation and jobs, and security of supply. But the innovation system cannot do this on its own. In view of the combination of knowledge and environmental externalities, together with path dependencies of dirty technologies, and given the urgency, the innovation system needs to be properly guided.

Environment-directed innovation policy cannot be neutral. It needs to make an ex ante choice for “clean” versus “dirty” technologies. It also has to choose among clean technologies and projects. Choosing among clean technologies should also take into account the path dependencies and externalities of any choice on nonselected clean technologies, calling for a good mix between vertical and horizontal instruments, with a carbon price, environmental regulations, strong horizontal complementary instruments, and recognition of the importance of ensuring competition as a level playing field. Having a vibrant innovation system that can produce a wide pipeline of new ideas, bridging them to prototype stage and beyond, should always be high on a clean tech directed policy agenda, so the world doesn’t miss out on future breakthroughs.

Central in an innovation-based clean tech strategy are public-private partnerships, where public entities mobilize innovation capacity, information, and resources at public research entities as well as at private firms to develop and deploy new solutions. What will ultimately define the success of a clean tech industrial policy is whether it succeeded in unleashing private sector innovative investments to meet society’s net-zero targets in a globally competitive and resilient manner.

Coordination among the many different stakeholders, policy governance areas, instruments, and projects will require strong operational governance for successful green innovation–based policy. And as a more directed approach is necessary, policymakers need to have the information capacity to allocate resources to technologies and projects, without creating more government failures than the market failures it will aim to address. This calls for a flexible policy design and policy experimentation, with monitoring, evaluation, and learning.

Another governance challenge has to do with the high uncertainty and the inherently long horizon. All this requires a highly competent and empowered governance body. How realistic one considers the feasibility of addressing the governance challenge will sort proponents from sceptics of green innovation–based policy.

Assessing the evidence on current clean tech innovation performance and the causal impact from deployed policies was sobering, because of both the poor quality, detail, and scope of the evidence on policy instruments and performance and the lack of analysis on policy impacts. Nevertheless, the partial and imperfect evidence clearly shows the power of the innovation system—and that it is not at full potential. Its underperformance and variance across time and countries can be associated with green innovation policy differences. In particular, the United States does not seem to fully leverage its innovation strengths for clean energy, ignoring that in this area a mix of policy instruments, with stronger coordination and commitment, are needed to shape private incentives for clean energy RD&D. It remains to be seen whether the IRA, beyond the big increase in public money, will mark a longer-term change in this respect and at what level of efficiency. The European Union faces challenges in coordinating and achieving necessary economies of scale due to fragmentation of tools, funding sources, and national industrial policies, especially in its NZIA. The current EU strategy misses a convincing whole-of-governance approach to an innovation-based clean tech industrial policy.

One recent trend is the growing emphasis on strategic autonomy and security of supply as objectives in clean tech policymaking. However, if this emphasis remains translated into local content restrictions, its effectiveness runs the risk of coming at the cost of environmental and economic efficiency and keeping the innovation system in low gear. This is particularly unfortunate also for achieving security of supply and strategic autonomy in clean tech, as the innovation system can be used to develop unique new clean tech solutions that would not only serve security of supply but also generate comparative advantages that can be exploited both locally and on world markets. Unfortunately, such an innovation-based security of supply policy trajectory is not on the radar.

THE GLOBAL ROADMAP

With climate change clearly a global challenge, a roadmap is needed with an eye toward good global outcomes. Because national clean energy industrial policy roadmaps already have a challenging agenda, as demonstrated in this paper, this will be all the more challenging at the global level. Competitiveness objectives, particularly when coupled with strategic autonomy objectives (and especially if they get translated into local content requirements), can easily turn into a zero-sum—if not negative-sum—game, reducing the scope for self-enforcing, stable international agreements.

Nevertheless, global cooperation on clean energy innovation has ample scope for a win-win. International agreements on clean energy innovation policy should find a good balance between cooperation and competition and reduce the global underinvestment problem jeopardizing global decarbonization. Global cooperation can bring advantages of cost and risk sharing and higher efficiencies from combining complementary knowledge and exploiting synergies.

More efficient clean value chains are more resilient to volatility. And national or regional competitiveness may also have the positive impact of sparking a race for innovation that spurs investments and learning spillovers, as long as there is coordination to avoid negative-sum subsidy wars and innovations can be accessed beyond their local markets.

Although there is inherently bottom-up global cooperation in the academic and private clean energy R&D community, national and regional public R&D entities are running behind in global coordination and collaboration. What is needed for a global policy agenda are (i) exchange of information and best practices, (ii) coordination of policy initiatives and joint programming, and (iii) cooperation in joint policy initiatives with pooled funding.

There are several global institutions and initiatives, but they are typically confined to bringing together partners and improving and sharing information. They all struggle with going beyond, to establish coordination and cooperation between the major players.[16]

None of the major players have international cooperation on R&D high in their clean energy industrial policy plans. Even the European Union, with its "open" strategic autonomy perspective, does not have a fully integrated clean tech industrial policy even at EU scale, and the NZIA seems to even be sending industrial policy actions back to member states. It also fails to have a proactive policy to push for international agreements with extra-EU partners, notwithstanding some notable good practices.[17]

To further the global governance of early-stage R&D in clean tech, the agencies responsible for supporting clean tech RD&D programs in their countries should be the key parties at the table, bringing along their public-private partnerships. The governance of this platform should ensure not only the sharing of information on existing and planned programs but also coordination among programs. It should make it easier to

- establish common R&D missions and funds, especially for high-cost, high-reward early-stage technology programs that may be hard to finance at a national level in the current economic climate;
- establish and fund dedicated global R&D missions and prizes for key global innovations, such as missions to develop mitigation and adaptation technologies tailored to developing countries; and
- provide access to funded technologies for the least developed countries and training for these countries' adoption of new technologies.

This global R&D platform with a selected coalition of relevant clean tech RD&D funding agencies can have a positive impact on decarbonization worldwide. The European Union and United States represent a sufficiently critical relevant mass of R&D capacity such that they can address the tragedy

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[16] Examples are Mission Innovation and Breakthrough Energy, launched at COP21 in Paris, and the UNFCCC Mitigation Work Program. None of them are sufficiently funded and holistic to reach effectively across all parts of the clean tech value chain, including upstream early-stage R&D.

[17] For instance, under its 2020 Action Plan on Critical Raw Materials, the European Union signed an agreement with Canada and convened in February 2022 to further develop policies, including to secure financial support for critical mineral projects and develop environmental, social, and governance criteria and standards.

of the global commons among them. They have a well-connected clean tech science and innovation ecosystem whose expertise and experience can be called on to create new collaborations, which are more likely to be stable and reduce incentives for cheating that might result from breaking up longer-term relationships.

International win-win agreements may be easier for the early-stage, precommercial phase of the upstream R&D process, when ideas are still far from possible commercialization and competition and when the high risks and costs call for sharing.

To align global coordination and cooperation on early stages of technology readiness with the later stages of development and deployment, this platform cannot operate in isolation. It should be regularly matched with a high-level coordination and cooperation forum, such as the EU-US Transatlantic Trade and Investment Partnership. At such a high-level forum the heads responsible for their country's or region's clean tech industrial policy could pave the way for EU-US coordination to avoid negatively spiralling subsidy wars.

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