CHAPTER 10

RESEARCH AND INNOVATION POLICIES FOR THE GREEN TRANSITION

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Summary

This chapter provides a selective review of policies that can help to foster a transition towards green technologies. R&I are crucial to tackling sustainability challenges, and public policies are needed to direct technological change towards more environmentally friendly products and processes. Supply-side policies, such as R&D funding, and demand-side policies, such as carbon pricing and clean technology standards, are complementary. While there is urgency to invest in deployment of green technologies today, investing in R&D remains a central pillar for the medium- and longer-term potential of the green transition. A critical takeaway is that there is no silver-bullet policy. Governments should adopt and implement a coordinated mix of policies to achieve carbon-emission reductions that are as large as possible at the lowest possible cost. Despite all the criticisms, carbon pricing remains an essential part of this policy mix.

1. Introduction

Humans are confronted with many environmental and natural resources issues. One of the most prominent in scale and complexity is climate change: higher atmospheric greenhouse gas concentrations result in more frequent floods, droughts, heatwaves, hurricanes and sea-level rise. Humans will undoubtedly adapt to many of those changes. However, beyond certain thresholds, opportunities for adaptation will be limited. Reducing emissions is, therefore, the only way to ensure humanity remains within a ‘safe operating space’ (Rockström et al., 2009). For a long time, studying environmental issues consisted in describing humans’ impact on the natural environment. Now that its magnitude has been ascertained, societies have decided to act, and a central question is: what can be done about it?

This chapter provides a selective review of policies that can help to foster a transition towards green technologies. Several important aspects are not covered due to lack of space but would deserve further attention, such as innovation ecosystems that could bring forward innovations at higher speed than before, financial architecture, international collaborations and the trade-offs between leap-frogging and catching-up strategies. This chapter, however, provides an overview of policies that support the supply of clean technologies, such as R&D funding, as well as those supporting demand, such as carbon pricing and clean technology standards. Demand-side policies typically aim at levelling the playing field between clean and dirty technologies, thereby fostering demand for clean products and processes.

First, Section 2 examines the role of technology in environmental issues and reaffirms the crucial part of R&I. Since reducing emissions, first and foremost, means that the economy must change the technologies it runs on, I discuss the need for public policies to direct technological change. Sections 3 and 4 review supply-side and demand-side policies, respectively, and what they mean for innovation. Section 5 examines how strong the case is for increasing spending on R&D as opposed to deployment. Finally, Section 6 highlights the necessity (and complementarity) of implementing both supply- and demand-side policies with increasing ambition over time.

2. Technology and the environment: a double-edged sword

2.1 New solutions, new problems?

R&I have the potential to lower humans' impact on natural systems. Ironically though, technology is also the reason why we have many environmental problems today. Three hundred years ago, humans had few cheap ways of converting energy into processes and goods. Starting with the Industrial Revolution in the 1850s, technological change brought us the combustion engine, modern chemistry and electricity, and with them, staggering improvements in living conditions. Technology has made our lives safer, easier and more comfortable. However, these technologies also release pollutants into the air and water and lead to the over-extraction of natural resources. As both consumption per capita and population have massively increased over the past decades, the magnitude of environmental impacts can no longer be ignored.

Technological change offers the prospect of substituting dirty technologies with cleaner ones. For example, in the 1990s, ozone-depleting substances such as CFCs were successfully phased out and replaced with ozone-safe molecules called HFCs. Electric vehicles can lower both local air pollution and CO_2 emissions (provided that the electricity they use is non-fossil). But green technologies sometimes get bad press: as they solve a problem, some argue they may create new ones that are just as thorny to deal with. HFCs, for example, are potent greenhouse gases, and therefore, even though they make the ozone layer safer, they worsen climate change. Similarly, electric vehicles may be great news for air pollution. Still, their batteries require the extraction and use of rare precious metals (often from countries with poor working conditions and even child labour (Sanderson, 2019)) and pose a challenge in how to dispose of them safely and efficiently (Harper et al., 2019).

2.2 About techno-pessimism

Whether we can (and should) rely on technology to solve environmental problems is an old debate. In the 1970s, and in particular with the publication of the book The Limits to Growth, intellectuals started discussing what 'sustainability' meant and whether economic development could realistically continue on its current path (Meadows et al., 2012). Scholars highlighted the negative environmental impacts of human activities and their reliance on finite non-renewable natural resources such as fossil fuels and precious metals. The arguments focused on whether these trends were sustainable and whether humanity could engineer a way out. The debate drew a line between two paradigms called 'weak' and 'strong' sustainability (Neumayer, 2003). In weak sustainability, technological change and input substitution (substituting dirty with clean inputs) are the primary mechanisms through which humans react and adapt to nature's constraints to support economic growth. In contrast, strong sustainability sees such mechanisms as exceptions and binding scarcity as the rule.

Debates about the role of technology are still alive and well. Should technological change be at the front and centre of the green transition? Are clean technologies an absolute requirement of success? Or will new technologies bring about new problems, and is the role of technology overstated? Typically, the limitations of clean technologies are used to argue either for inaction or for an approach focusing instead on cultural changes and 'degrowth.' The first camp, those in favour of inaction, claim that the cost of abating pollution is too high and that a net-zero transition would dangerously disrupt our economies. The strength of such arguments continues to weaken as the costs of clean technologies maintain their steady decline.

The other camp thinks that technology is more part of the problem than the solution because adopting new technologies still leaves our economy on a 'growth-addicted' path. They argue that the root causes of environmental degradation are not the technologies we use but rather over-consumption, population growth, poverty, industrial agriculture (Heinberg, 2017; Sugla, 2020). They emphasise that social norms and economic and political institutions have locked people into unsustainable lifestyles and that, even with cheap renewables, our economies will overshoot ecological limits and perpetuate social injustice. They insist, therefore, on rejecting 'the convenience of technological optimism' (Boucher et al., 2017) and instead focus on the social causes of the problems.

The most practical course of action, in their view, relies on a cultural shift that changes consumption patterns rather than finding cleaner means of production. Concretely, people should consume less energy, fewer goods (especially those with high ecological footprints), drive less and take fewer flights (and to closer destinations). We should also eat less beef or move altogether to vegetarian diets; embrace sobriety and minimalism – and contraception, since population growth is usually seen as a core driver of environmental impacts.

2.3 The need for directed technological change

There is no necessity to think of consumption and production in opposition. Shifts in cultural norms and technology change are not mutually exclusive. Both will be welcome and needed, and, in fact, innovations can be an important driver of both. For example, many employees worked from home during the COVID-19 pandemic, saving much energy that would have otherwise been spent on commuting and on heating and lighting office buildings. Without advancements in information and communication technologies, most employees would not have been able to work from home.

Arguably, blind faith in technology will not solve any issue on its own. Solutions to problems typically do not fall from the sky, or from market economies when markets are blinded to the problems. The response to the environmental crisis does not consist in waiting for cleaner technologies to come about but instead in designing government interventions that will tackle the various market failures at different points of the technological change pipeline. The story about how solar became cheap, for example, highlights how multiple policies from different jurisdictions at different points in time took turns in supporting the supply of and demand for photovoltaic technologies, which eventually led to impressive cost reductions (Nemet, 2019).

Notably, the policy response is not just about accelerating innovation in the general sense. What matters is the direction of technological change: clean technologies must improve, not just in absolute terms, but relative to dirtier ones. Scholars usually conceptualise the core issue at stake as a race between clean and dirty technologies (Acemoglu et al., 2012). Just like in Aesop's fable 'The Tortoise and the Hare', the two contenders are not on an equal footing: cleaner technologies remain more expensive than their dirtier substitutes. However, as we know from the fable, this does not preclude the initially less advanced sector from winning the race. And, indeed, an appropriate mix of policies can ensure that technological change is directed towards clean sectors.

2.4 Towards a diverse mix of policies

Economists have identified several market failures that contribute to clean technologies being under-provided (Jaffe et al., 2005; Popp et al., 2010). First is the environmental market failure: pollutants are emitted as a side effect of economic activities and impose a cost on society overall, for example, due to their negative impacts on the climate, human health and ecosystems. This is what economists call negative externalities. Typically, economic agents decide how much to produce and consume while ignoring that these economic activities incur broader social costs. The policy prescription here is straightforward: internalise the externality, that is, tax pollution. Importantly, as long as pollution is not priced in, it will be relatively cheaper to use polluting technologies. Demand-side policies such as carbon pricing ensure that clean technologies compete on an equal footing with dirtier ones and, therefore, support the demand for clean technologies.

A second market failure relates to the public-good characteristics of knowledge. When knowledge is created, it can often be acquired and used by others for free: economists call this positive externalities or spillovers. As a result, the private marginal returns from generating knowledge are smaller than the social ones, which leads to knowledge and new technologies being under-provided, even when intellectual property regimes are in place (e.g. patents). Again, the policy prescription here is straightforward: governments should support knowledge creation and technology development, for example, by funding R&D activities. Furthermore, technologies that generate higher knowledge spillovers should receive higher amounts of funding, and this seems to be the case for greener technologies. Indeed, Dechezleprêtre, Martin and Mohnen (2014) show that patents on clean technologies receive more follow-on citations than those on dirty technologies, suggesting that they generate more knowledge spillover.

Beyond knowledge spillovers, scholars have also shown that path dependency in R&D provides a further rationale for supporting R&D funding in clean sectors. Aghion et al. (2016) argue that firms that have a lot of prior experience with dirty technologies will find it more profitable to keep innovating in dirty technologies. This makes it harder to incentivise firms to start innovating in clean technologies. R&D subsidies are the best tools to help to break such path dependency as they provide the needed incentives to begin accumulating knowledge and expertise in clean technologies.

Although pricing pollution and subsidising R&D activities are the two most important policy recommendations, other market failures require governments' attention on the supply and demand sides of green technologies. On the supply side, new technologies typically exhibit strong learning-by-doing effects (a type of dynamic increasing returns) and increasing returns to scale in production. Hence, policies that subsidise the adoption of a particular technology (e.g. feed-in tariffs) can be justified to foster higher levels of adoption, which ensure that the increasing returns are realised.

There are also other market failures on the demand side that justify the use of policies other than carbon pricing. In the context of energy efficiency, several issues may lead to an under-investment and under-adoption of energy-savings products (Gerarden et al., 2017). For example, consumers may have high discount rates or may lack information about the technologies, such as their costs. There can also be agency problems when tenants would benefit from upgrades that landlords must pay for. In these cases, the use of standards, such as mandating a minimum energy-efficiency performance, can be Pareto-improving.

Another example where a technology standard is justified is the case of electric-vehicle charging stations. The benefits of purchasing electric cars increase as the network of compatible charging stations expands. However, in the absence of government regulations, manufacturers may develop chargers specific to their own brands, leading to a fragmented network. The government's role here is to mandate a technology standard for the charging plugs so that all vehicle owners can use them (Li, 2019).

2.5 Policy trade-offs

The variety of market failures in green technological change establishes the need for a mix of policies that go from carbon pricing and R&D subsidies to technology standards and adoption subsidies. There is broad consensus that carbon pricing is complementary to other policies targeting the upstream part of the innovation pipeline, but there has been more discussion (in the scholarship and in public debates) about the types of environmental policy instruments that we should use to deal with demand-side issues.

Some political scientists argue that although elegant and simple in theory, carbon pricing is grossly inadequate to tackle climate change (Mildenberger et al., 2020). They suggest we abandon the idea of pricing carbon and, instead, intervene with a mix of standards, adoption subsidies, procurement policies and regulations that would create a demand-pull for clean technologies. For example, policymakers can mandate clean electricity, clean cars or clean cement. In practice, many jurisdictions have already done so, e.g., with the renewable portfolio standard in the USA. The main argument in favour of standards is that they are much more politically palatable while still leading to increased adoption of low-carbon alternatives, like a carbon price would, in theory, do. A key difference is that the standards force adoption regardless of the costs of clean technologies. For that reason, they lead to higher compliance costs in the short term and are not considered as cost-effective.

Importantly, environmental policies with higher compliance costs in the short term imply that there may be fewer public resources to spend on supply-side measures such as R&D subsidies on clean technologies, which eventually are critical to lower long-term compliance costs. The overall policy objective should be about emission reductions at the lowest compliance cost possible both in the short and longer term. Supply- and demand-side policies are both essential to that objective, but given that government budgets are limited, there is a risk that costly demand-side measures get implemented at the expense of further support for supply-side policies. This opens a vital policy debate about the proportions in which we should do both, which I examine more closely in Section 5.

3. Supply-side policies

3.1 Clean-energy R&D spending

This section discusses how much public and private actors spend on energy R&D. According to Cunliff (2020), the energy and automotive industries invest about 0.5 % and 3.2 % of revenues in R&D, respectively. These numbers are much smaller than in other industries such as pharmaceuticals. Several factors may explain why private-sector investments in energy innovation are low. First, clean and dirty electrons look the same to consumers, and, as a result, price discrimination on the type of electricity is not effective, and clean technologies must compete on prices. The industry is also heavily regulated with strong policy pressures to keep prices low.

On the supply side, the industry's typical high capital intensity and long payback periods require patient investing with very deep pockets, which private-sector firms may not be able to provide easily. As a result, the public sector has a complementary role to play by having higher tolerance to risk and payback time, which is also critical when supporting the development of early-stage and more radical innovations. On the other hand, the private sector is better positioned to improve mature technologies and to develop nearly mature ones into marketable products. Firms have strong incentives to invest in these sorts of incremental innovations as they can easily materialise into short-term financial returns.

As highlighted above, R&D spending on clean energy in the private sector has not been high. Unfortunately, the COVID-19 pandemic may have worsened the situation. A key finding from an IEA survey run in May 2020 is that many firms believe that their R&D budget will likely be reduced, or at least has become more uncertain due to the COVID-19 crisis (IEA, 2020). Thankfully, public R&D funding seems to be less impacted, and some recovery packages have distinctive green flavours. In addition, in 2015, 24 countries came together under the Mission Innovation initiative to pledge a doubling of their annual clean energy RD&D budget by 2020. These countries represented more than 90 % of global public investments in clean energy at the time, and a doubling of their budget would have increased funding from USD 14.5 billion in 2015 to USD 28.9 billion (Myslikova et al., 2020).

Five years later, only a few countries had met the pledge: the Netherlands (+185 %, to EUR 285 million), the United Kingdom (+175 %, to GBP 550 million), South Korea (+100 %, to KRW 1.1 billion), as well as Chile, Japan and Norway (Mission Innovation, 2021a). If not doubling, at least, almost all countries increased their budget. The EU, for example, went from about EUR 1 billion in 2015 to EUR 1.8 billion in 2020; Germany from EUR 450 to EUR 780 million; and France from EUR 44 to EUR 49 million. The USA, which invests the largest amount, increased by 42 %, adding another USD 6.8 billion to the US Department of Energy (DOE)'s USD 14.8 billion energy budget. By 2019, China had added USD 2 billion to its clean energy R&D budget, which in 2015 was about USD 3.8 billion. Some emerging economies such as India or Brazil also substantially increased their budget.

In recent meetings, the Mission Innovation members did not reassert a pledge to keep increasing their clean energy budget after 2020. Instead, the initiative now focuses on more intangible aspects such as knowledge exchange across members and public-private partnerships (Mission Innovation, 2021b). Those aspects are, indeed, essential complements to R&D funding.

Still, it will be crucial that countries demonstrate their commitment to, at least, maintaining the current levels of clean R&D spending over the coming decades. Indeed, constraints will also come from human capital: training a new generation of young researchers will take several years, and clear signals that R&D support is there to stay will be instrumental in convincing talents to choose clean energy careers. There is evidence for such high adjustment costs in the case of the US National Institutes of Health (NIH) doubling of their budget between 1998 and 2003 (Freeman et al., 2009).

3.2 Beyond R&D spending: improving the involvement of the private sector

Beyond R&D spending, improving and supporting the involvement of the private sector should be a key policy objective of the green transition, especially given the low levels of private R&D spending in the energy industry. The recent success story of vaccine development during the COVID-19 pandemic has prompted renewed interest in how effectively the public and private sectors can cooperate. Other examples include the US space race and the Sematech public-private partnerships, highlighted in Myslikova et al. (2020). More insights into how to emulate these success stories would be useful.

Knowledge exchanges between public and private actors should be supported and fostered throughout the innovation pipeline. An excellent example in this area is the German network of Fraunhofer Institutes: 67 applied research institutes that bring together scientific and engineering expertise in different technological fields and are partly funded by industry (Dechezleprêtre, Martin and Bassi, 2019).

Other initiatives focus on demonstration and deployment rather than R&D. This is the case of Breakthrough Energy Ventures-Europe, a pilot fund investing in European companies working on low-carbon solutions that amounts to a total budget of EUR 100 million, half from the European Commission and half from Breakthrough Energy Venture, a group of about 50 private firms and individuals spearheaded by Bill Gates. Such public-private partnerships are ideal for building on the respective strengths of the public and private sectors. As highlighted before, energy R&D needs patient investors; the public sector here is therefore welcome. Conversely, the private sector is better positioned to identify promising companies because it holds more expertise and information about technologies and markets.

Finally, the Mission Innovation initiative could also play a role in spurring improvements in reporting systems and harmonising energy RD&D data. Tracking clean energy R&D spending in the private sector is not easy, and the initiative could ask its member countries to require firms to report investments made in clean energy R&D, as well as to clarify how R&D within state-owned firms is reported in official numbers (Myslikova et al., 2020).

3.3 Clean energy innovation policies in the EU and the USA

3.3.1 USA

The USA has historically been the leading contributor to clean energy R&D funding. Figure 1 illustrates the key initiatives for energy innovation policy, which, in the US, are managed within the DOE. The Office of Science supports early-stage and fundamental energy research, in particular via the National Laboratories. The applied research activities are structured around 20 programme areas such as energy efficiency, renewable energy, electricity, fossil energy and nuclear energy. These programmes include a wide range of tools aimed at supporting technologies at different levels of maturity: grants and tax incentives for supporting the upstream part of the pipeline (i.e. R&D) and loan guarantees to support demonstration projects. To help finance deployment and infrastructure, the DOE also leverages other types of credit enhancement and bond financing (Cunliff, 2020).

In parallel to the programme areas, the DOE has created a separate semi-autonomous agency, called ARPA-E, that focuses on high-risk high-impact early-stage technologies. ARPA-E stands outside of any of the other technology-specific programmes and targets topics that are generally cross-cutting. It is an attempt to reapply the success story of the Defense Advanced Research Projects Agency (DARPA). As in DARPA, the programme managers are critical elements: those managers are technical experts recruited from industry or academia for a period of 4 years (Bonvillian et al., 2011). The distinctive features of the agency seem to be bearing fruit: projects funded by ARPA-E are five times more likely to produce a patent or scientific publication than projects funded by programme areas. Since 2007, when ARPA-E was created, 850 projects have been funded with a total of USD 2.3 billion, and 161 projects attracted USD 32 billion in follow-on private investment (Cunliff, 2020).

Although the US DOE budget for energy innovation has increased over the last few years, it remains lower than the all-time high reached in 1978. In 2020, the US DOE budget was USD 8 billion, that is 0.04 % of US GDP. In 1978, the budget was, in fact, higher with USD 10.5 billion (in 2020 USD), corresponding to 0.14 % of GDP at the time (Cunliff, 2020). Given today's US GDP, this would be equivalent to a budget of USD 32 billion today, 4 times higher than the actual amount invested in 2020. The last three decades have not placed energy at the very top of the priority list. In the 1970s, oil crises and energy security concerns made investing in energy a bipartisan move. Since then, spending has been decreasing both in overall levels and in percentage terms; other areas, for example, health, have not suffered the same fate.

In the 2000s, the budget increased slightly, presumably because energy prices were rising, and some worried that the USA was falling behind in clean technologies (Cunliff, 2020). A significant one-time increase also came with the post-financial crisis recovery packages in 2009, particularly the USD 2.3 billion dedicated to creating ARPA-E. Since 2015, the DOE energy R&D spending has slowly increased from below USD 6 billion to USD 8 billion in 2020. With a total increase of more than USD 2 billion requested for the 2022 budget, the US energy-innovation budget may finally overtake the historical high of 1978 (Cunliff and Nguyen, 2021). However, we are still far from the historic high of 0.14 % of GDP, and, as highlighted before, this is also far from the doubling pledge made as part of Mission Innovation.

3.3.2 EU

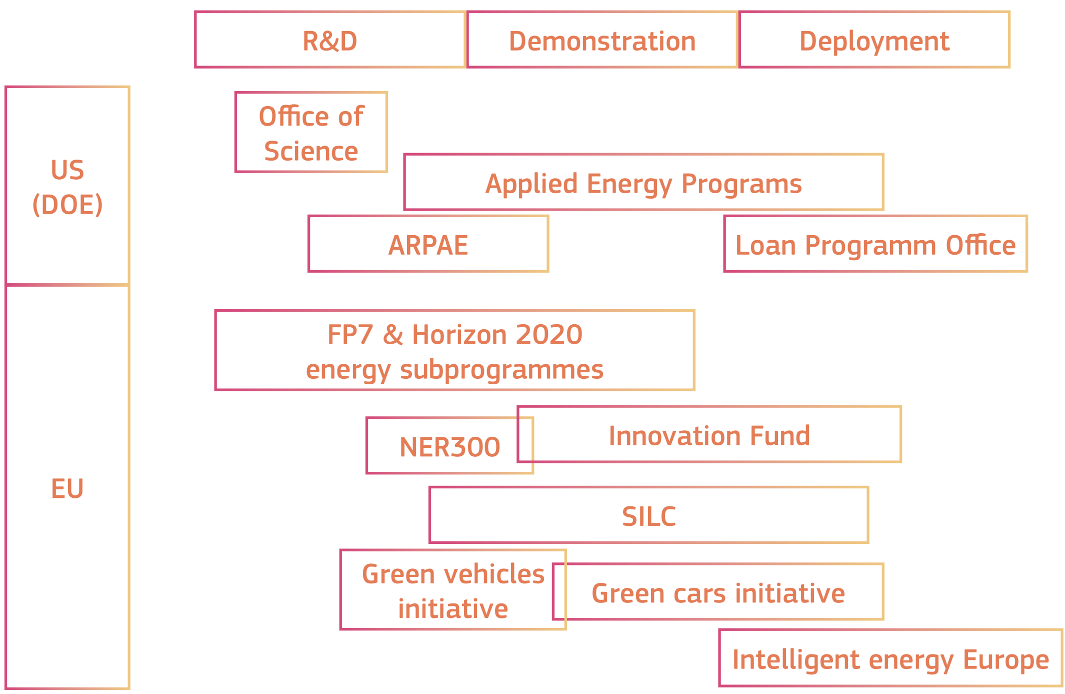
The European energy innovation policy landscape is scattered across several initiatives. The main channel for RD&D funding is via the Framework Programmes (FP) for Research and Technological Development. The FP introduced a specific energy subprogramme for the first time in 2007, with an allocated budget of EUR 2.35 billion. In 2014, the programmes were reformed (and rebranded under the name of 'Horizon') to adopt a more mission-oriented approach that organises funding, in part, around key societal challenges (Mazzucato, 2018). In this context, Horizon 2020 almost tripled the amount of funding to clean energy with EUR 5.9 billion for the 'Secure, Clean and Efficient Energy' challenge. This came in addition to another EUR 6.3 billion for 'Smart, Green and Integrated Transport' and EUR 3 billion for 'Climate action, Environment, Resource Efficiency and Raw Materials' (European Commission, 2021).

The move to a mission-oriented approach takes direct inspiration from the US DARPA and ARPA-E agencies and is an attempt to reapply lessons learned from past innovation success stories. Ex-post evaluations will be useful to understand to what extent the Horizon programmes successfully supported technological change and to assess what new lessons can be learned. Ex-ante, one may already highlight some potential pitfalls. First is the possibility that other considerations than innovation objectives influence the design and management of the programmes. A review of the selection process and how selection criteria are applied in practice would be informative. Second, a strategy of aiming for high-risk, high-reward projects requires a certain tolerance for failure, which may be challenging to implement at the European level. A central question is who takes responsibility for the risk and, incidentally, who can afford to lose political capital over failure.

Although mission-oriented R&D programmes in the EU have emerged only recently, several initiatives, such as the European Technology (and Innovation) Platforms, were already in place in the early 2000s to improve knowledge exchange in industries that were identified as strategic (e.g., wind and solar). However, these initiatives did not come with money attached and focused on more intangible aspects such as coordinating stakeholders (Consult, 2008).

Other smaller programmes exist beyond Horizon to support clean technologies, particularly at the demonstration stage. For example, NER300

Figure 10-1: Key energy innovation policies in the US and in the EU



Source: author's elaboration.
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-10-1.xlsx

and its successor, the Innovation Fund, recycle the revenues from the sales of new allowances in the EU Emission Trading Scheme (ETS) to fund projects on low-carbon technologies that stand between R&D and commercialisation. Initially endowed with a EUR 2 billion budget, the next phase has a larger budget of EUR 20 billion. In addition, the Sustainable Industry Low Carbon (SILC) was a small initiative between 2011 and 2020 that provided funding for the development, demonstration and dissemination of low carbon technologies in industrial sectors. Its successor, SILC II, has been included within Horizon 2020. NER300 and SILC also initially funded projects closer to the development stage, such as pilot plants, but the successor programmes are now more focused on demonstration.

Another programme worthy of mention is the EU Green Cars Initiative, which started in 2008 with a EUR 5 billion budget for public-private partnership for R&D projects focusing on electrification in the automotive industry. At the time, this initiative was part of the EU's wider Economic Recovery Plan. In 2013, the initiative was prolonged, rebranded as the European Green Vehicles Initiative, and funded as part of Horizon. Finally, Intelligent Energy-Europe was a EUR 45-million programme that, until 2013, funded soft-skills projects on energy such as capacity building, knowledge and skill exchange, policy input and awareness raising and information provision.

4. Demand-side policies (and their impact on innovation)

4.1 The arguments in favour of carbon pricing

The arguments in favour of pricing carbon rely on two fundamental aspects: static efficiency and cost-effectiveness. Static efficiency ensures that we reduce carbon emissions to the point where it makes us better off. In other words, at the margins, we should be indifferent between paying for an extra unit of pollution abatement or being exposed to one more unit of pollution. In the context of climate change, economic theory dictates that the carbon price be set to the level of the social cost of carbon, a number that has proven elusive in many regards and has lost relevance for some policymakers (Atkinson et al., 2018).

Indeed, the net-zero targets announced by various governments imply that the policy objective is to abate a particular **quantity** of carbon rather than the amount that would follow from setting a particular **price** on carbon. The focus on targets is evidence that the policy debate has moved beyond caring about efficiency, but this does not mean that carbon pricing is no longer relevant. Indeed, the level of the carbon price can be chosen based on technological options in order to remain consistent with specific targets. For example, discussions about the EU ETS have focused on limiting price variations, for example, by setting a floor price that would make it never profitable to generate electricity using coal or that would make green hydrogen competitive without subsidies. Kaufman et al. (2020) estimate that for the USA to be credibly on a net-zero path, the carbon prices need to be between USD 36 and USD 64 per tCO_2 by 2025 and between USD 77-124 per tCO_2 by 2030.

The second key theoretical motivation for carbon pricing is cost-effectiveness. Carbon pricing ensures that emission reductions are realised at the least cost because it is technology-neutral and it incentivises all economic actors to look for ways to reduce pollution. This mechanism leads to the cheapest technologies being adopted and ensures the lowest possible compliance cost in the short term.

4.2 The induced innovation effect of carbon pricing

Carbon pricing also incentivises economic actors to innovate and develop cheaper clean technologies. Doing so, firms can lower the cost of abating carbon: this is what economists call 'dynamic efficiency'. Importantly, this ensures that compliance costs are as low as possible in the longer term. Carbon pricing is able to induce innovation because it creates a market for clean technologies, thereby creating expectations of demand, which, for investors, means there will be profit-making opportunities in clean sectors. Without expectations of future profitability, investors would not be willing to invest money, time and effort into developing new technologies. As such, demand-side policies such as carbon pricing are critical to the dynamics of green innovation.

Carbon pricing, however, may not stimulate innovation as much as we would like. It may be more effective at fostering incremental innovation on technologies close to market rather than radical innovations further away from commercialisation. It remains a demand-side measure that is most effective at promoting the adoption of alternatives that are commercially available. Carbon pricing will provide incentives for firms to innovate, but those incentives will be stronger for technologies that are not characterised by high levels of uncertainty, for example, when reducing costs at the margins on technologies that are already proven. This may explain why we see path dependency in innovation outcomes. As highlighted before, supply-side support such as R&D subsidies is vital in such cases.

4.3 Political economy hurdles

Many industrialised countries are trying to set up carbon pricing mechanisms, either via carbon taxes or ETSs. Governments, however, have been very limited in their political ability to set high prices or to increase the number of firms and industries covered by ETSs. This is mainly due to concerns about competitiveness. In the USA, constrained by the low bi-partisan support for carbon pricing, the Biden administration is moving ahead focusing instead on sectoral standards and green public procurement.

Much of the debate around the pros and cons of carbon pricing focuses on the massive political economic hurdles that it faces. It is unpopular, and some also argue that it is an easy target for polluting lobbies to demonise, which tends to polarise the debate and leads to a policy standstill (Mildenberger et al., 2020). The only politically feasible prices may be too low to induce the changes needed in the necessary timescales (Hepburn et al., 2020). Therefore, other instruments such as regulations or standards, even if not the first best according to economic theory, must be used.

Arguably, the level of the carbon price is critical not just to spur adoption of more expensive clean technologies but also to induce innovation. The stronger and more stringent the policy, the clearer the signal sent to investors and innovators. Some have argued that there is little empirical evidence for the induced innovation effect of carbon pricing, but few countries have enacted high carbon prices. We should not be surprised if low carbon prices provide weak incentives to invest in clean energy R&D. Calel et al. (2016), in fact, showed that innovation did increase with the EU ETS but only after a substantial price increase that took place in the second phase.

4.4 Standards as imperfect alternatives

High carbon prices are unlikely to be politically feasible to implement, at least as long as clean technologies remain expensive. Standards and regulations may be more appealing because the costs are less visible. However, one way or another, citizens still pay the bill for carbon abatement. And the distributional aspects could be worse than those of carbon pricing (Metcalf, 2019; Rausch et al., 2014).

Greenstone et al. (2020) estimate that the costs of renewable portfolio standards in the USA were generally above USD 100 per tCO_2. The Legislative Analyst's Office of the State of California highlighted that the state's rooftop solar policies may have cost between USD 150 and USD 200 per tCO_2 (Petek, 2020). Gillingham et al. (2018) also reviewed many similar studies, and the overall conclusion is that many environmental policies to reduce carbon emissions end up being multiple times more expensive than what would usually be expected of a carbon tax.

As standards, subsidies and regulations accumulate and overlap, the shadow price of some emissions can also become much higher than others. This is the inherent inefficiency of the regulatory approach: the cheapest technologies are not necessarily used, leading to higher compliance costs than if the whole economy had one carbon price. The fundamental argument in favour of carbon pricing, as opposed to standards, is its ability to reduce compliance costs in the short and longer-term. Concretely, it means that we can reduce emissions more for the same costs. Resources are scarce, and carbon pricing can direct those resources to the cheapest emission reductions.

Designing and implementing specific guidelines for each sector is also a difficult task. To decide what and how things are produced and consumed, policymakers must know a lot about technologies, such as their emissions, costs and future potential. The private sector typically knows much more about these things, and regulators, who are subjected to lobbying, may find themselves at a disadvantage when negotiating and drafting regulations. The odds of policy mistakes, such as a regulatory design incurring unfortunate unintended consequences and administrative errors or malpractice, are also much higher.

Furthermore, the process of designing regulations can take many years. If we are pressed for time, as is the case, there is an important argument to be made in favour of carbon pricing, which is faster and easier to implement since it does not require a central authority with much knowledge. A price on carbon changes the whole system at once by shifting choices and behaviours in many different sectors without needing to know much. The level of ambition is also very transparently demonstrated by the level of the price itself. Within a regulatory approach, it is less obvious what defines ambitions, and there is a higher risk that lobbying restrains their magnitude (Majkut, 2020). Finally, regulations are not likely to be more popular with industry than carbon pricing because many firms favour straightforward and predictable climate policies rather than a regulatory piecemeal approach.

4.5 Carbon pricing, systemic changes and path dependency

Framing the problem as a market failure leaves some with a definite taste of over-simplicity, a belief that simply pricing in externalities will not suffice, and a view that a more systemic approach is needed (Rosenbloom et al., 2020). When it comes to reaching and impacting all parts of a system at once, carbon pricing is, in fact, a great policy tool. However, an argument can be made that changing prices at the margin may not help as much as we would think if many of changes needed are structural in nature and if there is path dependency.

This is most evident with urban planning, for example, with large cities designed around the use of automobiles. Infrastructure was developed in blissful ignorance of pollution impacts. This infrastructure is still with us and constrains many of our marginal choices. Similarly, it may be argued that our history of cheap but polluting energy has locked cultural norms around comfort and attire that are not helping to decarbonise heating systems. Since our economies have developed without paying much attention to environmental impacts, we may have locked ourselves into carbon-intensive paths.

The assumption that there is stickiness in the way our economy works and in the way agents and firms make their choices implies that changing prices at the margin may not suffice. Structural aspects may respond weakly or slowly to marginal price changes, and in these cases, standards and public spending on green infrastructure can be more effective (Hepburn et al., 2020).

5. Supply vs demand: investing in R&D or deployment?

5.1 Too late for R&D?

Policy advocacy for R&D spending has never been an easy task. Taking a technology from the lab to commercial deployment requires time, financial and human capital investments. The process can also be a long and twisted road paved with slow-paced activities and uncertain returns. Typically, many incremental successes are made along the way, but they rarely make the headlines, despite their importance to improving our understanding of technologies and reducing their uncertainties and costs.

As a result, R&D investments look to some as money not well spent, especially given the opportunity costs. For example, McLaren et al. (2020) argue that focusing on developing technological solutions delays concrete immediate actions and advocate instead for spending more on deploying behavioural responses and technologies that are already available.

A sense of emergency has also emerged in recent policy discussions about climate change, with calls for massive emission reductions to happen in the next 10 years. Investing in R&D does not chime well with such calls because it does not translate into emission reductions in the short term. The framing of emergency may lead some to believe that it is 'too late' and that we cannot take the time to invest in R&D.

5.2 RD&D support remains critical

Citizens may even doubt that we need more R&D as they regularly hear that we 'have' the necessary technologies. For example, in 2014, the IPCC report concluded that carbon-free economies were feasible. There has, indeed, been very impressive progress in renewable energies, but this is not sufficient. We know which technologies we will need but the issue is that many are not ready yet.

The IEA modelled what it would take to reduce emissions to meet a net-zero target by 2050 (IEA, 2020). According to their model, 17 % of the emission reduction relies on technologies that are still in the lab or prototypes. Another 17 % depends on technologies that are only at a demonstration stage. Another 41 % of reduction relies on technologies that are today in early adoption. Finally, only 25 % of reduction can depend on mature technologies such as wind and solar electricity.

Key technologies have yet to receive adequate support, for example, grid-scale storage, which will be needed as more of our electricity is generated by renewable energy. Hydrogen is also a central technology to reduce emissions in hard-to-abate sectors such as long-distance shipping, steel and cement. Finally, carbon capture and storage has seen much progress over the last decade and is included in most pathways to net-zero. Yet it is still not commercially ready.

Many technologies have been shown to work in the lab or at a pilot scale. But they must be demonstrated at full scale. In other words, they must be shown to work at the scale at which they would eventually be commercialised. Demonstration is crucial to convince investors that the technology performs as intended and that the costs are as expected. Only then can a technology be widely adopted. This process can take many years, even decades, and can suffer from persistent uncertainties and rollbacks. Scientists and engineers may have ideas about how to make the technology cheaper or more resilient to field conditions, but there is also no guarantee that things will work out.

Further R&D investments are therefore crucial to ensure that we can indeed reduce emissions in 20 or 30 years from now (Harrabin, 2020). If everything goes well, high-income countries will then aim at 100% clean electricity rather than 80%, and the focus will also shift to hard-to-abate sectors such as cement, aviation and shipping. The pace of progress is inherently linked to public policies, and given the lag times in innovation processes, the policies decided and implemented today will determine the speed and success of green technologies tomorrow. How much we invest in R&D this decade will therefore determine whether we can fully decarbonise in the medium and longer term.

5.3 Are we spending too much on energy R&D?

Another crucial question is whether spending on R&D and spending on demand-side policies such as adoption subsidies are appropriately balanced. Are we spending too much on one and not enough on the other? An argument in favour of demand-pull policies is that they allow cost decreases thanks to learning by doing, learning by using and economies of scale. Hence, investments in both supply-side and demand-side policies may be warranted. But, in the end, the optimal balance will depend on the magnitude of the spillovers at play.

Fischer et al. (2017) develop a model to look at the optimal ratio of deployment vs R&D spending and find that spendings disproportionately favour the former. They argue that, for a technology such as wind, the ratio should not be more than one. Only when assuming extreme learning by doing spillovers, the ratio may rise as high as 10. Next, they compare their theory-derived optimal ratios with empirical estimates. In 2010, the six largest EU countries spent EUR 315 million in R&D on solar and wind. Meanwhile, several key regulations were in place to spur the adoption of solar and wind, which bore an implicit cost of EUR 48 billion for the same year (Zachmann et al., 2015). The ratio between the two types of spending was, therefore, about 150. It seems reasonable to qualify this as unbalanced.

In the context of solar, we have evidence that R&D money was money particularly well spent. When looking at the dramatic drop in photovoltaic costs, we may wonder how much of it can we really attribute to R&D (as opposed to non-R&D phases of technological change). Kavlak et al. (2018) argued that this may be as much as 60% and suggest that R&D was a strong contributor to this technology due to the intense competition between different designs (e.g. crystalline silicon and thin films). Admittedly, economies of scale have also played an important role, especially in recent years, and account for about 20% of cost declines.

A few other studies make a similar case for other energy-related technologies. For example, Dowd (2017) attempted to quantify the benefits generated by investments made by the DOE's clean energy R&D programmes. He estimates that those investments offered a return of USD 32 on every dollar invested. These studies already make a strong policy case for increasing overall investments in R&D, but a further rationale is that those investments generally do not spill over abroad as much as demand-pull policies, argument which policy makers may find effective in swaying public opinion (Dechezleprêtre and Glachant, 2014).

6. Demand-side and supply-side measures need each other

6.1 For domestic policy-making

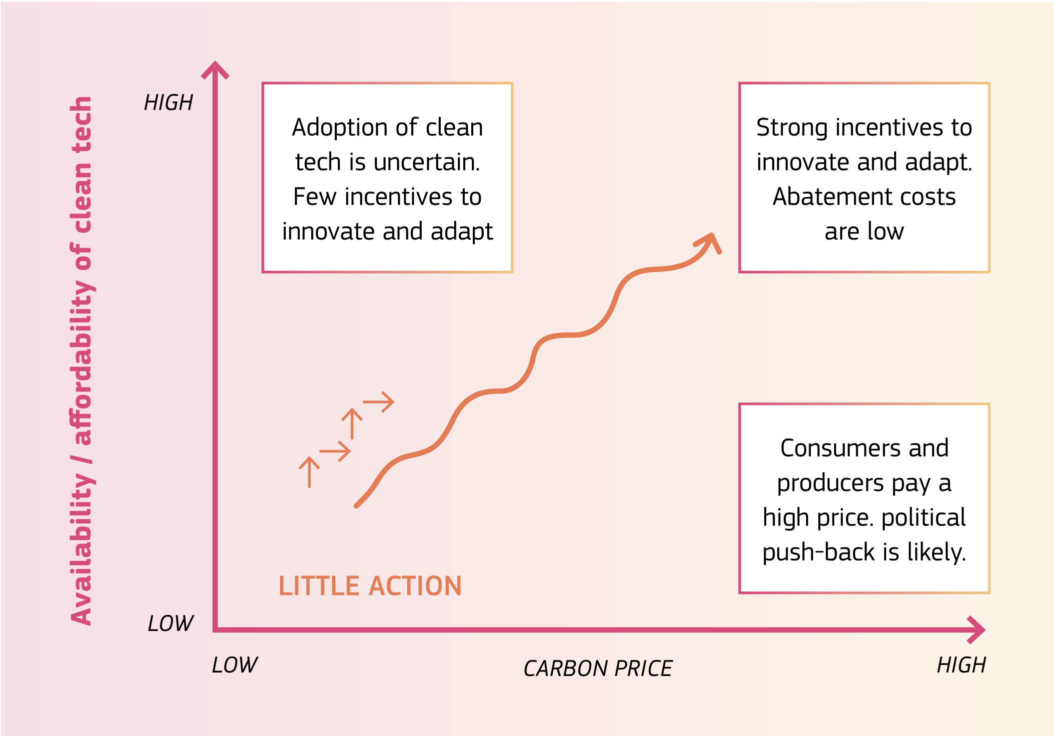
An important argument in favour of putting science and innovation front and centre of the green transition is that green innovations make the benefit-cost equations of domestic environmental policies more attractive and less politically polarising. Often, governments do not sufficiently intervene to tackle environmental issues because they fear that would make them unpopular with the general public or because special interests have lobbied them effectively. As the costs of renewable energies and battery technologies have gone down, we have seen many countries announcing plans to increase adoption. For example, Texas, a mostly republican state with an ever-present oil and gas industry, has seen its share of wind power increase steadily over the years. The abundance of wind resources and the lower cost of wind turbines meant business opportunities, which spoke louder than climate sceptics' words (Subramanian, 2017). Cheaper clean technologies, therefore, represent a formidable opportunity to make environmental policy more ambitious.

On the other hand, a carbon price would level the playing field for clean technologies, creating expectations of future business opportunities in clean sectors and fostering innovation and further cost reductions. In short, carbon pricing and innovation need each other to take our economies onto carbon-neutral paths. Figure 2 illustrates this point. At one extreme, in the bottom-left part of the graph, let us imagine a world with no commercially available clean technologies and a low carbon price. Clean alternatives are too early-stage and uncertain, and the carbon price is too low to provide strong incentives for firms to invest in these alternatives. Consumers, therefore, continue to buy carbon-intensive products while paying a small carbon fee. In these conditions, we may expect little carbon abatement to happen in the present and in the future.

The bottom right of the graph is a world with a high carbon tax but few commercially available clean technologies. In this case, the carbon price makes carbon-intensive production and consumption expensive. In the long term, this should induce innovation in green technologies, but in the short term, consumers and producers pay a high price for a limited amount of carbon reduction. Indeed, as Heal et al. (2019) highlight, alternative technologies must be commercially available for a carbon price to work.

In the opposite scenario, at the top-left corner, the carbon price is low but clean technologies are cheap. In this case, the adoption of clean technologies is uncertain because it will depend on whether clean technologies become more affordable than their carbon substitute. A small carbon price, however, should, in this case, be sufficient to phase out carbon-intensive technologies.

Figure 10-2: Combining carbon pricing and innovation policy to accelerate the transition to net-zero



Source: author's elaboration.
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-10-2.xlsx

Finally, a world with cheap clean technologies and a high carbon price, at the top right, would have strong incentives for innovation and adoption while abatement costs remain low. This is the best possible state of the world, which governments should strive to foster. Arguably, today, we are closer to the lower-left corner than the top right. But by combining both supply-side and politically acceptable demand-side policies, including carbon pricing, we may step by step take a path to the top-right corner. As clean technologies get cheaper, the burden imposed by carbon pricing will reduce and higher carbon prices will progressively become politically acceptable.

6.2 For global cooperation

As argued above, improvements in greener technologies lower the costs of environmental policies and make them more politically acceptable. A similar logic applies at the international level: cheaper clean technologies will make global cooperation easier. This should be seen as a core argument for making science and innovation the top priority. Many environmental problems are global in nature. Climate change can be tackled only if CO_2 emissions are reduced at the global level. The UNFCCC was set up to provide a framework for countries to discuss and negotiate how to do so. The inherent weakness of such international negotiations is that no third party can enforce the agreements. No world government exists, and countries remain sovereign.

The literature on the economics of IEAs has considered at large how to construct agreements that would be self-enforcing (Barrett, 2005). A self-enforced agreement makes it costly for a country to defect on its pledge. For example, the Montreal Protocol to protect the ozone layer included trade restrictions and possible trade sanctions in the case that a signatory did not reduce its CFC emissions by as much as it had committed itself to do. However, no sanctions were ever needed because the chemical industry was quickly able to offer viable CFC substitutes.

Unfortunately, self-enforced agreements are rare. But theory predicts that we are most likely to negotiate them if the costs of mitigating the environmental issue at stake are low (Barrett, 1994). This does not necessarily mean we must have all the ins and outs of green technologies figured out, but that, at least, some technologies must exist on paper or in the lab, and a path to commercialisation is seen within reasonable uncertainties. That is the story behind the success of phasing out ozone-depleting substances. In 1987, high-income countries negotiated an agreement that scholars have qualified to be self-enforced. With this agreement, countries committed their domestic industries to reducing CFC emissions. The reduction targets set in Montreal were far from a full phase-out which environmental NGOs at the time requested. But they were a concrete step that countries deemed technologically feasible.

What happened next is possibly the best example of induced green innovation at the global level. Firms scaled up their efforts to ensure they would meet the targets. Evidence of such efforts is the large increase in the number of patents and scientific articles in the aftermaths of the treaty's signature (Dugoua, 2021). The treaty was soon renegotiated to make targets more ambitious and include more substances in the list of molecules to phase out. Today, the ozone layer is recovering.

Improving the science and engineering of green technologies will be a key enabler of global cooperation on sustainability. Even if scientists and engineers do not provide us with all the ready-made solutions that we would like to have at our disposal, they can nonetheless provide us with a beginning of a solution that may be enough to convince parties to lock our institutions into the right incentives.

7. Conclusions

An array of policy solutions is available to policymakers to direct technological change away from dirty and towards clean technologies. Supply-side policies such as R&D funding are better positioned to impact and direct the earlier stages of technological change. Policies such as carbon pricing, standards or adoption policies create a demand-pull for clean technologies, which influences all stages of technological change. This chapter has highlighted some critical trade-offs to consider. In particular, lowering compliance costs in the longer term requires investing in R&D to reduce the costs of clean technologies. Lowering compliance costs in the short term would be easier with market-based instruments such as carbon prices, but they are unpopular, and governments often opt for standards and adoption subsidies that are typically more expensive.

A critical takeaway is that there is no silver-bullet policy. Governments should adopt and implement a coordinated mix of policies to achieve as much carbon-emission reduction as possible at the lowest possible cost. Despite all the criticisms, carbon pricing remains an essential part of this policy mix. Governments should aim at implementing politically acceptable carbon prices on all carbon emissions in the economy. In the short term, the carbon price levels are likely to be too low to induce as much emission reduction as we'd like. As a result, other policy instruments such as standards or adoption subsidies may be needed to ensure polluting technologies are phased out. Over the medium and long term, however, as the costs of clean technologies decrease, governments should find it more politically manageable to increase carbon prices.

References

Acemoglu, D., Aghion, P., Bursztyn, L., Hemous, D. (2012), 'The Environment and Directed Technical Change.' *American Economic Review*, 102 (1), pp. 131–166.

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., Van Reenen, J. (2016), 'Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry.', *Journal of Political Economy* 124 (1), pp. 1–51.

Atkinson, G., Braathen N. A., Groom B., and Mourato S. (2018), 'Chapter 14: The Social Cost of Carbon.' In *Cost-Benefit Analysis and the Environment: Further Developments and Policy Use*, edited by OECD, pp. 335–372. OECD Publishing, Paris.

Barrett, S. (1994), 'Self-enforcing International Environmental Agreements.' *Oxford economic papers*, pp. 878–894.

Barrett, S. (2005), 'Chapter 28 The theory of international environmental agreements.' In *Handbook of Environmental Economics*, edited by Karl-Göran Mäler and Jeffrey R Vincent, 3, pp. 1457–1516. Elsevier, January.

Bonvillian, W. B., Van Atta, R. (2011), 'ARPA-E and DARPA: Applying the DARPA Model to Energy Innovation.' T*he Journal of Technology Transfer* 36 (5), pp. 469– 513.

Boucher, M. J., and Loring P. (2017), OPINION: Climate change is more than a tech problem, so we need more than a tech solution. https://ensia.com/voices/climate-change-social-fix/?utm_source=pocket_mylist. Accessed: 2021-10-6.

Calel, R., Dechezleprêtre, A. (2016), 'Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market.' *The Review of Economics and Statistics* 98, no. 1 (March), pp. 173–191.

Consult, Idea. (2008), *Evaluation of the European Technology Platforms (ETPs)*. IDEA Consult nv.

Cunliff, C. (2020), Energy Innovation in the FY 2021 Budget: *Congress Should Lead* [inen]. Technical report. Information Technology and Innovation Foundation.

Cunliff, C., Nguyen, L. (2021), *Energizing Innovation: Raising the Ambition for Federal Energy RD&D in Fiscal Year 2022*. Technical report. Information Technology and Innovation Foundation.

Dechezleprêtre, A., Glachant, M. (2014), 'Does Foreign Environmental Policy Influence Domestic Innovation? Evidence from the Wind Industry.' *Environmental & Resource Economics* 58, no. 3 (July), pp. 391–413.

Dechezleprêtre, A., Martin, R., Bassi, S. (2019), Climate change policy, innovation and growth, In *Handbook on Green Growth*, Edward Elgar Publishing.

Dechezleprêtre, A., Martin, R., Mohnen, M. (2014), *Knowledge spillovers from clean and dirty technologies*. CEP Discussion Paper 1300.

Dowd, J. (2017), *Aggregate Economic Return on Investment in the US DOE Office of Energy Efficiency and Renewable Energy*. US Department of Energy 2.

Dugoua, E. (2021), *Induced innovation and international environmental agreements: evidence from the Ozone regime*, Grantham Research Institute on Climate Change and the Environment Working Papers (363), Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science, London, UK.

European Commission. (2021), Horizon 2020 structure and budget. https://ec.europa.eu/research/participants/docs/h2020-funding-guide/grants/applying-for-funding/find-a-call/h2020-structure-and-budget_en.htm Accessed: 2021-10-7, July.

Fischer, C., Preonas, L., Newell, R. G. (2017), 'Environmental and Technology Policy Options in the Electricity Sector: Are We Deploying Too Many?' *Journal of the Association of Environmental and Resource Economists* 4, no. 4(4), pp. 959-984.

Freeman, R., Van Reenen, J. (2009), 'What If Congress Doubled R&D Spending on the Physical Sciences?' *Innovation Policy and the Econom*y 9 (January), pp. 1–38.

Gerarden, T. D., Newell, R. G., Stavins, R. N. (2017), 'Assessing the energy-efficiency gap.' *Journal of economic literature* 55 (4), pp. 1486–1525.

Gillingham, K., Stock, J. H. (2018), 'The cost of reducing greenhouse gas emissions.' *The journal of economic perspectives: a journal of the American Economic Association* 32(4), pp. 53–72.

Greenstone, M., Nath, I. (2020), *Do renewable portfolio standards deliver cost-effective carbon abatement*? Becker-Friedman Institute Working Paper.

Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Anderson, P. et al. (2019), 'Recycling lithium-ion batteries from electric vehicles' [in en]. *Nature* 575(7781), pp. 75-86.

Harrabin, R. (2020), 'Climate change: Clean tech 'won't solve warming in time'.' *BBC* (February).

Heal, G. M., Schlenker, W. (2019), Coase, Hotelling and Pigou: The Incidence of a Carbon Tax and Co 2 Emissions, *NBER Working Paper*, w26086.

Heinberg, Richard. (2017), Why Climate Change Isn't Our Biggest Environmental Problem, and Why Technology Won't Save Us. https://www.resilience.org/stories/2017-08-17/climate-change-isnt-biggest-environmental-problem-technology-wont-save-us/?utm_source=pocket_mylist Accessed: 2021-10-6, August.

Hepburn, C., Stern, N., Stiglitz, J. E. (2020), 'Carbon pricing special issue in the European economic review' [in en]. *European economic review* 127, pp. 103440.

International Energy Agency. (2020), Energy Technology Perspectives 2020 - *Special Report on Clean Energy Innovation*.

Jaffe, A. B., Newell, R. G., Stavins, R. N. (2005), 'A Tale of Two Market Failures: Technology and Environmental Policy.' *Ecological economics: the journal of the International Society for Ecological Economics* 54 (2), pp. 164–174.

Kaufman, N., Barron, A. R., Krawczyk, W., Marsters, P., McJeon, H. (2020), 'A near-term to net zero alternative to the social cost of carbon for setting carbon prices' [in en]. *Nature climate change* 10(11), pp. 1010-1014.

Kavlak, G., McNerney, J., Trancik, J. E. (2018), 'Evaluating the causes of cost reduction in photovoltaic modules.' *Energy policy* 123, pp. 700–710.

Li, J. (2019), 'Compatibility and Investment in the U.S. Electric Vehicle Market.'

Majkut, J. (2020), The Immediate Case for a Carbon Price [in en]. https://www.niskanencenter.org/the-immediate-case-for-a-carbon-price/ Accessed: 2021-10-7, October.

Mazzucato, M. (2018), *Mission-Oriented Research and Innovation in the European Union: A Problem-Solving Approach to Fuel Innovation-Led Growth*. Technical report. European Commission.

McLaren, D., Markusson, N. (2020), 'The co-evolution of technological promises, modelling, policies and climate change targets' [in en]. *Nature climate change* 10(5), pp. 392-397.

Meadows, D., Randers, J. (2012), *The limits to growth: the 30-year update*. Routledge.

Metcalf, G. E. (2019), 'The distributional impacts of U.S. energy policy.' *Energy policy* 129, pp. 926–929.

Mildenberger, Matto, and Leah C Stokes. (2020), The Trouble with Carbon Pricing. https://bostonreview.net/articles/leah-c-stokes-matto-mildenberger-tk/ Accessed: 2021-10-6.

Mission Innovation. (2021a), *Country Highlights 6th MI Ministerial 2021*. Technical report.

Mission Innovation. (2021b), *Mission Innovation 2.0 Vision*. Technical report.

Myslikova, Z., Gallagher, K. S. (2020), 'Mission Innovation is mission critical' [in en]. *Nature Energy* 5, 10, pp. 732-734.

Nemet, G F. (2019), *How Solar Energy Became Cheap: A Model for Low-Carbon Innovation*.

Neumayer, E. (2003), *Weak Versus Strong Sustainability: Exploring the Limits of Two Op-posing Paradigms* [in en]. Edward Elgar Publishing, January.

Petek, G. (2020), Assessing California's climate policies—electricity generation. https://autl.assembly.ca.gov/sites/autl.assembly.ca.gov/files/CalifLAO- ElectricityEmissions.pdf. Accessed: 2021-10-7.

Popp, D., Newell, R. G., Jaffe, A. B. (2010), 'Chapter 21 - Energy, the Environ-ment, and Technological Change.' In *Handbook of the Economics of Innovation*, edited by Bronwyn H Hall and Nathan Rosenberg, 2, pp. 873–937. North-Holland, January.

Rausch, S., Mowers, M. (2014), 'Distributional and efficiency impacts of clean and renewable energy standards for electricity.' *Resource and Energy Economics* 36(2), pp. 556-585.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Foley, J. A. et al. (2009), 'A Safe Operating Space for Humanity.' *Nature* 461 (7263), pp. 472-475.

Rosenbloom, D., Markard, J., Geels, F. W., & Fuenfschilling, L. (2020), 'Opinion: Why carbon pricing is not sufficient to mitigate climate change–and how 'sustainability transition policy' can help' [in en]. *Proceedings of the National Academy of Sciences of the United States of America* 117(16), pp. 8664-8668.

Sanderson, H. (2019), 'Congo, child labour and your electric car.' *Financial Times* (July).

Subramanian, M. (2017), In West Texas Where Wind Power Means Jobs, Climate Talk Is Beside the Point. https://insideclimatenews.org/news/26122017/wind-energy-jobs-booming-texas-clean-renewable-power-climate-change/
Accessed: 2021-10-7, December.

Sugla, R. (2020), Opinion: We need massive societal change if we're going to survive and thrive on Earth. https://ensia.com/voices/opinion-we-need-massive-societal-change-if-were-going-to-survive-and-thrive-on-earth/?utm_source=pocket_mylist
Accessed:2021-10-6.

Zachmann, G., Serwaah-Panin, A., Peruzzi, M. (2015), When and how to support renewables?—Letting the data speak, In *Green energy and efficiency*, pp. 291-332. Springer, Cham.