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IT'S NOT A SPRINT, IT'S A MARATHON: REVIEWING GOVERNMENTAL R&D SUPPORT FOR ENVIRONMENTAL INNOVATION*

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In a race against excessive global warming, the world must accelerate the development and adoption of environmental innovations (EIs). EIs are crucial in decarbonizing the economy and meeting the net-zero targets. In this literature review, we delve into the role of governments in promoting EIs across stages of maturity and the likeliness of such support to reduce emissions and mitigation costs. Various theoretical justifications, such as knowledge externalities, dynamic increasing returns, path dependency and incomplete information, highlight the necessity to promote EI through governmental Research and Development (R&D) support. While emission pricing remains the most cost-efficient climate policy, it fails as a stand-alone instrument to sufficiently encourage EI. Accordingly, the optimal approach is a policy mix complementing emission pricing with governmental R&D support. The theoretical finding is backed by empirical studies on the development and deployment of renewable energies, which also show that investment in R&D can effectively reduce emissions and mitigation costs. By combining theoretical and empirical research, the review concludes by examining two pivotal policy actions aimed at accelerating the take-off of EIs: The US Inflation Reduction Act and the European Green New Deal Industrial Plan. We evaluate their specific aspects and limitations to effectively and efficiently contribute to decarbonization.

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1 Introduction

The urgency to combat climate change heightens as the deadline for net-zero emission targets is rapidly approaching. However, existing clean technologies are inefficient in achieving emission reduction targets beyond 2030 (International Energy Agency, 2021). For further decarbonization and achieving net-zero emissions, it requires environmental innovation (EI)[1] to bring immature clean energy technologies to market readiness and develop a suite of novel technologies. Despite the importance of EI, green patenting activity has shown a considerable downward trend in the past decade such that the current innovation level is deemed to be insufficient to derive a net-zero economy (Cervantes et al., 2023; Probst et al., 2021). But the green transition is not only a race against global climate change but also one for market power. The IEA forecasts that the clean technology industry will be worth US$650 billion annually by 2030 (International Energy Agency, 2023). Serving that industry can contribute to economic prosperity in a net-zero emission future.

The passing of the Inflation Reduction Act (IRA) in the US has catapulted governmental support for research and development (R&D) for EI back on the political agenda in pursuit of hitting the net-zero emissions target by mid-century as well as capturing a front-row seat in the clean energy market. As part of the IRA, the US commits US$370 billion in tax credits to a clean energy economy to empower American environmental innovators (The White House, 2023). While the IRA might have fueled the discussion, the US is not alone in its efforts to decarbonize its economy while boosting it. Similar green industrial policies are observable in other world regions, most notably Europe's Green Industrial Plan embedded in the European Green Deal worth around 600 billion € to fund a just energy transition.[2] Despite the enormous amounts of funding allocated to these efforts, the question remains how effective innovation policy is in achieving environmental objectives.

In this literature review, we analyze the role and impact of governmental R&D support in addressing climate change and facilitating the green transition towards a net-zero future. Governments play a significant role in addressing market failures and thus in promoting R&D to incentivize investment in EIs These market failures include knowledge creation, reduced environmental degradation, network externalities, the path dependency of innovation, or incomplete information, to name a few (Acemoglu et al., 2012; Bond et al., 2005; Cervantes et al., 2023; Jaffe et al., 2005; Popp, 2006; Rennings, 2000; Rubin et al., 2015). While there are challenges and trade-offs, governmental support for green R&D is the most popular climate policy (Dabla-Norris et al., 2023; Dechezleprêtre et al., 2022). However, as a stand-alone policy instrument, R&D policy is cost inefficient in reducing environmental degradation (Fischer & Newell, 2008; Popp, 2006). Nonetheless, governmental R&D support complements carbon pricing, reducing overall emission mitigation costs because it addresses several market failures related to EI creation and diffusion (Bertram et al., 2015; Fischer & Newell, 2008; Otto et al., 2008; Veugelers, 2012). Accordingly, combining carbon pricing and R&D subsidies in a well-balanced policy mix can effectively and efficiently accelerate innovation and mitigation.

Theoretical motivation validates that green R&D effectively supports the take-off of EIs. Examining the policy strategy for renewable energy (RE), we find that governmental green R&D has significantly increased the innovation activity for RE (Johnstone et al., 2010), supported the capacity expansion of RE (Polzin et al., 2015) due to cost savings from green R&D (Klaassen et al., 2005), and thus, leads to the decrease in CO_2 emissions at the country-level (Paramati et al., 2021). As firm-level analysis show,

[1] The term environmental innovation is established in the field. However, it is a synonym for other terms used such as green innovation or eco-innovation. EIs include innovations at different stages, e.g., green patent vs. adoption of already established EIs in a sector. In general, we refer to EIs as innovations which lead to reduced environmental degradation throughout their life cycle compared to their alternatives (e.g., Kemp & Pearson (2007) and Ghisetti & Pontoni (2015)).

[2] For further information on the European Green Deal visit: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en , accessed on 25 July 2023.

green R&D also reduces both the energy and carbon intensity of technologies, leading to emission reductions (Alam et al., 2019).

The theoretical and empirical necessity for governmental R&D support EIs has been recognized by governments across the globe that have started to introduce extensive industrial policy packages to address climate issues through EI – most notably the US IRA and the EU Green Deal Industrial Plan. The latter can successfully accelerate the take-off of EI since it complements carbon pricing in the EU. The IRA's environmental success is likely constrained to the short-run as it is designed to favor mature clean technologies and neglects the importance of immature EIs for the long-run. Additionally, the IRA combines different political targets in one policy, blurring the lines between environmental and industrial policy goals to the detriment of the former. By replicating the IRA for industrial policy reasons, the EU Green Deal Industrial Plan risks inefficiencies in a first-best policy scheme. Ultimately, the support for EI can advance clean technologies from which the global community may benefit.

With this literature review, we contribute to the EI literature in multiple ways. First, a large body of research analyzes the role of governmental R&D in fostering EIs but different literature streams are widely unrelated despite including insights relating to each other. Especially the connection between the extensive theoretical and empirical works is seldomly connected. Both highlight the role of governmental R&D support in supporting EI but its full potential can only be reaped in a policy mix that combines both environmental and innovation aspects. Second, we go beyond reviewing the direct effect of governmental R&D support on innovation by examining the indirect effects on the climate through CO_2 emissions. We do not only echo the importance of governmental R&D support for EI but attempt to answer the question of whether and how public R&D strategies can be a fruitful environmental policy. Third, we take these insights to add to the debate of the recent and powerful governmental industrial policy packages – namely the IRA and the EU Green Deal Industrial Plan – and discuss their ability to foster EI and, importantly, contribute to emission reductions.

The paper comprises several policy implications. Our main policy implication is that governmental R&D support is a crucial part of the environmental policy package due to the twin-market failures between the environment and innovation. Accordingly, the success of policies depends on the existence of both an environmental and innovation policy, while a stand-alone policy is insufficient. Taking this insight to discuss the recent policy activities in the US and the EU, the EU Green Deal Industrial Plan can be a successful complement to the carbon pricing scheme, while the IRA is unlikely to achieve emission reductions in a cost-efficient way. In addition, both policy packages risk favoring mature EIs and neglect the importance of nascent EIs to reach net-zero targets.

We structure the literature review as follows: We start by drawing on the extensive theoretical literature on the justifications for green governmental R&D support (Section 2) and the importance of governmental R&D in a policy mix (Section 3). The theoretical results are compared to empirical evidence of the support of governmental R&D on the innovation and deployment of clean technologies (Section 4) and in its ability to foster emission reductions (Section 5). The lessons learned are then used to discuss current R&D policies in their ability to not only act as an innovation/industry policy but also as an environmental policy (Section 6).

2 Justifications for Green Governmental R&D Support

In this chapter, we explore the numerous justifications for governmental intervention in supporting EIs. Often, they are related to market imperfections or even market failures. To provide a structured overview, we group them into five categories, even though we acknowledge that these sometimes overlap.

2.1 Externalities: Knowledge Creation and Reduced Environmental Degradation

Knowledge is non-rival and often non-excludable. Due to these public good characteristics, innovative firms cannot fully internalize the gains of innovations (Grossman & Helpman, 1991). The diffusion of knowledge to other market participations can be significant. For US firms, Myers and Lanahan (2022) find that every governmental supported grants resulted in spillover effects leading to three more patents by others. Though the study is not limited to green patents, Rodrik (2014) argues that the novelty of EIs, the highly experimental nature, and the risks for pioneering entrepreneurs are characteristics making EIs prone to the market failure of not internalized knowledge spillovers. In addition, EIs are characterized by reduced environmental degradation, e.g., decarbonization. In combination, the positive knowledge creation and reduced environmental degradation lead to an underinvestment of firms in EIs, which is known as the double externality problem (Jaffe et al., 2005; Popp, 2006; Rennings, 2000). EI policy is thus part of an optimal set of public policies to incentivize green investment. Such an EI policy is relevant for the invention and diffusion phase of EIs. A lack of governmental policies results in less investment as it would be socially desirable (Jaffe et al., 2005). However, finding an optimal R&D subsidy to internalize externalities is not an easy task. The main reason is the intertemporal dimension of EIs induced by dynamic increased returns (Lancker & Quaas, 2019).

2.2 Dynamic Increasing Returns: Learning by Using, Learning by Doing and Network Externalities

Adoption externalities describe that the costs of using a particular technology depend on the number of users who have already adopted it and the production of the good itself. Such dynamic increasing returns can be generated by learning by using, learning by doing and network externalities (Jaffe et al., 2005).

Learning by using refers to the learning process that occurs when others observe the application of a new technology. Consequently, the adopter of EI creates a positive externality by generating information about the existence, characteristics, and success of the new technology (Jaffe et al., 2005). Learning by doing sheds light on the supply-side of the EI adoption. With production experience, costs tend to fall significantly (Jaffe et al., 2005). Goulder and Mathai (2000) distinguish between R&D-based and learning by doing-based knowledge creation. R&D-based knowledge creation lowers the marginal costs of abatement in the future but increases the costs of abatement today relative to the future. Similarly, learning by doing-based knowledge creation affects marginal costs in the present and future. In addition, abatement today lowers the costs of abatement in the future. The learning rate describes the reduction of cost for each doubling of cumulative production or capacity and defines the so-called learning curve that links, e.g., the cumulative production of a technology to its costs. Productivity gains obtained by learning by doing are also a justification for governments to over-proportionally subsidize costlier technologies because these costs might fall considerably in the long run (Lancker & Quaas, 2019). Already in 2006, Nemet (2006) emphasizes the historically unique speed of technology development observable in solar photovoltaics. However, he finds that learning by doing is only weakly driving the decline in production costs. Instead, a broader set of influences, such as technical barriers, industry structure and characteristics of demand are relevant drivers explaining the decline. However, Lindman and Söderholm (2012) emphasize the geographical domain of learning and that studies allowing for the presence of global learning find higher learning rates. By systematically analyzing the literature on the learning rates reported for 11 power generating technologies, Rubin et al. (2015) show that learning curves can be powerful. For instance, for onshore wind, they find an average learning rate of 12% and for solar photovoltaic energy systems a learning rate of even 23%.

Lastly, network externalities describe that the value of technologies increases with the number of users (Berndt et al., 2003; Jaffe et al., 2003). This dynamic can lead to a dominance of technology, even though close substitutes are available (Aghion et al., 2019; Berndt et al., 2003). Such a lock-in - also known as path dependency - is observable for some fossil technologies and is a major constraint hampering the market-based take-off of EIs (Cervantes et al., 2023). The dynamic nature and path dependency of EIs make it more challenging to design optimal R&D support that holds to be optimal in the long-run gets (Acemoglu et al., 2016; Lancker & Quaas, 2019). We discuss the path dependency of innovation in more detail next.

2.3 Path Dependency of Innovation

Path dependencies have been shown to exist for clean and dirty production. Aghion et al. (2016) empirically reveal for the automotive sector that regions and firms with a specialization in dirty patenting, show lower activities in green patenting in the future. Interestingly, they also find a path dependency in clean technologies: Firms' history in green patenting determines the likelihood of future green patenting.

Acemoglu et al. (2012) emphasize that avoiding a technological lock-in in dirty production calls for governmental action. Governments have a crucial role in preventing the economy from heading towards an environmental disaster due to the path dependency of dirty technologies. Innovation and production would be directed to dirty sectors because these sectors have a comparable advantage against clean technologies. First, a market size effect directs innovation towards the sectors with larger input markets, e.g., in the market of established technologies. Furthermore, scientists build on the existing stock of knowledge and direct their research to areas that are well funded and where other experienced scientists are working. These scientists can build their research on the ideas and knowledge to 'stand on the shoulders of giants'. Second, a price effect directs innovation towards sectors with higher prices, which is naturally the relatively pollutant sectors.

Aghion et al. (2019) discuss further sources for a path dependency directed towards dirty technologies. First, there is a network effect because of incentives to deploy innovations that use existing infrastructure, e.g., charging stations for electric vehicles vs. patrol stations for cars with a combustion engine or smart grids are the foundation for smart meters. Breaking path dependencies requires switching costs, which private actors might not be willing to pay. Second, especially in the initial phase, shifting to a green economy ties up production factors, which potentially restricts drivers of long-run economic growth. Third, different technologies unfold a higher payoff as complements, e.g., renewable energies show a higher payoff complemented by storage capacities.

Notably, Lancker and Quaas (2019) model the optimal subsidy to internalize externalities, while considering the intertemporal dimensions of EIs induced by path dependency and learning by doing. They find that the optimal subsidy should consider the initial productivity of a technology. As a result, subsidies should be higher for less advanced technologies, providing incentives for technology diversification. The approach is deemed optimal when productive sites are scarce, limiting future knowledge utilization, and when technologies mature rapidly with limited potential for further learning.

2.4 Incomplete Information and Financial Constrains

Uncertainties regarding investment costs and the returns to innovation are an additional domain of market imperfections (Jaffe et al., 2005). While innovators have a more comprehensive understanding of the risks and opportunities of new green technologies, investors face incomplete information, leading them to demand a risk premium to compensate for such uncertainty. As a result, there is less R&D activity than what is socially desirable. Such a pattern for instance partly explains underinvestment in energy-saving technologies, such as those related to housing. House owners may be hesitant to invest in energy-saving technologies if they have uncertainties about the magnitude of savings in their energy bill, which can ultimately result in reduced or even non-existent investments in energy savings (Jaffe et al., 2005).

In general, Bond et al. (2005) empirically show that financial constraints significantly discourage investments in R&D. A lack of access to external funds hinders especially young and small companies to innovate. This can reduce the pace of green transformation because new companies are typically the companies which innovate radically, while older companies focus on incremental changes. Venture capital is a vehicle to enable greater risk taking and to unfold the innovative capacity of these companies (Cervantes et al., 2023). Governments can support venture capital by different means such as tax breaks or beneficial regulations for funds to invest in respective startups and small companies showing high growth rates. Financial constraints might also be an issue for private households.

2.5 Acceptability and Green Industrial Policy

As outlined so far, without governmental intervention there is an underinvestment in green R&D in the private sector. Rodrik (2014) discusses why many economists are traditionally reluctant to favor green R&D policy. First, the capability of policymakers in achieving well-targeted and effective interventions is questioned. Second, the justifications for governmental action discussed so far are valid from the perspective of a decision maker aiming to improve global welfare. However, for environmental degradation, where the damage is global and not locally restricted, such justifications are not necessarily binding for national governments targeting domestic welfare. Third, knowledge externalities of R&D are frequently global rather than national. In an interconnected world, knowledge and learning rapidly spillover borders, e.g., along global value chains (e.g., De Loecker (2007), Hanley & Semrau (2022), Semrau (forthcoming)) or between different affiliations of multinational companies (e.g., Brucal et al. (2019) and Kannen et al. (2021)). The international diffusion of EIs opens opportunities for global climate action because most green R&D activities take place in industrialized countries while the bulk of emission growth is happening in emerging countries (Cervantes et al., 2023; Copeland et al., 2022). However, governments anticipating such spillovers might be reluctant to financially support green R&D (Rodrik, 2014).

Although the benefits of green R&D policy are often at the global level rather than national level, green R&D support is a popular policy tool around the world. The popularity can be explained by the fact that other climate policies, such as emission pricing, have distributional consequences for business models in dirty technologies and alternatives have little political appeal once they risk reducing economic activities (Fischer & Newell, 2008). In line with this, Dechezleprêtre et al. (2022) find in a cross-country survey that green R&D support schemes are more popular among voters and citizens than alternatives, such as carbon pricing, bans or regulation. Similarly, Dabla-Norris et al. (2023) show that carbon pricing is a relatively unpopular policy instrument. However, they stress that using revenues to support green infrastructure and low-carbon technologies can increase public acceptability. Furthermore, Rodrik (2014) states support of the domestic industry in global competition is the main reason for governments to subsidize green R&D. Green industrial policy can potentially create a first-mover advantage by redirecting economic activities towards clean technologies and enabling long-term comparative advantages. However, the intention to shift rents from foreign producers to domestic producers targeting to create national benefits comes at the social costs of other countries and is well-known as a beggar-thy-neighbor policy.

In summary, there is a strong theoretical foundation for the global need for green R&D support schemes. Governments can step-in to break market imperfections and to improve global social welfare. Conversely, green industrial policy is normally at the national or regional level and creates distortions by itself. Facing this trade-off, Rodrik (2014) highlights the highly second-best context of green industrial policy and concludes that boosting green industries for competitive reasons increases global welfare only as long as there are no barriers against foreign market entry. But what do we know about the effectiveness of R&D support schemes to foster EIs and reduce CO2 emissions? To this end, the policy mix plays a crucial role. We discuss this issue in the next section.

3 R&D support in the climate policy mix

In this chapter, we discuss the role of green R&D policies in a broader climate policy mix and how they complement, substitute or contradict other policies.

Given the explained market imperfections related to EI, it is no surprise that once such imperfections are incorporated into a theoretical model, R&D support is part of an optimal policy mix. This goes hand in hand with the Tinbergen rule stating that each market failure policymakers aim to address requires its own policy instrument (Tinbergen, 1952). Related to this Fischer and Newell (2008) show for the electricity market that in the presence of R&D spillovers and learning by doing optimal governmental policy includes a carbon price, a subsidy for R&D into renewable energy and a production subsidy for the deployment of renewable energy. In other words, while emission prices correct for the environmental externality, R&D and deployment support are needed to correct for the knowledge spillovers and learning by doing effects. Fischer et al. (2017) extend the model developed by Fischer and Newell (2008) and introduce additional market failures, such as the undervaluation of investment returns in energy efficiency by consumers. The study confirms that R&D support is an efficient complement to carbon pricing in addressing these issues. However, aggressive deployment policies might conflict with achieving overall welfare gains, especially when emissions pricing is already sufficiently implemented. Policymakers need to carefully consider the specific circumstances and characteristics of each market failure to devise a comprehensive and robust climate policy mix.

The described cost efficiency of combining carbon taxes with R&D subsidies is also shown by several other studies. For instance, the theoretical model in Otto et al. (2008) also results in an optimal policy mix including carbon pricing, R&D subsidies and production subsidies. Calibrating the model to the European Emission Trading Scheme (EU ETS) shows that combining the EU ETS with R&D subsidies leads to increased cost efficiency. The cost reduction is particularly strong once climate policy is differentiated - even rudimentary - between technologies, e.g., CO_2 intensive vs. non-CO_2 intensive. The main explanation is that the EU ETS fails to correct for R&D related knowledge spillovers and this market failure affects technologies differently. Veugelers (2012) highlight the role of governments to leverage private R&D. Thereby, green R&D support again unfolds its full potential in a policy mix. Building on an empirical analysis of firms in Belgium, she states that an optimal policy mix combines carbon pricing, performance-based regulations and public funding. Ang et al. (2017) emphasize the relevance of a credible long-term price on emissions combined with R&D support for long-run investment and innovation in early-stage renewable technologies. Even though private green R&D spending shows higher efficiency and has more positive economic implications, Fragkiadakis et al. (2020) highlight that public R&D is particularly important to push the development of immature and highly uncertain technologies. In addition, they also show that complementing carbon prices with public and private R&D results in better cost efficiency.

Starting from an optimal policy mix, the question arises which of the instruments is the most important as a second-best, stand-alone policy. By evaluating each climate policy instrument in isolation, Fischer and Newell (2008) back the standard claim of many economists that emission pricing is the most cost efficient measure to mitigate climate change, while green R&D subsidies alone are cost inefficient. Furthermore, emission pricing can encourage the adoption of technologies, though effectiveness varies between different environmental policies (Requate & Unold, 2003). In general, prices are a major driver of (environmental) innovation (Newell et al., 1999; Popp, 2002).

In comparison, Popp (2006) finds that green R&D support boosts R&D activities but has little impact on the climate itself. The failure of R&D support to address the environmental externality, by encouraging the diffusion of existing EIs, explains this pattern. Accordingly, he concludes that there is no free lunch in climate policy and R&D policy cannot substitute more restrictive emissions pricing. However, R&D support can improve the cost efficiency of climate policy when it complements emission pricing.

However, climate policy takes place in a second-best context where the theoretically most efficient option is unattainable (Bertram et al., 2015; Fischer et al., 2021; Rodrik, 2014). In such a second-best world, it is not politically feasible to set carbon prices to their optimal level or to correct for all market failures through market-based approaches. By modelling different combinations of carbon prices and R&D subsidies, Bertram et al. (2015) find that under sub-optimal carbon pricing, cost efficiency losses can be minimized by R&D support to pave the way for future decarbonization efforts. Also, Fischer et al. (2021) find that solely relying on carbon pricing in the EU leads to a policy cost increase of approximately 30 percent in fulfilling the EU CO_2 emissions target. This increase is due to the failure to internalize externalities such as knowledge spillovers from R&D and learning by doing effects.

Fischer, Greaker, et al. (2017) also recognize that climate policy operates in an imperfect world. They highlight the need to consider the global effects of climate policy and analyze how R&D policy can mitigate emission leakage, which refers to the shift of global emissions induced by environmental policies to less regulated markets. Such leakage can undermine a country's welfare and hinder efforts to effectively reduce emissions on a global scale. The study reveals that the effects of R&D policy vary along the value chain. Downstream subsidies have mixed effects, tending to increase global abatement technology prices while reducing pollution abatement abroad and increasing emission leakage. Opposed to this, upstream subsidies can decrease abatement technology prices and limit emission leakage, thus improving global welfare.

Finally, a different policy mix can be superior even in the presence of cost inefficiencies associated with overlapping policies (Böhringer et al., 2016; Fischer & Preonas, 2010). Yet, overlapping policies can also decrease the effectiveness of individual policies (Lindman & Söderholm, 2016). Going into more detail, also the design of R&D support is important. Fischer and Newell (2008) argue that the main reason for the fact that R&D support as a single instrument is not efficient is that under green R&D support efforts to displace dirty technologies are postponed until costs are brought down. Notably, they focus on incremental improvements in technologies. When accounting for emission reductions of breakthrough EIs, the importance of green R&D support might be higher. From the climate policy perspective, this limitation is crucial because, in the short run, deployment of already available EIs is necessary. But in the long run, a breakthrough in technologies which are still far from the market is necessary (International Energy Agency, 2021; Veugelers, 2012).

Nevertheless, policies often tend to favor technologies that are already closer to the market. One reason is that policy instruments like tax credits offer a quicker payback time (Cervantes et al., 2023). However, concentrating solely on short-term benefits could lead to adverse consequences in the long run. Gillingham and Stock (2018) discuss various challenges related to the costs of reducing carbon emissions, emphasizing the importance of distinguishing between dynamic and static costs. One of these challenges arises from politically appealing programs that may appear low-cost initially but can ultimately prove expensive due to technological limitations or behavioral responses. Yet, some highly visible programs might be perceived as costly, while their actual expenses are relatively low compared to other existing programs. Given the long-term nature of climate change opting for low-cost interventions without adequately considering their future implications, such as perpetuating reliance on fossil fuel infrastructure, may lead to an undue emphasis on short-term cost-effectiveness.

In this context, Acemoglu et al. (2012) have developed a growth model demonstrating the potential effectiveness of taxes on dirty inputs complemented by subsidies for clean inputs. They show that for sufficiently substitutable dirty and clean inputs, sustainable long-run growth can be achieved by combining carbon taxes and R&D subsidies. Notably, environmental policies are only necessary temporarily. Once the path dependency on dirty technologies is broken, a shift towards clean technologies occurs through directed technical change. However, the absence of climate action can lead to significant costs. First, dirty technologies directly contribute to environmental degradation. Second, as long as a path dependency towards dirty technologies persists, the technological gap between dirty and clean alternatives widens. Early and proactive governmental responses are essential to shorten the slow growth phase of the transition ideally. By addressing these challenges promptly, policymakers can pave the way for a smoother and more expedited shift towards sustainable and cleaner technologies.

In a similar vein, Acemoglu et al. (2016) explore the concept of path dependency and emphasize the critical role of technology push through R&D subsidies, particularly when clean technologies lag significantly behind dirty alternatives. In this case, directing research towards it will likely result in incremental innovations that cannot effectively compete with the established dirty technology. Only if research efforts are consistently maintained over time can a series of incremental innovations eventually lead to a self-sustaining scenario of successful clean technologies. However, this process is often slow in practice. To support their findings, they parameterize their endogenous growth model using data from the US energy sector. One of their key results reveals that delaying the implementation of optimal policies by 50 years results in a significant welfare cost, with a permanent 1.7 percent drop in consumption. The cost efficiency of a policy mix comprising carbon taxes and research subsidies is further underscored by welfare costs of 1.9 percent when the economy relies solely on carbon taxes.

Overall, we conclude that carbon pricing is the most important climate policy instrument to reduce emissions efficiently and to induce necessary innovation (Fischer & Newell, 2008; Popp, 2006). However, R&D support schemes can effectively complement carbon pricing to reduce the respective costs of emission mitigation. The main reason is that carbon pricing alone cannot address all market failures, such as knowledge spillovers from R&D and learning by doing effects (Acemoglu et al., 2012, 2016; Fischer & Newell, 2008; Otto et al., 2008). In addition, an efficient R&D policy must consider both the stage within a value chain and the stage in the innovation process. First, upstream R&D policy support can lead to a decrease in global technology prices, while downstream subsidies may increase global technology prices (Fischer, Greaker, et al., 2017). Second, governmental R&D support plays a crucial role, particularly for immature innovations, which often have uncertain long-term payoffs (Acemoglu et al., 2016; Ang et al., 2017; Bertram et al., 2015; Fragkiadakis et al., 2020). In reality, policy makers favor R&D support for innovations in the deployment phase and this bias could undermine the effectiveness of a long-run carbon pricing strategy (Bertram et al., 2015).

4 Effectiveness of green R&D investment on EI

As outlined above, there are good reasons for governments to support the uptake of green R&D activities, especially at early innovation stages. In this chapter, we place the spotlight on empirical studies examining the link between R&D expenditures and EIs. In so doing, we especially focus on the effectiveness of R&D support to accelerate the take-off of EIs and reduce emissions.

To date, one of the most comprehensive environmental strategies was undertaken in the effort to develop and advance RE (solar, wind, and bioenergy but also nuclear). What started in the 1970s in a search for alternative energy sources in a response to the oil crisis, has led to a targeted strategy to support the R&D of RE peaking in the late 90s (Meyer, 2007). Accordingly, ample data and evidence have been collected on the effectiveness of R&D support on RE from which valuable conclusions can be drawn.

Various studies examine the correlation between R&D support for RE and the number of patent applications related to RE – as a proxy for innovation – across countries. Across studies, there is overarching evidence that green R&D is successful in inducing innovation, i.e., increasing the number of green patents, for RE in general (Ang et al., 2017; Johnstone et al., 2010) but also for specific technologies such as solar PV (Palage et al., 2019) and wind (Lindman & Söderholm, 2016). For example, Johnstone et al. (2010) study the effect of technology specific R&D expenditure on patent numbers as a proxy for innovation for a whole range of RE technologies and show that green R&D is effective for all RE technologies but biomass and waste – although Costantini et al. (2015) could find a significant positive effect for patenting for bioenergy in the long-run. Additionally, research supports the already mentioned importance of the targeted technology stage. The effectiveness of green R&D depends on the maturity of the technology, with a greater effectiveness for immature solar where there is a greater learning potential than mature biomass (Johnstone et al. 2010). Most studies bundle various types of green R&D despite their inherent differences. Hille et al. (2020), however, differentiate between upfront R&D subsidies and tax credits, showing that only the former effectively increases patenting activities. R&D subsidies alleviate the risk associated with R&D, even incremental R&D, while tax credits are contingent on a profitable firm and hence, favor mature technologies. Furthermore, the effectiveness of domestic public R&D funding on innovation is restrained by a country's national borders and thus, governmental R&D funding can be interpreted as an indicator of a country's innovation output (Peters et al., 2012).

Governmental R&D to support REs is often deployed alongside demand-pull instruments (e.g., feed-in tariffs). Demand-pull instruments, by themselves, effectively support patenting across various RE sources (Pitelis et al., 2020), especially when deploying feed-in tariffs (Hille et al., 2020). First, the mere presence of a demand-pull instrument sends a signal to stakeholders regarding the importance of a technology, which can induce EI (J. Lee et al., 2022). Second, demand-pull policies target the early deployment of technologies, which induces innovation through learning by doing (Klaassen et al., 2005). Importantly, the interaction between technology-push and demand-pull instruments positively effects innovation activity (Lin & Chen, 2019; Lindman & Söderholm, 2016; Palage et al., 2019). Nevertheless, Lindman and Söderholm (2016) show that models without the interaction effect may overestimate the effectiveness of green R&D in inducing innovation, validating the importance of a well-designed policy mix (Section 3). Having a policy mix consisting of a technology-push and demand-pull instrument fosters "both exploration and exploitation innovation activities", even when the addition of another policy may reduce the effectiveness of a policy mix (Costantini et al., 2017). The latter pattern matches the theoretical arguments that it requires two policies for two market failures (Tinbergen, 1952).

Counter to theoretical arguments Popp (2006) governmental R&D support cannot only foster EI but can also promote the diffusion of clean technologies. Studying the effect of RE policies including R&D on RE capacity, revealed that R&D subsidies can positively affected RE capacity in Germany (Polzin et al., 2015) and in the US (Carley, 2009), by decreasing the cost of technologies (Klaassen et al., 2005).

Beyond RE studies, the literature on the effectiveness of policy instruments on EI is scarce. An exception is Haščič and Johnston (2011) who study the effectiveness of R&D for electric or hybrid motors in the automotive industry and find the effect to be highly inelastic; an increase in public R&D spending of 1% only leads to an increase in innovation (i.e. patenting) by 0.07-0.19%. Instead, the authors find that the automotive industry reacts more strongly to standards to innovate than through green R&D support.

The studies discussed above, link the level of EI activities to the presence of green R&D and demand-pull instruments. Nevertheless, a positive effect on patents does not necessarily imply a successful innovation. Plank and Doblinger (2018) show that the significant positive effect between green R&D and innovation cannot be replicated when using citations per patent as the dependent variable. Thus, while green R&D effectively promotes EI, it is uncertain to what extent this leads to actual emission reductions.

5 R&D support and CO_2 emission reduction

Ultimately, we are interested in how R&D expenditure does not only lead to EI but how these innovations lead to actual emission reductions. Innovation can have a direct and an indirect effect on emissions: First, innovation can induce efficiency gains which in turn leads to emissions reductions from business as usual (e.g., Chen et al. (2022) and Mo (2022)). Second, innovation can reduce the cost of mitigation (Gillingham & Stock, 2018). In the following, we discuss the contribution of R&D efforts to emission reductions. While some studies directly assess the link between R&D expenditures and emissions others link patent data (as the outcome of R&D efforts) to emissions.

For innovation to result in actual emission reductions, it requires that rebound effects - the increased use of a new or improved clean technology – do not entirely offset emissions savings (see Brockway et al., 2021). The higher the level at which we examine emissions, the more likely reductions in emissions can be offset by increases elsewhere. Accordingly, we initially examine the lower tiers on the effectiveness of green R&D on firm emissions before broadening our horizon and examining country-level emissions.

5.1 Firm-level Effects of R&D support on CO_2 emissions

There is a large body of literature on the impact of R&D expenditures on CO_2 emissions at the firm-level where detailed information is available on both firms' R&D expenditures and emissions. Studies investigate the effect of R&D investments on corporate CO_2 emissions, but also energy intensity. Several studies find that increased R&D expenditure leads to lower CO_2 emissions or equivalently higher emission reductions (Alam et al., 2019; K.-H. Lee & Min, 2015; Mo, 2022). Firms' paths to CO_2 emission reductions can equally occur via reducing energy or carbon intensity. Studying G6-countries indexed firms, Alam et al. (2019) show that firms' R&D investments have a significant negative effect on energy intensity and CO_2 intensity. Additionally, Lee and Min (2015) find in their study of the Japanese manufacturing sector that investments in green R&D reduce a firm's carbon emissions while benefitting the financial performance simultaneously. Similarly, Mo (2022) shows that there is a negative long-run relationship between R&D and $C0_2$ for Korean firms under an ETS obligation with an increase in R&D by 1% leading to a decrease in CO_2 emissions by 0.015%. Nevertheless, the authors show that this effect only holds for the process industry but not for the beverage or semiconductor industry. Using a similar approach, Fethi and Rahuma (2020) show that the negative relationship between R&D and CO_2 emissions also holds for the petroleum industry, another CO_2 intensive industry. The authors further show that the effectiveness of R&D expenditure is constrained to the short-run while it requires investment in abatement to achieve long-term emission reductions at the firm-level.

The same negative relationship between innovation and emissions can also be found with regard to sulfur dioxide (SO_2), an indirect greenhouse gas. Chen et al. (2022) study the relation between patent data (rather than investment to have a better understanding of firm's research output) and a firm's SO_2 emissions in China, finding that an additional patent application decreases a firm's SO_2 emissions by 2.7%.

While the aforementioned studies primarily considered private R&D expenditure rather than governmental R&D support, these studies indicate that R&D investments lead to emissions reductions of various gases at the firm-level – even when subjected to an emissions cap. This holds in various countries and is most pronounced in heavy emitting industries. Nevertheless, whether such environmental improvements can hold at the macro-level will be explored subsequently.

5.2 Country-level Effects of R&D support on $C0_2$ emissions

A second set of empirical literature analyses the impact of green R&D on overall emissions and thus its effectiveness as a climate policy rather than an innovation policy. Wang et al. (2012) explore the nexus between energy technology patents and CO_2 emissions in China. Examining carbon-free and fossil energy technology patents, they show that only an increase in carbon-free energy technology patents reduces CO_2 emissions (across all Chinese regions and at the national level) but not an increase in fossil-fuel energy technology patents. Thus, it is not the energy efficiency path that leads to emission reductions at the macro-level but targeted R&D for carbon-free energy technologies. Nevertheless, Paramati et al. (2021) show in their panel estimation of EU countries that reductions in CO_2 emissions only depend to a small extent on increasing RE consumption. They find that a 1% increase in R&D expenditure (both public and private) leads to a 0.41% increase in RE consumption – which is in line with the research by Polzin et al. (2015) – and a decrease of 0.14% in CO_2 emissions. Meanwhile, a 1% increase in RE consumption reduces CO_2 emissions by 0.2% and thus, explains around 0.11% of the reduction in CO_2 emissions from green R&D. Therefore, the expansion of RE cannot be the sole contributor to emission reductions and other factors, such as improvements in efficiency or incremental innovations, must have contributed to the reduction in CO_2 emissions. Replicating the study for OECD countries, Alam et al. (2021) again show the significant negative R&D expenditure on CO_2 emissions, with a 1% increase in R&D expenditure leading to a 0.25% reduction in CO_2 emissions. So, while a reduction in CO_2 emissions from (green) R&D can be found, it is hard to discern its drivers.

Another relevant strand of literature related to the nexus between innovation and CO_2 emissions is concerned with the Environmental Kuznets curve (EKC) (Mensah et al., 2018). It builds on Kuznets (1955) who hypothesized that the relation between income inequality and economic growth is characterized by an inverted u-shape: At the beginning, emissions increase with growth but with economic growth comes the possibility to innovate and decouple emissions from economic growth and decrease. Therefore, R&D investments play an essential role in decarbonizing the economy.

Studying patent data in OECD countries, Mensah et al. (2018) only find a significant, negative relationship between CO_2 emissions and innovation through patents in a few OECD countries and ultimately, could only partially prove the validity of the EKC. For West Asian and Middle East countries, Kihombo et al. (2021) show that while financial development contributed to environmental degradation, R&D helped mitigate emissions and thus avoid environmental degradation. In the most extensive research endeavor, Shahbaz et al. (2020) use historical data from 1870-2017 to study the impact of economic growth and R&D expenditures on UK emissions in the short and very long-run. They find that the relationship between R&D expenditures and emissions can indeed be represented by an inverted u-shape as hypothesized by the EKC.

Ultimately, both firm and country-level analyses highlighted that green R&D reduces CO_2 emissions, showing that R&D expenditure – whether private or governmental – is an effective tool to encourage decarbonization. While at the firm-level R&D expenditure is shown to be effective in the short-run, the reduction in national CO_2 emissions through R&D is most likely a long-term process. While these studies examine R&D in general and do not specify governmental R&D, they imply that increased governmental support for green R&D can contribute to emission reductions. Since the investments in green R&D and the expansion of RE lead to actual emissions reductions, the rebound effect does not counteract the full effect of governmental R&D support on CO_2 emissions.

6 Comparing the US Industrial Inflation Reduction Act and the EU Green Deal

In many countries, governments have started to roll out massive green R&D financing schemes for a (just) green transition. Most notable are the passing of the IRA in the US in 2022 and the announcement of the EU's Green Deal Industrial Plan in 2023 as part of the comprehensive EU Green Deal. Both policy packages are substantial financial programs to boost the development and expedite the deployment of clean, emissions-free technologies to both decarbonize and strengthen their respective economies. While the Green Deal Industrial Plan is a direct reaction to the IRA, both differ considerably in policy instruments, technology focus, and expected environmental effectiveness. Acknowledging the previously described research, we discuss these two green technology support programs with respect to their capacity to contribute towards an optimal net-zero policy mix. We start with a general discussion of the policy mix in the EU versus the US and then assess the effectiveness, efficiency and design of the specific measures. This brings us to some further specific aspects of optimal policy design, not yet stressed in the previous review. Before doing so, it should be mentioned that the IRA has already been passed and the funding amount of US$370 billion and its distribution is specified, while to date, the EU's Green Deal Industrial Plan is mainly an announcement, where only some of the included programs such as the Innovation Fund (worth 40 billion €) or the InvestEU Programme (worth 26 billion €) are already in place.

The EU and the US differ considerably in their general climate policy setting. The EU countries being part of Annex B in the Kyoto Protocol were among the first countries to internationally commit to emission reductions and jointly overachieved their targets. To achieve this, the EU implemented the EU emissions trading system (EU ETS) in 2005, covering particularly the energy sector and energy intensive industries and about 40% of EU emissions (ICAP, 2023). Though accompanied by many other policy measures, the EU's carbon pricing scheme is its main climate policy measure.[3] While the EU's climate policy strategy might face criticism for its broad scope, it aligns with the recommended optimal policy by combining a carbon price addressing the environmental externality and an EI policy for the additional market failures, such as knowledge externalities (e.g., Fischer and Newell, 2008).

In comparison, the US has a questionable history with climate policy, having signed though not ratified the Kyoto Protocol[4] and having ratified, dropped out, and rejoined the Paris Agreement.[5] Though the idea of emission pricing originated in the US, several attempts to implement national carbon pricing failed and carbon pricing schemes only exist at the sub-national level (ICAP, 2023), covering only 6.4 % of US GHG emissions in 2021 (OECD, 2022). Acknowledging that carbon pricing is less popular among voters (e.g., Dabla-Norris et al., 2023; Dechezleprêtre et al., 2022), the IRA is only a second-best policy combining environmental, social, and competitiveness aspects into one policy tool. The resulting beggar-thy-neighbor policy due to its 'America First' approach may lead to trade wars and create barriers for foreign market entrants can reduce global welfare (e.g., Rodrik, 2014). While the trade

[3] For more information on the EU emission trading scheme visit https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en, accessed 4 August 2023.

[4] See the United States archives for more information https://1997-2001.state.gov/global/global_issues/climate/fs-us_sign_kyoto_981112.html , accessed 4 August 2023.

[5] See statement by the Unites States government https://www.state.gov/the-united-states-officially-rejoins-the-paris-agreement/, accessed 4 August 2023.

implications have been discussed repeatedly (Attinasi et al., 2023), we focus on the suitability of the IRA as an environmental policy in this paper.

6.1 Implications of different design choices

The IRA considers several specific green technologies like RE, hydrogen, carbon dioxide removal, and batteries. Technology specific support ensures that a broad range of technologies are supported according to their specific needs such that more immature technologies are supported next to mature ones. Though numerous and broad the list of technologies is, it is not technology open. For example, the IRA gives out production tax credits to solar polysilicon or solar wafer but not to solar thin film technology (Credit Suisse, 2022). The selection of particular technologies matches the concern of governments' limited ability in picking winners (Acemoglu et al., 2016). Mainly because it excludes novel approaches and is prone to lead to an inefficient technology mix since for example, today's most efficient technologies may not be the most efficient in the future depending on further opportunities for learning and technological improvements (Lancker & Quaas, 2019). Therefore, the IRA can induce technological lock-in and path dependencies (Cervantes et al., 2023). This is even more problematic as carbon pricing as a general market-push instrument is missing (Fischer & Newell, 2008).

The type of technology addressed is also influenced by the choice of support instruments. In American policy tradition, the IRA is mainly providing tax credits for production and investment. At times, these are combined with a competitive bid to ensure support for the most efficient technology. Grants only play a minor role. Although both tax credits and grants target the same goal – increasing the investment in green R&D – they distinguish themselves by the timing of the payment. Grants imply an upfront payment while tax credits are only received subsequent to production and investment. With tax credits the risk for governments is low and the payback time is short (Cervantes et al., 2023), while firms still face the brunt of the risk associated with R&D investments. Thus, there is a risk that the IRA cannot fully address the market failure related to knowledge creation (see Section 2.1). In addition, and as discussed in Section 4, there is empirical evidence for the governmental support of RE that the effectiveness to induce innovation is lower under tax credits in comparison to grants (Hille et al., 2020). Going beyond this, firms need to incur taxes to receive tax credits, which requires a marketable and profitable product – though this is partially circumvented by allowing for transfers (The White House, 2023). Therefore, tax credits by design preselect mature, deployable products and exclude nascent technologies. The preselection may be beneficial to push existing technologies and reap the low-hanging fruits in emission reductions but the lack of support for incremental innovation can have long-run effects on the environment as further developments of immature and novel EIs will be necessary for net-zero emissions (International Energy Agency, 2021). Furthermore, Roy et al. (2021) demonstrate that tax credits achieve lower emission reductions at a higher cost in comparison to carbon pricing, questioning the suitability of tax credits as a second-best environmental policy further.

There is not only the question of which technologies are supported but also how much support a certain technology receives. Efficiency would warrant that all emission reductions from equally mature technologies receive the same subsidy payment and competitiveness will select the winner. However, this is not the case in the IRA. For example, green hydrogen from electrolysis can receive a higher production tax credit than blue hydrogen (from fossil fuels with carbon capture and storage) as a hydrogen production tax credit can be combined with a RE production tax credit but not with carbon capture and storage production tax credit (Credit Suisse, 2022). Yet, the net emissions are the same and both green and blue hydrogen have further environmental drawbacks that make weighing them difficult (heavy reliance on freshwater and risk of carbon leakage, respectively). Accordingly, such differentiation is not warranted from an efficiency perspective and instead, threatens technological lock-in. This could be detrimental for the long-run environmental objective.

Furthermore, the IRA is constructed in a way that there is a base credit amount that can be increased with bonus credit amounts when certain criteria are met. For example, the production tax credit for RE has a baseline rate of 0.3 cents/kW and can be increased fivefold when the project meets a prevailing wage requirement, can be increased by 10% if domestic products are used in the manufacturing process or if located in an energy community (The White House, 2023). Since the IRA targets environmental, competitiveness and social domains with one policy instrument – thus, killing many birds with one stone, it is prone to cost inefficiencies (Fischer et al., 2021; Tinbergen, 1952). First, using a single policy instrument may blur the lines between the different market failures. Second, providing bonus credits is efficient if credit amounts have been set optimally. High credit amounts are necessary to counter the inexistence of a carbon price. Nevertheless, this is solely contingent on the presence of a market failure; if there is no underlying market failure, there is also no reason for a bonus credit. Competitiveness is not associated with any market failure and hence, an increase in the tax credit amount for RE production based on local content requirements is not warranted. Such mixing of industrial policy targets with environmental policy unnecessarily increases the cost and inefficiency of the environmental policy to increase RE.

Furthermore, with the ability of firms to stack various credits together, the efficiency of the IRA is put into question. For example, if a producer of emission free aviation fuel can secure a production credit for producing such fuel, credits for producing RE for its manufacturing process, for using carbon capture and storage in its process, and for using domestic products, the production process may not be chosen for efficiency reasons but for financial reasons by choosing the process by which the most tax credits can be reaped. Additionally, this can lead to technological lock-in, threatening the IRA's ability to achieve emission reductions in the future.

In summary, with its focus on tax credits, the IRA can increase the competitiveness of mature technologies and accelerate their deployment. For the same reasons, however, the IRA's success in achieving emission reductions is likely constrained to the short-run by focusing on a set of specific and more mature technologies. Moreover, tax credit rates may become inefficient due to the use of a single policy instrument to address different market failures, through the possibility to increase tax rates for non-technological standards, and due to the ability to stack various credit rates. It is also questionable if the IRA can achieve actual emission reductions both in the short and long-run, not only due to its focus on existing technologies but also due to possible rebound effects (Section 5) that become likely because of missing complementary carbon pricing. Although the national success of the IRA is questionable, the heavy subsidization of the IRA may lead to global welfare improvements by reducing the cost of EIs, increasing their take-up globally, and thus potentially reducing global emissions.

Compared to the IRA, the EU Green Deal Industrial Plan foresees a greater variety of instruments and technologies. The EU focuses on grants as well as public procurement strategies, competitive auctions, but also tax credits. As "one size does not fit all" (see Pitelis et al. (2020)), various policy instruments for different technologies and sectors can target technologies of various maturity levels. Although the EU Green Deal Industrial Plan focuses on the same technologies as the IRA it is less technologically specific. For example, the Innovation Fund promotes any project that can lead to significant emission reductions (European Commission, 2023b) and thereby, does not single out any specific technologies. However, the Innovation Fund supports only projects that are stated "to be sufficiently mature in terms of planning, business model and financial and legal structure".[6] Therefore, the Green Deal Industrial Plan can capture a broad spectrum of technologies and is open to novel clean technologies.

[6] For more information visit https://climate.ec.europa.eu/eu-action/funding-climate-action/innovation-fund/what-innovation-fund_en, accessed 3 August 2023.

Although the details of the EU Green Deal Industrial Plan are not clear yet, it pledges to adjust subsidy payments to those of other countries (e.g., the US) to remain competitive and avoid EU firms relocating (European Commission, 2023a). Thus, if the IRA specifies a certain subsidy level that is greater than what can be received via an EU funding program, the EU ensures that domestic firms receive the same amount. While this may be important to level the playing field with the US, such a pledge may not only fuel a subsidy war (Inagaki et al., 2023) but it also means that possible inefficiencies of the IRA will be replicated in the EU. Furthermore, it ignores that by design the IRA needs to employ higher support volumes to achieve given emission targets since national emission pricing is missing. Ultimately the overall cost of climate policy in the EU would substantially increase and deviate from the first-best policy mix.

The EU's multifaceted approach has a greater potential to reduce emissions while also being more efficient. The EU Green Deal Industrial Plan covers an array of policy instruments and technologies in various stages of development and is embedded in an array of other policy and funding schemes and most importantly accompanied by a strong carbon pricing scheme. By setting, it can be both cost-efficient and effective in reducing emissions. Nevertheless, especially the IRA but also the EU's Green Deal Industrial Plan prioritize the deployment of clean technologies for industrial policy reasons as an attempt to have a potential first-mover advantage and gain valuable market shares in the clean energy market worth billions (International Energy Agency, 2023). However, it remains questionable whether a focus on mature clean technologies will be the winning strategy for countries to capture the lion's share of the green industry or whether countries will maneuver themselves into technological lock-in. Nevertheless, the global community may benefit from the push of EI close to the market.

7 Conclusion

Our review shows that governmental research and development (R&D) support for Environmental Innovation (EI) should be part of an effective and efficient policy mix to achieve net-zero emission targets. It is well-established, in theory, and replicated in empirics, that the optimal policy mix combines an environmental policy, in particular emission pricing, with an innovation policy to cover the twin-market failures. Overall, a policy mix fosters the development and deployment of EI, significantly reduces the cost of reaching given emissions targets, and ultimately reduces emissions effectively.

As a standalone policy, neither emission pricing nor an R&D policy can efficiently target market failures. In theory, several market failures, such as not-internalized knowledge creation, dynamic returns of EIs and path dependency, justify governmental R&D support. In addition, empirical results show that R&D support increases EI activities, supports the deployment of clean technologies and reduces emissions. However, R&D support is significantly less efficient as a standalone policy compared to emission pricing. Nonetheless, innovation policies are widely adopted as second-best environmental policy – as is the case with the US IRA. The observation that R&D policy is more publicly accepted and politically feasible than a first-best policy mix explains this bias towards innovation policy.

When designing public R&D support for EI, intervention is especially relevant for immature clean technologies, where dynamic returns for instance through learning-by-doing can significantly reduce the costs of production. This calls for differentiated technology support, even though focusing on static costs only, would imply that each technology receives the same support per unit of emission reduction. At the same time, technology open support is necessary to avoid government's failure in picking winners, which is notoriously difficult due to the dynamic returns and path dependency.

Based on the insights of the literature review, we discussed and compared both the US's IRA and the EU Green Deal Industrial Plan in their ability to support EI and achieve emission reductions. Trying to achieve environmental, social, and competitive goals in a single policy, the IRA is ineffective in achieving the various targets. The use of tax credits and the focus on existing technologies can achieve emission reductions in the short-run by pushing the deployment of mature technologies and helpings the US secure a first-mover advantage. Nonetheless, it lacks the long-run perspective by picking winners early on and by disregarding the importance of immature innovations for net-zero emissions.

In comparison, the EU Green Deal Industrial Plan can effectively complement the existing carbon pricing scheme of the EU and achieve a theoretically first-best policy mix, reducing the cost of achieving climate targets. The EU Green Deal Industrial Plan intends to combine various existing schemes into a comprehensive scheme to push EI. Thereby, it allows for greater technological openness than the IRA through a focus on the same core, mature technologies are evident. However, its plan to increase subsidy levels to equal those of the IRA is inefficient as the required support levels of the EU are lower because the EU must not cover the environmental perspective as the IRA has to. Such actions only increase the cost of environmental policies for the EU and add fuel to a potential subsidy war.

While we argue that these insights include valuable lessons for decision takers, we acknowledge that more specific policy recommendations are difficult to derive. The findings are typically either theoretical or linked to very specific settings and thus do not allow, for example, to say much about which technology to support through which exact measure and with which amount. So when, e.g., looking at the EU Green Deal with its several technology support programs or the US Inflation Reduction Act, one can say only very generally whether this is in line with an optimal policy mix (in general yes for the EU and no for the US), potentially leading to inefficiencies (probably both, but more so for the IRA) or which the main contribution towards decarbonization is (lower costs of reaching given targets in the EU, reaching emission reductions at all in the US). In addition, there exist many different forms of R&D policy, so it is not homogeneous itself. The discussion of the design of an optimal R&D policy in the environmental policy mix goes beyond the scope of the paper but opens the door for future research.

In addition, we only touched upon another interesting global pattern, which gives room for future research. There is an ongoing debate about fostering national industries and their competitiveness besides efficiently and effectively reaching emission targets as additional targets of R&D support measures. We have only touched upon this issue, since it is not the focus of this paper and relates to other strands of literature dealing, e.g., with strategic trade policy or industrial policy. Acknowledging that domestic welfare is a target for politicians for which they are most likely elected, assesses an optimal R&D support program even more difficult.

Overall, it will remain important to increasingly evaluate specific public R&D programs to learn more about what makes them successful in environmental and economic terms. Empirical assessments of governmental R&D support are primarily limited to RE technologies and thus, there is a selection bias focused on technology winners. Letting the technology winners write history may overestimate the effectiveness of public R&D on innovation. Additionally, many empirical studies do not differentiate between governmental R&D support and private R&D expenditures and hence, possibly, lack to reveal differences in public and private R&D. In summary, these identified limitations, coupled with the comprehensive literature review, can provide valuable insights to steer forthcoming theoretical and empirical studies concerning the role of governmental R&D support in accelerating the take-off of EIs.

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