CPB Netherlands Bureau for
Economic Policy Analysis

Green innovation policies: a literature and policy review

An effective and efficient energy transition requires two ingredients: pricing activities that are bad for the climate and stimulating innovation in green technologies. Unpriced environmental damage and path dependency put green innovation at a disadvantage compared to innovation in general.

This report explores how governments can contribute to green innovation. It provides an overview of the literature on green innovation policies. It further briefly reviews green innovation policy in the Netherlands.

CPB Background Document

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Summary in Dutch

Voor een effectieve en efficiënte energietransitie zijn er volgens de economische theorie twee ingrediënten nodig: zowel het correct beprijzen van activiteiten die slecht zijn voor het klimaat als het stimuleren van innovatie in groene technologieën, oftewel technologieën die koolstofarmer en schoner zijn dan 'grijze' (koolstofrijkere en vuilere) technologieën.

Dit rapport verkent hoe overheden kunnen bijdragen aan groene innovatie. Het geeft een overzicht van de literatuur over hoe beleid de ontwikkeling van nieuwe groene, duurzame technologieën kan bevorderen en versnellen. Het laat daarbij zien dat twee typen argumenten een rol spelen in het denken over groen innovatiebeleid: marktfalens en missies. Beide argumenten kunnen een onderbouwing geven voor de sturing van technologische verandering richting groene technologieën. Vervolgens biedt het rapport een korte beschouwing van het groene innovatiebeleid in Nederland.

Groene innovatie verschilt in een aantal opzichten van innovatie in het algemeen. Ten eerste betalen de baten van innovaties in groene technologie zich onvoldoende uit, voor zover uitstoot van broeikasgassen en schade aan het milieu niet (volledig) zijn ingeprijsd. Ten tweede zet het optreden van padafhankelijkheid groene innovatie op achterstand; de bestaande basis van kennis en innovatie bij grijze technologieën maakt dat innovatie daar winstgevender kan zijn. Ook zijn infrastructuur en regelgeving vaak afgestemd op bestaande grijze technologieën. Ten derde onderscheidt groene innovatie zich door de gerichtheid op specifieke – groene – doelen. Hierdoor is bij groene innovatie niet alleen de ontwikkeling van nieuwe technologie, maar ook de brede toepassing ervan belangrijk: groene doelen kunnen pas worden bereikt als de groene technologieën en producten op grote schaal worden toegepast.

We onderscheiden vier fasen in het proces van groene innovatie en bespreken per fase de geschikte beleidsinstrumenten. Het rapport besteedt ook kort aandacht aan meer algemeen beleid dat een effect heeft op groene innovatie, zoals regulering, beleid rond infrastructuur en CO_2-belastingen. Met de lessen uit het literatuuroverzicht in het achterhoofd, gaan we vervolgens in op de belangrijkste innovatiebeleidsmaatregelen in Nederland.

In de eerste fase van groene innovatie (fundamenteel onderzoek) bestaat overheidsingrijpen vooral uit bekostiging van onderzoeksinstellingen en universiteiten, en onderzoekssubsidies. Deze fase is technologisch het meest onzeker en kent de grootste marktfalens, dus overheidsingrijpen is hier het meest gerechtvaardigd.

In de tweede fase (pre-commercieel) is de rol van de overheid om te zorgen voor gunstige randvoorwaarden voor bedrijven en het oplossen van mogelijke financieringsproblemen, zodat zij lang genoeg kunnen overleven om de stap te maken naar levensvatbaarheid op de markt. Beleidsmaatregelen moeten zorgen voor voldoende liquiditeit; subsidies lijken in deze fase meer efficiënt dan voordelige leningen. Op winst gebaseerde innovatieprikkels zoals een lagere vennootschapsbelasting (bijvoorbeeld de innovatiebox) zijn waarschijnlijk niet effectief voor beginnende innovatieve bedrijven, omdat dergelijke bedrijven vaak hoge kosten en lage opbrengsten hebben. Het is van groot belang om te zorgen voor ondersteunende financiële mogelijkheden, omdat de onzekerheid nog steeds groot is en er vaak een tekort aan risicokapitaal is. Overheidsgaranties, directe investeringen en door de overheid gesteunde durfkapitaalfondsen in deze tweede fase kunnen helpen. Wel dienen deze instrumenten behoedzaam ingezet te worden om onnodig gebruik te beperken. Bedrijven die in nieuwe technologieën investeren kunnen gebruikmaken van ingehouden winsten, maar liquiditeit en toegang tot kapitaalmarkten blijven doorgaans beperkt.

In de derde fase (productmarkt) concurreren groenere producten en technologieën met grijze. De rol van overheden is om een brede toepassing van deze groenere producten en technologieën te stimuleren, als ze

een missie van een netto-nul uitstooteconomie willen bereiken. Adoptiesubsidies (subsidies die het voordeliger maken om groenere producten en technologieën te gaan gebruiken) zijn hiervoor nuttig, maar deze moeten wel zorgvuldig worden ontworpen. Bijvoorbeeld, instrumenten die de initiële kosten verlagen (zoals directe subsidies die de prijzen verlagen) werken beter voor huishoudens dan instrumenten die de levensduurkosten verlagen, zoals belastingaftrek en energiebesparing. De overheid kan in deze fase ook innovatie stimuleren door ervoor te zorgen dat de institutionele omgeving (financieel, regelgevend, infrastructuur etc.) klaar is voor de energietransitie. Standaardisatie kan ook de adoptie bevorderen, maar het moet technologisch neutraal zijn om te voorkomen dat we blijven hangen in ondermaatse technologieën (*lock-in*) en om verdere innovatie aan te moedigen.

Een portfolio van instrumenten lijkt optimaal. Mislukkingen moeten hierbij wel ingecalculeerd worden. Regelmatige evaluaties en transparantie helpen beleidsmakers bij het vinden van de meest doelmatige instrumenten, zodat ze tijdig kunnen bijsturen. Zulke inzichten zijn makkelijker op te doen als het beleid wordt ontworpen om evaluaties mogelijk te maken. Bijvoorbeeld, tevoren nadenken over data-eisen en rapportage, kan evalueren eenvoudiger maken.

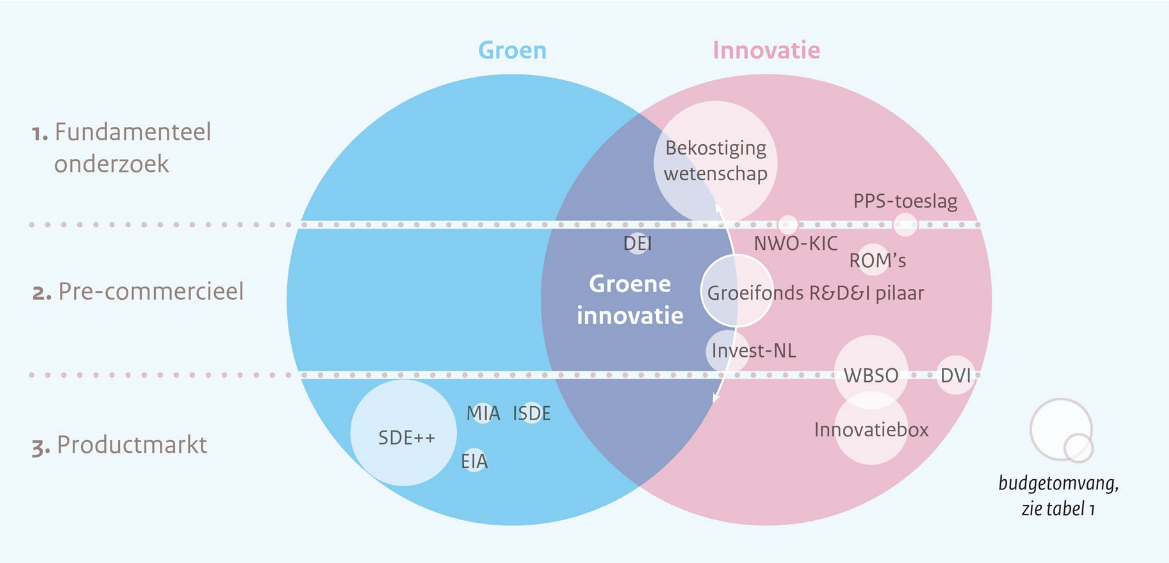
Algemene toepassing is de vierde en laatste fase van groene innovatie. Deze wordt bereikt als groene goederen en diensten de standaardoptie in de markt zijn en niet alleen maar concurrenten voor grijze goederen en diensten. In deze fase is de technologische onzekerheid grotendeels weggenomen en zijn de kennis*spillovers* beperkter dan in eerdere fasen. Wanneer groene goederen en diensten de standaardkeuze zijn, is onbeprijsde milieuschade ook kleiner dan in eerdere fasen, waardoor er aanzienlijk minder reden is om in te grijpen.

In Nederland bestrijken beleidsinstrumenten alle fases van innovatie, waarbij grotere budgetten worden uitgetrokken voor fundamenteel onderzoek (fase 1) en de productmarkt (fase 3). De totale onderzoek- en ontwikkel (o&o-)uitgaven komen overeen met het Europese Unie (EU) gemiddelde, maar zijn lager dan in Duitsland en Denemarken. De literatuur geeft geen duidelijke richtlijnen over de optimale o&o-uitgaven of de verdeling ervan over innovatiefases, maar Nederland zou ruimte kunnen hebben voor meer o&o-uitgaven in fase 2, de pre-commerciële of vroege ontwikkelingsfase.

Fundamenteel onderzoek wordt vooral gefinancierd via de bekostiging van universiteiten en subsidies waarom wordt geconcurreerd. De literatuur suggereert dat dit waarschijnlijk effectieve instrumenten zijn om innovatie te bevorderen.

De pre-commerciële of vroege ontwikkelingsfase is het minst vertegenwoordigd (naar budgetomvang). De literatuur suggereert dat overheidsinterventie in die fase effectief kan zijn, dus er zou ruimte kunnen zijn voor meer middelen om nieuwe ideeën, pilots en demonstraties in groene technologieën aan te moedigen.

Figuur 1 Gestileerde weergave van innovatiebeleidsinstrumenten in Nederland, die prikkels geven voor groene activiteiten (links), innovatie in generieke activiteiten (rechts) en innovatie in groene activiteiten (intersectie) (budgetten boven € 100 miljoen).



De huidige milieu- en innovatie-instrumenten zouden beter kunnen worden afgestemd op de bestaande strategische missies, zoals het terugdringen van de broeikasgassen met 95% tegen 2050 of de EU-doelstelling om tegen 2050 klimaatneutraliteit te bereiken. Klimaatbeleid kan, bijvoorbeeld via het beprijzen van CO_2-emissies, enkele belemmeringen voor groene innovatie wegnemen. Ook zou innovatiebeleid meer gericht kunnen worden op het (door)ontwikkelen en opschalen van groene technologieën.

De omvangrijkste regelingen in Nederland behandelen groene innovatie niet als een doel, maar eerder als een bijproduct. Instrumenten zoals de Stimulering duurzame energieproductie en klimaattransitie (SDE++) betreffen vooral adoptiesubsidies en richten zich niet direct op de ontwikkeling van nieuwe groene technologieën. Andere instrumenten, zoals de belastingaftrek bij de Milieu-investeringsaftrek (MIA) en de Energie-investeringsaftrek (EIA), beperken zich tot de toepassing van specifieke technologieën, waardoor de prikkel beperkt is om nieuwe *knowhow* te ontwikkelen.

Er zijn in Nederland ook negatieve prikkels voor groene innovatie: de beprijzing van CO_2-intensieve productieprocessen is in diverse sectoren laag; bovendien lijken de huidige regels en regulering aanzienlijke impliciete subsidies te verstrekken aan fossiele brandstoffen. Dit vertraagt de energietransitie.

De Nederlandse innovatieregelingen met de grootste budgetten zijn generiek en stimuleren dus niet specifiek groene technologieën. De huidige regels weerhouden bedrijven er niet expliciet van om innovatieregelingen zoals de innovatiebox of de Wet Bevordering Speur- en Ontwikkelingswerk (WBSO) te gebruiken voor grijze innovatie. Het effect van sommige impliciete subsidies voor grijze technologie kan worden verzacht door specifiek groene technologie te stimuleren of expliciet grijze technologie uit te sluiten van overheidssubsidies. Het afstemmen van de innovatieprikkels op de klimaatdoelen van Nederland kan synergie creëren tussen de beleidsinstrumenten en de energietransitie bespoedigen.

Tot slot blijft internationale afstemming een belangrijk thema voor groen innovatiebeleid. Investeringen in groene technologieën door ontwikkelde economieën kunnen leiden tot positieve overloopeffecten en de groene transitie voor alle landen versnellen. Vanuit een wereldwijd economisch perspectief is het realiseren van een significante kostenreductie van groene technologieën van het grootste belang. Grootschalige onderzoeksprojecten en voortdurende internationale dialoog blijven van vitaal belang.

Executive summary

An effective and efficient energy transition requires two ingredients, according to economic theory: correctly pricing activities that are bad for the climate and stimulating innovation in green technologies, that is, technologies which are lower-carbon and cleaner than 'brown' (higher-carbon and dirtier) technologies.

This report explores how governments can contribute to green innovation. It provides an overview of the literature on how policies can promote and accelerate the development of new green, sustainable technologies. It shows that two types of arguments play a role in thinking about green innovation policies: market failures and missions. Both arguments can provide a basis for directing technological change towards green technologies. The report then offers a brief review of green innovation policy in the Netherlands.

Green innovation differs from innovation in general in a number of respects. First, the benefits of innovations in green technology do not pay off sufficiently, insofar as greenhouse gas emissions and environmental damage are not (fully) priced in. Secondly, the occurrence of path dependency puts green innovation at a disadvantage; the existing basis of knowledge and innovation in brown technologies means that innovation can be more profitable there. Moreover, infrastructure and regulations are often geared to existing brown technologies. Lastly, green innovation distinguishes itself by the focus on specific – green – goals. As such, for green innovation, not only the development of new technology counts, but broad application is important too: green goals can only be achieved if the green technologies and products are adopted on a large scale.

We distinguish four stages in the process of green innovation and review the appropriate policy instruments for each stage. The report also briefly examines more general policies that have an effect on green innovation, such as regulation, infrastructure policies and carbon taxes. With the lessons from the literature review in mind, we then discuss the most important innovation policy measures in the Netherlands.

In the first stage of green innovation (fundamental research), government intervention mainly consists of funding for research institutes and universities, and research grants. This stage is the most technologically uncertain and has the greatest market failures, so government intervention is most justified here.

In the second stage (pre-commercial), the role of government is to provide favorable external conditions for companies and to solve possible financing problems, so that they can survive long enough to make the step to market viability. Policy measures must ensure sufficient liquidity; grants seem more efficient than low-cost loans at this stage. Profit-based innovation incentives, such as a lower corporate tax rate (e.g., patent boxes), are unlikely to be effective for innovative start-ups, because such companies typically have high costs and low returns. It is critical to ensure a supportive financial environment, as uncertainty is still high and there is often a shortage of venture capital. Government guarantees, direct investments, and government-backed VC funds can help in this second stage. However, these instruments should be used cautiously to limit unnecessary use. Companies that invest in new technologies can draw on retained earnings, but liquidity and access to capital markets are typically limited.

In the third stage (product market), greener products and technologies compete with browner ones. The role of governments is to stimulate widespread adoption of these greener products and technologies if they are to achieve a net-zero economy mission. Adoption subsidies (subsidies that make the use of greener products and technologies cheaper) are useful to this end, but they need to be designed carefully. For instance, instruments that lower upfront costs (such as direct subsidies that decrease prices) work better for households than instruments that lower lifetime costs, such as tax deductions and energy savings. The government can also encourage innovation in this stage by ensuring the institutional environment (financial, regulatory, infrastructure etc.) is prepared for the energy transition. Standardization can also foster adoption, but it must be technology neutral to avoid locking into sub-par technologies and to encourage further innovation.

A portfolio of instruments seems optimal. This does require taking into account failures. Frequent evaluations and transparency help policymakers to find the most effective instruments so that they can make timely adjustments. Such insights are easier to gather if policies are designed such that they allow for evaluations. For example, thinking ahead about data requirements and reporting can make evaluation easier.

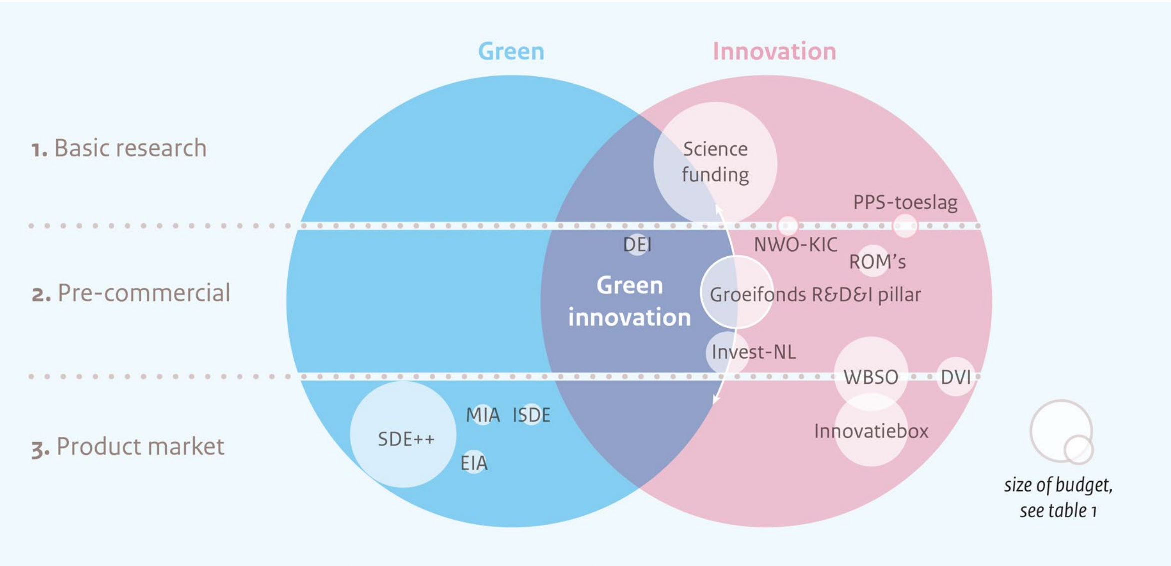
Mass adoption is the fourth and last stage of green innovation. This is achieved when green goods and services are the default option in the market and not just competitors for brown goods and services. In this stage, the technological uncertainty has largely been eliminated and the knowledge spillovers are smaller than in the earlier stages. When green goods and services are the default choice, unpriced environmental damage is also smaller than in earlier stages, significantly reducing the need to intervene.

In the Netherlands, policy instruments cover all stages of innovation, with larger budgets being dedicated to basic research (stage 1) and the product market (stage 3). Total research and development (R&D) spending is in line with the EU average, but below Germany and Denmark. The literature does not provide clear guidelines on optimal R&D expenditure or its distribution across innovation stages, but the Netherlands could have room for more R&D spending in stage 2, the pre-commercial of early development stage.

Basic research is mainly financed through university funding and competitive grants. The literature suggests these are likely effective instruments to foster innovation.

The pre-commercial or early development stage is the least represented (by budget size). The literature suggests that government intervention can be effective at that stage, so there could be room for more resources to encourage new ideas, pilots and demonstrations in green technologies.

Figure 1 Stylized presentation of innovation policy instruments in the Netherlands that provide incentives for green activities (left), innovation in generic activities (right), and innovation in green activities (intersection) (budgets above €100 million).



Current environmental and innovation instruments could be better aligned with the adopted strategic missions, such as reducing greenhouse gases by 95% by 2050 or the European Union (EU) goal to achieve climate neutrality by 2050.[1] Environmental policies could remove some barriers to green innovation, for example by pricing CO_2 emissions. Innovation policy could also be more focused on the (further) development and upscaling of green technologies.

The largest schemes in the Netherlands do not treat green innovation as a goal, but rather as a by-product. Instruments like the *Stimulering duurzame energieproductie en klimaattransitie* (SDE++) mainly concern adoption subsidies and do not focus directly on the development of new green technologies. Other instruments, such as the tax deduction of the *Milieu-investeringsaftrek* (MIA) and *Energie-investeringsaftrek* (EIA), are limited to the application of specific technologies, which limits the incentive to develop new know-how.

There are also negative incentives for green innovation in the Netherlands: the pricing of CO_2-intensive production processes is low in various sectors; moreover, the current rules and regulations seem to provide significant implicit subsidies to fossil fuels. This slows down the energy transition.

The Dutch innovation policies with the largest budgets are generic and, therefore, do not specifically encourage green technologies. The current rules do not explicitly prevent companies from using innovation schemes, such as the innovation box or the *Wet Bevordering Speur- en Ontwikkelingswerk* (WBSO), for brown innovation. The effect of some implicit subsidies for brown technology can be mitigated by specifically promoting green technology or explicitly excluding brown technology from government subsidies. Aligning innovation incentives with the climate goals of the Netherlands can create synergy between the policy instruments and accelerate the energy transition.

Finally, international coordination remains a salient issue for green innovation policy. Investments in green technologies by developed economies can lead to positive spillovers and accelerate the green transition for all countries. From a worldwide economic perspective, achieving a significant cost reduction of green technologies is of utmost importance. Large-scale research projects and continued international dialogue remain vital.

1 Introduction

An effective and efficient energy transition[2] requires policy action in order to (1) correctly price environmental externalities of current technologies, for instance, by taxing environmental damage (Pigou, 1912; Baumol and Oates, 1971) and (2) explicitly address positive externalities by incentivizing innovation in and upscaling of green technologies (henceforth green innovation), i.e., innovation in technologies that are lower-carbon and cleaner than ‘brown’ (higher-carbon and dirtier) ones (Bovenberg and Smulders, 1995; Acemoglu et al., 2012).

Stimulating green innovation is even more important when the scope of addressing negative externalities through taxes is limited. Carbon pricing instruments, such as the EU Emissions Trading System (EU ETS), are usually introduced with low price levels. They also include exemptions and grandfathering clauses to ensure

[1] With climate neutrality the EU means net-zero greenhouse gas emissions.
[2] In this report, we focus on directing innovation policy to support the transition from carbon-intensive to carbon-extensive energy sources. Yet, the analyses and conclusions in this report are also relevant for the transition to a cleaner and more circular economy.

the consensus necessary for their adoption (Dolphin et al., 2020). Such political constraints limit the role taxes play in curbing carbon emissions, so the optimal policy given these constraints might require more incentives for green R&D.

In this report, we focus on how green innovation can be influenced directly, rather than seeing it as a mere by-product of other policies. The design of incentives for green innovation has received less attention in the literature than carbon pricing. Previous research on green innovation tends to focus on how innovation activities are indirectly affected by climate policy, whereas innovation policy itself plays an important role in stimulating green innovations directly. In this paper, we provide an overview of the recent literature on how governments can directly encourage green innovation in different stages of innovation.

The rest of this paper is organized as follows. Chapters 2 and 3 describe the academic literature. Chapter 2 offers an overview of the arguments for government intervention. Chapter 3 uses a taxonomy of the stages of green innovation and analyzes problems arising in each stage as well as possible government interventions to address these. Chapter 4 describes the main policies affecting green innovation in the Netherlands and draws some conclusions based on the literature. Chapter 5 concludes with suggestions for future research.

2 Reasons for government intervention in green innovation

The economic literature features two main arguments for government intervention in (green) innovation: market failures, which we cover in Section 2.1, and missions, covered in Section 2.2. We also discuss how both arguments are closely related and can serve as an argument for directed technological change (Section 2.3). Policymakers are informed by both arguments to direct innovation policy towards green technologies. Both arguments thus can provide a basis for ambitious green innovation policy, while welfare economics can serve as an input for formulating missions and reaching missions in a cost-efficient manner.

2.1 Market failures

Welfare economics argues that market failures prevent green innovation from reaching a socially optimal level. Government intervention is, therefore, needed to fix market failures, provided that intervention improves the situation and does not create large undesirable by-effects (e.g., see Lehmann, 2012). In this sub-section, we discuss two main market failures that prevent green innovation from achieving the socially optimal level: externalities and financial market failures.

2.1.1 Externalities

Externalities are the main reason why markets provide too little green innovation. We discuss both positive and negative externalities.

Innovation exhibits knowledge spillovers, a positive externality, which implies that markets under-invest in research from a social perspective[3] (Arrow, 1972). Because knowledge may spill over from the innovating firm to others, the benefits from innovating can typically not be appropriated in full.

The literature further suggests that this underinvestment problem is more pronounced in case of innovation in green technologies due to the strong path dependencies that exist for brown technologies. Given that the stock of knowledge about brown technologies has grown large over time, research in brown technologies tends to be more profitable than research in new green technologies (Bovenberg and Smulders, 1995; Acemoglu et al., 2012; Aghion et al., 2016). Current infrastructure and regulatory systems may also be seen as a form of path dependence. For instance, further development of new technologies such as electric cars and green hydrogen first require large investments in infrastructure, which are usually done only when sufficient demand is expected. The path dependence of past innovation in brown technologies effectively acts to weaken the incentives for developing new green technologies and products.

Given that positive externalities are particularly salient for green technologies, in many circumstances there is an economic argument to *direct* innovation policy such that green technologies receive additional support compared to regular/incumbent technologies.[4] Note that in some circumstances, green technologies might benefit from knowledge spillovers from brown technologies. For instance, in the electricity sector, innovations in solar photovoltaic (PV) and wind technology highly benefit from prior innovations in the same technology, whereas waste energy and geothermal energy build on innovations in other technology fields (see Aalbers et al., 2013). Besides, a too specific focus on certain green technologies may also hinder active learning about the cost of different clean technologies.

Innovation activity is also influenced by negative externalities. Most notably, unpriced carbon emissions act as implicit subsidies to brown (high-carbon or more polluting) technologies, giving them an unfair competitive advantage compared to green technologies. To eliminate this market failure, economists recommend correcting prices to reflect environmental costs and align private and social incentives (Pigou, 1912). Climate-economy models show the importance of policies to support mass deployment of green technologies and stimulate learning-by-doing to bring down costs (Grubb et al., 2021). The importance of urgent policy action is especially salient in models that incorporate goal uncertainty and risk aversion, irreversibilities, and tipping points (Pindyck, 2012; van der Ploeg, 2018; Barnett et al., 2020). Policymakers can incorporate this urgency by applying higher carbon prices and low discount rates for public investments in green innovation.

2.1.2 Financial market failures

Financial constraints may limit the amount of innovation that firms can carry out. Innovation is an intangible asset, which complicates bank funding, as firms have no collateral. Equity might be an alternative for bank funding, but the asymmetry of information might be an obstacle (Bloom et al., 2019). Firms have private information about their abilities and they may misinform investors. This is a standard principal-agent problem in investor relationships (Aghion and Tirole, 1994). Firms may also have information about their environmental footprint and planned investments in green or brown assets, which is particularly relevant for investors concerned about environmental impact. The lack of consistent and homogenous information makes it hard to compare investment alternatives and gauge the overall impact of portfolios. Such information asymmetries seem to limit the supply of capital available to innovative companies (see Hall and Lerner, 2010).

[3] Note that, in some cases, positive product market spillovers can lead to *over*investment in innovation due to information asymmetry of consumers. A classic example is the pharmaceutical industry, where firms may invest massively in minor innovations that allow them to slightly differentiate their drug from competitors in order to capture a large market share. This isn't necessarily beneficial for society (Bloom et al., 2019).
[4] This requires the existence of path dependencies, the ability to direct innovation policies, and substitution possibilities of brown technologies or inputs for green alternatives (Aalbers et al., 2013).

However, the fact that firms might face financial constraints for innovation projects is not necessarily a reason for government intervention. Governments may also suffer from information asymmetry, even worse than private investors. As such, it will be difficult to design appropriate interventions (Bloom et al., 2019).

2.2 Missions

In light of the urgency of global warming, some governments have set missions to guide their policies: for instance, the EU pledged to achieve climate neutrality by 2050. The Netherlands is also part of this pledge and has also formulated missions like 'reaching a fully circular economy by 2050' (see Appendix, Table A.1).

The missions argument states that, achieving societal goals (*missions*) in time can be seen as a public good, and providing this good requires government to take on an active role to *direct* innovation towards the goals. This is because achieving missions like climate neutrality by 2050 requires urgent and radical transformation to new, sustainable technologies (Bloom et al., 2019). This would require government to act as a *market maker* and to 'kick-start' green technologies (Mazzucato, 2013; Mazzucato, 2021). A government that only engages in *market fixing "(…) is less useful when policy is required to dynamically create and shape new markets; that is, 'transformation'."* (Mazzucato, 2016, p.7). Government would need to take a broad vision and engage in 'courageous' public investment to support new industries. For instance, electric vehicles, green hydrogen, and synthetic fuels require significant investment in infrastructure before they can become broadly attractive. Active government support would be needed to create sufficient support for these technologies in time.

Mission-based policies are *"systemic public policies that draw on frontier knowledge to attain specific goals"* (Mazzucato, 2018). They usually have an ambitious goal and require coordination of many actors in order to solve a complex problem. Mission-based policies take inspiration from innovation efforts like the Apollo program, to focus innovation support on particular sectors or technologies (Bloom et al., 2019). The Apollo program had a well-defined and measurable goal, namely to put a man on the moon and return him safely home, it was government-funded and controlled, and had a clear timeline with technological milestones. Other examples of government-sponsored innovations include jet engines, radar, and the internet (Mazzucato, 2013).

More so than the Apollo program, achieving climate missions requires coordination between actors and innovations in different fields. For instance, electric cars would not be able to become a viable alternative to combustion-engine cars without numerous innovations in battery technology, which have decreased costs by 85% between 2010 and 2019 (BNEF, 2020a) and increased efficiency and capacity. Cooperation also happens between countries, as shown by the fusion project ITER in Southern France.[5] Additionally, coordination is also needed between various government agencies and their goals. For instance, climate policy can be subverted if the government (implicitly) subsidizes fossil fuel use to promote other goals, such as economic growth.

2.2.1 What defines a good mission?

Mazzucato (2018) emphasizes that proper missions should satisfy a couple of criteria. A mission should be well defined, i.e., with a clear and measurable objective and timeline, inspiring but feasible, and it must be democratically legitimate. In addition, a mission should comprise of a portfolio of projects that aim to reach the final goal. Since innovation carries a significant amount of uncertainty, diversification helps ensure that

[5] The ITER (International Thermonuclear Experimental Reactor) project is the largest fusion experiment in the world and is a collaboration of 35 countries. Nuclear fusion has numerous advantages over existing sources of energy: it produces no carbon emissions and relatively little radioactivity, it is efficient and much safer than nuclear fission. ITER experiments are designed to make fusion power plants possible, see link.

mission will be reached even if individual projects fail (Mazzucato, 2018). This implies governments investing in multiple promising innovation projects and updating their approach as uncertainty resolves, gradually concentrating resources to the likely 'winners'. Uncertainty and learning from occasional failures are embedded in such a process. Even if certain projects fail, the overall portfolio of investments moves society one step closer to achieving its mission. Lastly, missions should include clear priorities, which are then translated into specific policy instruments to be applied at all levels.

2.2.2 Risks of mission-based innovation policy

Using missions to determine innovation policies, however, also comes with risks. Notably, missions can be ill-defined (multi-interpretable, for instance 'a sustainable economy'), difficult to measure or impossible to reach (for instance, 'a 100% circular economy'). As a result, it may remain unclear what such missions imply for the innovation budgets and policy instruments to be used.

Another risk is that the mission does not fulfil the criterion of social desirability. This might be less problematic for climate-related missions, but for cases like the Apollo mission social desirability could be debated. The program was not the most resource efficient way to spur innovation (Bloom et al., 2019). Relatedly, a risk of missions-based public investments is misallocation of resources, examples of which include the Concorde supersonic jet (see Lerner (2009) for more examples).

2.3 Market failures and missions: arguments for directed technological change

The missions argument for green innovation policy can be seen as a specific form of *directed technical change*. Acemoglu et al. (2012) argue on the basis of market failures that the optimal government policy requires both a Pigouvian tax to internalize the environmental externality and a subsidy to encourage innovation in green technologies. They make a strong case for governments to *direct* technical change away from brown towards green technologies. Without intervention, the market size effect and the initial productivity advantage of brown inputs would direct innovation and production to the brown sector. To steer both the amount and the direction of technical change, governments would need to clearly distinguish green from brown activities, decide which activities are to be encouraged and *how*, which is a difficult task (Aalbers et al., 2013).

Policymakers are informed by both the mission and the market failure arguments for directing innovation policy to align with climate policy goals and in support of green technologies. While the missions argument informs policymakers to direct innovation policies towards achieving long-term policy targets, the input from economic theory is useful for formulating targets that are socially desirable and for analyzing instruments that help reach missions in a cost-efficient manner. In the context of net-zero missions, policymakers are therefore called upon to not only support green technologies but, importantly, to price negative externalities (e.g., carbon pricing), as this creates incentives for both emission reduction and innovations in green technologies (see Acemoglu et al. 2012; Aghion et al. 2016).

3 Policy options for supporting green innovation

Green innovation is a complex, uncertain process which features multiple market failures (see section 2.1 for an overview). In this section, we split the innovation process into four stages of decreasing technological uncertainty: (1) basic research, (2) pre-commercial (or early development), (3) product market (or late development) and (4) mass adoption. Note that this is a simplified representation and the innovation process may also involve stepping back and forward between stages (CPB, PBL and SCP, 2014). As technological uncertainty gradually resolves through further research, standard issues of profitability and risk take center place in the later stages (Ghosh and Nanda, 2010). Financial institutions are equipped to handle these issues, so private capital is much more prevalent in later stages of the innovation process. In the following, we cover each stage and the bottlenecks that show up when advancing from one stage to the next. We also review the evidence on (green) government policies that affect each stage and the trade-offs inherent in each policy.

3.1 Innovation policy

Basic research, also known as fundamental research, aims to enhance knowledge about a subject, without necessarily targeting immediate practical applications. Nevertheless, improvements in the knowledge of fundamental processes can lead to whole new industries: research into the structure and workings of genes developed into biotechnology, fundamental research into semiconductors led to the development of modern computers and photovoltaics and research into statistical methods led to the development of artificial intelligence. In terms of the EU's Technology Readiness Levels (TRL)[6], this stage would be equivalent to levels 1-2 (see Appendix, Table A.2).

Pre-commercial research is the second stage of innovation. This is an early development stage that involves applied research, i.e., translating results of fundamental research into potential products. It often takes the form of pilot, demonstration, and proof of concept programs, which examine the technical feasibility and business case of an idea. This is a fairly wide stage in our analysis, approximately equivalent to TRL 3-7.

The third stage of green innovation, the product market, is a late development stage where the product has already proved its technological feasibility. The green technologies are commercially available and can compete with brown or grey ones. However, widespread adoption is not yet the norm and clean technologies are not the default. In TRL-terminology, this is equivalent to latest levels 8-9.

Widespread adoption is the final stage of green innovation. In this stage, green technologies have become competitive to brown alternatives. This requires wide availability and convenience in addition to commercial viability. In TRL-terminology, this is equivalent to the final level 9 and reaches beyond the TRL-levels.

Our stages are meant to cover the whole road to achieving climate goals, and as such do not stop at technology readiness or reaching the market unaided (as in, for example, Polzin et al., 2016). The first two stages can be found in most models of innovation, while the last two are more specific to target-driven green innovation.

[6] For an overview of the TRLs, see Appendix, Table A.3.

Commercial viability means the technology is competitive without support. In principle, it can be achieved already in the product market stage, so this is where many models of innovation would stop (see Ghosh and Nanda, 2010; Polzin et al., 2016; Polzin and Sanders, 2020). In TRL parlance, the product market stage could already include levels 8 and 9, while mass adoption would include TRL 9 and beyond. By this logic, wind and solar PV would already be considered mature technologies in the final stage of innovation. However, with a mission to use only renewables, such as wind and solar PV, these technologies are not yet default options compared to fossil fuels, and as such have not reached the final innovation stage of mass adoption.

Each stage of innovation involves different levels of uncertainty and various reasons for government intervention, as well as different types of trade-offs. We analyze each in turn.

3.1.1 Basic research

Basic research generates the most knowledge spillovers (Van Elk et al., 2017): when breaking new ground, it can lead to the creation of whole new industries and many subsequent discoveries.

Basic research is generally not an attractive business case for private financing, due to its slow speed, high uncertainty and large knowledge spillovers. For this reason, the public and non-profit sectors have traditionally been the main investor in basic research. A large share occurs in universities or research institutes usually affiliated with universities or government departments. National laboratories (such as DARPA (Defense Advanced Research Projects Agency) and ARPA-E (Advanced Research Projects Agency–Energy) in the United States (US)), public research institutes (Max Planck in Germany, CEA (Alternative Energies and Atomic Energy Commission) in France), non-profit research institutes (Wellcome Trust in the United Kingdom) are all examples of institutions whose main mission is to advance the frontier of science, without specifically searching for economic gains. Some basic research projects are so large that they require multiple countries to pool resources: examples include the Human Genome Project, the Large Hadron Collider and ITER.[7]

Policy options

University funding and research grants are the traditional instruments for encouraging basic research. Grants usually involve a competitive element, where multiple proposals apply for financing in order to solve specific issues intended by the grant. In the EU, the largest such grant-funding scheme is Horizon 2020.

There is strong evidence that government grants encourage innovation, but there is no consensus about the size of their effect or the effect of targeting green innovation. Tabakovic and Wollmann (2019) and Azoulay et al. (2019) found positive effects of increasing research support and grants on articles published, patents, and licensing incomes. Ganguli (2017) found large positive effects of grants given to Soviet scientists at the fall of the Soviet Union, suggesting grants have high marginal return for low funding levels and high supply of human capital. However, Arora and Gambardella (2005) and Jacob and Lefgren (2011) found that receiving funding from the National Science Foundation and National Institute of Health only weakly affected publications. These studies focused only on the effect of marginally winning or losing a grant, so it could be that the total effect of the grant is higher.

Azoulay and Li (2020) argue that grants are the most appropriate instrument when the desired outcome of the research is hard to define and/or compare. They are particularly suited for exploratory basic research, which tends to be highly uncertain and unpredictable, making an ex-ante definition of success counterproductive.

[7] The Human Genome Project (1990-2003, link) was the world's largest collaborative biological project and aimed to map out the human DNA and was a collaboration between six countries. The Large Hadron Collider (2009-present) is the world's largest particle accelerator and is used for fundamental research in physics. It is the successor of initiatives that were started in the 70s by the European Organisation for Nuclear Research (CERN, link) and is a collaborative effort of 23 countries.

Contests are similar to government grants, but are most suited for situations where ex-ante technical requirements can be clearly defined (Azoulay and Li, 2020). This makes them particularly suitable to the energy sector, as the product (electricity) is homogeneous and criteria can be defined in terms of emission reductions or costs. However, contests shift technological risk to the supplier of research, which limits their appeal and can explain their relatively niche status.

3.1.2 The pre-commercial stage (early development)

The early stages of innovation are also the most uncertain. Often, they require large investments and take the form of a high-stakes lottery: if the project succeeds, there is a technological breakthrough with follow-on innovations and possible industrial-scale disruptions down the line. However, in case of failure, investors can be left with little to show for their efforts. In the case of basic research, the main investor is the public sector and has the financial power to withstand such risks. Furthermore, with the rise of open publishing requirements for publicly-funded research, even failed projects can lead to valuable insights, if published and widely disseminated. However, for very early-stage commercial endeavors, failure often means bankruptcy, and the lessons learned are also less likely to be disseminated.

The distance from commercial viability is the main reason this second stage of innovation is often considered the riskiest for private capital, giving rise to a so-called "valley of death". Firms entering this stage can fall through the cracks of the R&D financing system: they are too risky for private capital, but too applied to attract public funds intended for basic research. Exiting this stage is also risky: in order to develop a commercial product, companies often require substantial investments in capacity and a relatively long investment horizon, which private capital can be reluctant to provide. Even when such funding is provided, it is often volatile and requires investments from multiple parties (Kerr and Nanda, 2015), so many companies run out of cash before proving their commercial viability enough to attract more capital (Polzin and Sanders, 2020).

As technological uncertainty resolves, more traditional financial institutions can step in (Kerr and Nanda, 2015). Banks have experience quantifying economic uncertainty and are able to develop credit strategies. However, companies focusing on green innovation are also exposed to uncertainty from future environmental policy, which banks cannot properly estimate. This can limit financing available to green projects.

Current financial regulation (i.e., the rules imposed by financial regulators to protect the stability of the financial system) could exacerbate the financing issues of green innovation. Banks might face difficulties lending to long-term green innovation projects given strict liquidity requirements (Liebreich, 2013). Financial institutions with a long time horizon, such as pension funds, are legally bound to limit their risk-taking. High-risk institutions, on the other hand, such as VC funds, typically have a shorter time horizon than many green innovation projects require in the second stage.

Policy options

The role of government intervention in the pre-commercial stage is to bridge the valley of death, for instance by ensuring liquidity, so that companies live long enough to prove their commercial viability.

Governments can help companies directly by ensuring liquidity, usually in the form of outright grants for R&D or subsidized loans. Evidence from the US suggests that energy-related start-ups benefit greatly from government grants, especially in the pre-commercial stage (Howell, 2017). The SBIR program in the US[8], which offers early-stage grants of 150,000 USD for proof-of-concept work, strongly encourages innovation, increases patenting and firm revenues, and does not seem to crowd out private capital. Receiving such a grant

[8] SBIR (Small Business Innovation Research) is a grant that combines extramural research budgets of various government agencies in the US and provides research contracts and grants to innovative businesses in a range of strategically important sectors.

furthermore doubles the probability that a firm continues with the project and receives subsequent venture capital (VC) funding. This suggests that government funding not only may solve liquidity problems but can have signaling value too, allowing awardees to attract more private funding and thus help bridge the valley of death.

There is evidence that small, young, innovative firms benefit most from state R&D grants and loans. Bronzini and Piselli (2016) find that it was mostly small companies that benefited from an R&D grant scheme in the early 2000s in Italy, as the program had the largest effect on their number of patent applications. Zhao and Ziedonis (2020) find that an R&D loan in Michigan mostly benefited small, young, innovative companies.

There is some evidence that grants have a stronger effect on start-up R&D spending than subsidized loans. Hottenrott and Richstein (2020) suggest that combining grants and loans can lead to a stronger positive effect on innovation, future revenue and employment. They find that German start-ups which received government grants increased their R&D spending, while those that received subsidized loans did not.

Relaxing financial constraints for green companies can also provide liquidity. Policy can focus on providing outright financing to green investments or changing financial regulation to better fit the energy transition.

To ensure a constant funding to societal missions, governments can set up state investment banks (SIBs). These financial institutions are better positioned to focus on addressing long-term societal challenges than most regular investors. Unlike grants or subsidies, SIBs allow funds to revolve and grow through time, ensuring a dependable source of financial support. This is the case of Germany's KfW (*Kreditanstalt für Wiederaufbau*), which was originally set up in 1948 to manage the funding coming through the Marshall Plan and has grown to be a significant funder of mission-based investment (Mazzucato and Penna, 2015).

Governments can also help companies with equity injections through state-backed VC funds. VC funds are investment funds that invest in promising early-stage companies. Governments can set up such funds on their own, or pool resources with private investors. By investing in the equity of private companies, the public sector can share in gains if companies become more valuable over time or pay out dividends. There has been a proliferation of state-backed VC funds in recent years. In the US, the 2010 State Small Business Credit Initiative alone has given rise to state-backed VC funds in more than 30 states. While not specifically aimed at green investments, these funds should provide a wealth of information about best practices in the future. In Germany, the KfW has also started to increasingly provide more equity investments, resembling the function of a VC fund (Mazzucato and Penna, 2015).

So far, however, the limited empirical evidence suggests that state-backed VC funding is not necessarily helpful. Dubovik and Steegmans (2017) find that start-ups which received funding from state-managed funds fared worse than those funded purely from private sources. Brander et al. (2015) found that low levels of state-backed VC funding improves company performance, while high levels impairs performance. However, it is not clear to what extent other considerations (such as environmental impact) are affected.

Tax credits and other favorable terms linked to profits are ways to subsidize innovative companies. However, these instruments are unlikely to help with liquidity, as companies in this stage tend to have high costs and little income. Tax credits with another basis than profits, for example labor costs, may help companies in this stage by improving liquidity. Bloom et al. (2019) conclude, for innovation in general, that R&D tax credits have a substantial positive effect on the volume of R&D and on productivity at the national level.

Lastly, financial regulation could be altered so that financing constraints for green technologies are lowered and become more stringent for brown technologies; also, financial incentives of banks' could be made in line with climate policy goals (Campiglio et al., 2018; Schoenmaker, 2021). Such policy options, however, are hardly researched and still heavily debated. For instance, concrete policy options would be to offer more favorable reserve requirements to banks investing in green sectors (Rozenberg et al., 2013) or greening monetary policy by increasing the share of green bonds purchased by central banks (Spencer and Stevenson, 2013). For the moment, we are only aware of the European Central Bank program plans to increase its share of green bonds in the portfolio, up from 3.5% in January 2021. The Bank of England also announced in May 2021 an intention to focus its corporate bond-buying program “in support of net-zero”.

3.1.3 Product market

Products in the late development stage have proven technical feasibility, meaning that much of the uncertainty of the previous stages has been resolved. However, if governments aim to achieve ambitious missions like carbon neutrality, it is not enough for green products to be technically and even economically feasible: they need to become the default option for the energy transition to become a success.

There are several barriers that can prevent green products from reaching the mass adoption stage.

First, the institutional and regulatory framework can provide implicit advantages to old technologies. Rigid regulation can pose significant barriers to new technologies, as these might not fit current standards. For instance, the lack of an efficient CO_2 price in some sectors (such as manufacturing) makes brown technologies cheaper and more attractive than green alternatives. New technologies also sometimes require standardization in order to encourage further adoption: for instance, there are circular economy standards that ensure the quality of re-used parts in medical refurbished equipment.

Second, there is a coordination problem: some new technologies require massive infrastructure investments in order to be generally used. In some cases, this can give rise to a vicious circle: infrastructure is warranted only if there is enough demand, but demand is low due to lacking infrastructure. Electric charging stations for cars and green hydrogen generation are a case in point.

Third, financial constraints are also present in late development. Since technological uncertainty in this stage is largely resolved, financial institutions such as banks and pension funds should also become relevant players in financing the green innovation process. However, IRENA (2020) suggests this might not be the case to date.

Pension funds are important suppliers of patient capital which firms in this stage require for further development. However, green projects do not fit well in the current regulation that aims to limit pension funds’ long-term risk-taking, so the green investments of such institutions are limited.

Policy options

We found three categories of instruments to encourage green innovation in this stage and reach mass adoption: supply-side instruments aimed at relaxing liquidity constraints (grants, tax credits etc.), demand-side instruments (subsidies and public procurement) and regulation (environmental, financial).

Supply-side instruments

There is little causal evidence on the impact of government grants on firms in this stage, but there is reason to believe it would be more efficient to split large grants into smaller ones and target early-stage new companies with innovative approaches. The results for the SBIR program in Goldstein et al. (2020) and Howell (2017) suggest that their effect is more limited than in the pre-commercial stage. Howell (2017) finds that the SBIR’s second stage, which offers grants of 1 million USD, had a positive effect on citation-weighted patents, but the effect was much smaller than that observed for the small grants.

R&D tax incentives may also encourage further innovation (Becker, 2015), but need careful design in order to achieve the desired effects. If not specifically targeting green innovation, they can damage the low-carbon agenda by encouraging more brown innovation.

Policymakers should take particular care when designing patent boxes, as there is evidence these boxes can be used for aggressive tax planning. A patent box aims to promote innovation by offering favorable tax treatment to income from intellectual property (such as patents). However, multinational companies can move patents to other countries and use patent boxes to decrease their overall tax burden. Alstadsæter et al. (2018) find no clear effect of patent boxes on local R&D, but they do find evidence consistent with firms using patent boxes for aggressive tax planning. Bloom et al. (2019) conclude that because of aggressive tax planning risks, patent boxes are inferior to other tax-based policies like R&D tax credits. Their conclusions echo CPB et al. (2014), who suggested tax credits covering social security contributions of R&D staff could be the most effective R&D tax incentive: they are targeted, provide liquidity, and are less likely to enable aggressive tax planning than profit-based policies.

Infrastructure can also increase the demand for green products by lowering the barriers affecting their use and harnessing network externalities. Causal evidence of the effects of infrastructure investment on adoption is scarce, but Egnér and Trosvik (2018) find that investments in charging stations in Sweden led to an increase in the purchase of electric vehicles.

Demand-side instruments

Governments can encourage the private demand for green goods and services, but also demand from the public sector. The latter usually takes the form of rules for public procurement (i.e., the purchasing of goods and services by the public sector) that include environmental standards.

Adoption subsidies are one of the main instruments to encourage take-up of green products. They can allow the market to grow and mature through learning-by-doing effects.

Empirical evidence suggests environmental subsidies indeed may speed-up the adoption of greener products. De Groote et al. (2016), find that Flanders' environmental subsidies encouraged the installation of solar PV systems. Chandra et al. (2010) find that Canada's tax rebates increased hybrid vehicles sales. Jenn et al. (2013) found that a so-called cash-for-clunkers program in the US increased the sale of hybrids, but only for large enough incentives. In the presence of high demand uncertainty, suppliers limit their inventory risk by producing less, so subsidies should be even larger than in more deterministic markets (Cohen et al., 2016).

There is strong evidence that instruments that lower upfront costs, such as sales tax waivers, have a larger positive effect than later income tax rebates (Diamond, 2009). Gallagher and Muehlegger (2011) find sales tax waivers are associated with more than a ten-fold increase in hybrid sales relative to income tax credits. This is confirmed by Clinton and Steinberg (2019), who find that direct purchasing rebates increased the sales of electric vehicles, but tax credits had no effect. A possible explanation is given by De Groote and Verboven (2019), who find that households strongly discount future streams of lower energy costs.

The public demand for green goods and services can also be increased through green public procurement. By setting environmental standards in addition to price and quality standards, governments can act as launching or scale-up customers, providing green ventures the necessary market scale for further development.

There is little causal empirical evidence whether green public procurement is an effective tool. Sweden has implemented in 2006 a green public procurement policy which has been the focus of some empirical work. Lundberg et al. (2015) find that green award criteria had a limited effect on the decision to participate in and bid for tenders for cleaning contracts. They argue that adding green requirements to the already complex process of procurement can act as a strong deterrent. There is some evidence that public procurement can encourage innovation more generally. Czarnitzki et al. (2020) find that public procurement aimed at innovation is associated with an increase in revenues from new products. Belenzon and Cioaca (2021) do find a positive effect of US government contracts on corporate publications, but not on patents. However, we are not aware of causal evidence on the effect of such procurement policies on long-term profitability or innovation.

Regulatory environment

States can also relax the financing constraints of green companies by modifying financial regulation, as discussed in Section 3.1.2.For instance, state-backed VC funds and development banks can also finance the scale-up stage of green innovation. An alternative is to modify financial regulation to require financial institutions to better take into account climate impact of the companies they finance. See, for instance, the recent Environmental, Social, and Governance (ESG) and climate risk disclosure requirements (link).

There are also more targeted instruments that can encourage banks to lend to green companies in the product market stage. State guarantees, for instance, help limit investors' downside risk and attract private capital (Taghizadeh-Hesary and Yoshino, 2019). Empirical evidence on such mechanisms is scarce, but there is some evidence that programs aimed at generic SMEs (small and medium-sized enterprises) have positive credit effects (de Blasio et al., 2018). However, state guarantee schemes should be carefully designed and monitored, as they could lead to moral hazard and excessive risk taking by banks (Gropp et al., 2014).

Regulation supporting the deployment of renewable energy technologies can also spur green innovation. Böhringer et al. (2017) find that the German feed-in-tariffs for renewable electricity production led to the development of high-quality patents in these technologies, but caution that over-generous tariffs might not have additional effects. Palage et al. (2019) find that renewable energy certificates can also induce patenting activity, but that the generous feed-in-tariffs have a larger effect.

Environmental regulation can foster green innovation activity[9] (Porter and van der Linde, 1995). Kiso (2019) shows that energy efficiency regulations in the automobile sector induced a 3-5% improvement in fuel efficiency. The literature on the effectiveness of building codes is mixed: Noailly (2012) found the stringency of energy requirements in building codes to increase patents. However, Fowlie et al. (2018) found savings from energy investment requirements to be more modest than expected. This is line with Levinson (2016), who found no effect of California's stringent energy efficiency codes on energy consumption. Potentially, a rebound effect is at play, where homeowners increase consumption once heating costs drop (Lemoine, 2020).

Standards can facilitate the adoption process for green technologies, but can also hinder further innovation if they are technology-specific or if they are set too early (Olmos et al., 2012). Technology-specific standards risk locking in sectors a long time and can discourage innovation outside the standard. The European Commission (2013) recommends setting technologically-neutral standards, to allow the market to choose the most efficient way to comply and leave room for new technologies. There is some empirical evidence that technologically-neutral environmental standards in the automobile industry encouraged green innovation (Lee et al., 2011).

Policies can also mitigate the asymmetric information about environmental impact. The main instruments include: taxonomies, methodologies for calculating environmental impacts, and reporting requirements. Labeling can ease comparison between alternatives, though a proliferation of labels from different sources can be confusing. One of the best-known energy labeling policies is the EU's compulsory energy labeling

[9] Popp (2019) and Hille et al. (2020) provide comprehensive reviews of the effect of environmental regulation on green innovation.

scheme for electric appliances. Newell and Siikamäki (2014) find in an experimental setting that labels that rank products (such as the EU's scheme) can guide consumers towards more energy efficient products.

3.1.4 Mass adoption

In principle, in the mass adoption stage, technologies are sustainable and green by default, so negative environmental externalities should not be a significant policy problem anymore. However, if there are still positive externalities, such as knowledge spillovers, standard innovation policies should increase innovation to the socially optimal level. These include increasing liquidity and providing tax breaks for R&D.

3.2 Other factors affecting green innovation

3.2.1 Carbon pricing

Carbon pricing will encourage green innovation and provide incentives to move away from environmentally damaging products and technologies. A common line of argument in this vein is the Porter hypothesis, which suggests environmental regulation can lead to an increase in green innovation (Porter and van der Linde, 1995; CPB, 2018). Pricing carbon makes green products more competitive and attractive for investments compared to a baseline with no such prices (Acemoglu et al., 2012, Aghion et al., 2016; Aalbers et al., 2013). This theoretical effect is borne by some empirical evidence: Calel and Dechezleprêtre (2016) find that the EU ETS increased low-carbon innovation by 10%, with no evidence that this crowded out other technologies.

Relatedly, current (explicit or implicit) subsidies for fossil fuel use act as a negative carbon price signal and discourage companies to use sustainable energy alternatives. The European Commission (2019) estimates that yearly fossil fuel subsidies amounted to €55 billion in the EU alone, ten times the entire Horizon 2020 budget for "Secure, clean & efficient energy". At the global level, Coady et al. (2017) estimate that fossil fuel subsidies amount to 6.5% of GDP. This is much more than global investments in renewable energy, which are estimated at about €300 billion in 2020 (BNEF, 2021b). In the Netherlands, fossil fuel subsidies amounted to at least €4.5 billion (OECD and IEA, 2020).[10]

3.2.2 Generic innovation policies

Broad-based innovation subsidies may be used for brown innovation activities, perpetuating the implicit advantages of brown technologies. Since the stock of knowledge about brown innovation is larger, further investments in this area could yield more private returns than investing in green technologies, widening the gap (Bovenberg and Smulders, 1995; Acemoglu et al., 2012; Aghion et al., 2016). Current infrastructure and regulatory systems are also attuned to brown technologies, which makes investments in new green technologies or products less attractive and more cumbersome. For example, innovations in electric cars and green hydrogen first require large investments in new infrastructure, for which initial demand tends to be low.

3.2.3 Institutions

In general, there appears to be link between good institutions and innovation. Countries at the top of the innovation rankings also tend to be those in the top of ranks on ease of doing business such as the World Bank's Ease of Doing Business and on bottom ranks on corruption and graft. Protection of property rights is also associated with more innovation (Chen and Puttitanun, 2005; Sweet and Eterovic Maggio, 2015).

[10] Budgetary estimates were made for 7 of 13 subsidy schemes identified. No estimate was made for, e.g., the degressive energy taxes.

Intellectual property rights can help innovative companies but can also limit further discoveries. Many public research institutions allow free access to their findings. For instance, projects funded by the EU's Horizon 2020 are required to make peer-reviewed articles openly accessible. Other institutions, such as those in the Human Genome Project, require generous licensing policies to allow wide dissemination of results.[11]

Research and development require a well-educated, scientifically literate workforce, capable of taking intellectual risks. Human capital can be increased by supporting universities and their quality, stimulating technology-focused programs (Bloom et al., 2019).

Knowledge networks are also important for innovation. Policies to create collaboration networks between academia, business and finance can increase the dispersion of knowledge, give rise to new ideas and decrease transaction costs by increasing trust between parties. Governments can encourage the creation of such networks by building innovation hubs, as well as by ensuring publicly funded research is widely available. This can be achieved by mandating openness for government-funded programs (where possible), making publicly funded research freely available and conditioning public funding on collaboration.

3.2.4 Regulatory and technological uncertainty

Stable and credible climate goals provide the private sector with clarity and regulatory predictability, which can encourage investments in green technologies considered today (Rogge and Schleich, 2018). Policy stability is also associated with more investment in renewable energy capacity (Schleich et al., 2017). By contrast, a lack of credible goals and concrete regulatory instruments may raise risk premia for investors, which ultimately increases the cost of the energy transition (Trinks, 2020). Credibility also depends on public support for specific technologies, as illustrated by the case of nuclear power after the Fukushima disaster.

One way to approach the uncertainty of green innovation projects is to adopt a portfolio approach and invest in multiple projects and technologies (Mazzucato and Perez, 2015; Azoulay and Li, 2020; Hille et al., 2020). This not only diversifies the risk, but it increases the probability of finding a successful solution and generating inter-technological spillovers.

A portfolio approach requires normalizing failure as part of the innovation process and looking at the aggregate picture rather than specific failures and successes (Cromwell and Schmisseur, 2013). Well-designed policies can also mitigate the economic and political costs of failure. Publicly funded projects should be designed to promote learning, providing other researchers with easy access to results and clear reporting requirements (Hendry et al., 2010). Transparent ex-ante targets and methods of evaluation for the entire portfolio are crucial to maintain public support. Such clear specifications might be difficult in the case of open-ended early scientific exploration projects, but should be feasible for the vast majority of green innovation programs (Rodrik, 2014).

Since green innovation is a complex process involving multiple market failures, the literature suggests government policy should use a portfolio of targeted and general instruments (Aalbers et al., 2013; Costantini et al., 2017). Targeted subsidies focus on the policy goals but require more information and tend to have higher administrative costs. Generic subsidies are easier to implement but can be allocatively inefficient. A portfolio of instruments is particularly suited for green electricity, as sustainable sources are imperfect substitutes, *inter alia* due to intermittencies and spatial constraints (Aalbers et al., 2013).

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[11] The Human Genome Project went even further, requiring "all human genomic sequence information, generated by centres funded for large-scale human sequencing, should be freely available and in the public domain in order to encourage research and development and to maximise its benefit to society. (…) It was agreed that these principles should apply for all human genomic sequence generated by large-scale sequencing centres, funded for the public good, in order to prevent such centres establishing a privileged position in the exploitation and control of human sequence information." (Human Genome Project, 1996)

A difficult question: how to adapt green innovation policies to new developments?

If policymakers adopt a portfolio approach and build flexibility into green innovation policies, a natural question arises: how to make adjustments?

With generic innovation policies, new products and markets are created by the innovation process spontaneously, i.e., without the government coordinating end results. As long as private and public incentives are aligned and no other market failures are present, those new products are optimal from a social perspective.

By contrast, reaching a specific target in a given amount of time, such as the EU's pledge for climate neutrality by 2050 makes interdependencies and dynamics particularly salient for green innovation policies. A portfolio approach to green innovation investment can give rise to many possible paths, but as time passes by and some uncertainties are resolved, new adjustments need to be made.

It is unlikely that policymakers (and researchers) will be able to grasp all possible interdependencies between all sectors required to reach climate neutrality. A boundedly-rational perspective might be in order: analyzing the interdependencies most likely to be relevant, focusing on clearing some of those critical paths and committing to reconvene after specific amounts of time, to evaluate existing policies. New developments might give rise to new trade-offs, so committing to incorporating new information into the policies at specific times could mitigate the risk of committing for too long to obsolete paths.

3.2.5 General considerations about green innovation policies

A recurrent question regarding (green) innovation policy regards additionality, i.e., whether government funding encourages further development and private funding. Recent studies suggest public funding actually crowds in private R&D spending (Becker, 2015). Moretti et al. (2019) find evidence of crowd-in effects in sectors traditionally considered strategic and Hottenrott and Richstein (2020) found no evidence of grants or subsidized loans crowding out private investment in German start-ups.

There is some evidence that green innovation policies have skewed effects, so government action could affect market concentration and compound inequalities. The average positive effect found in many studies could be due to a small number of firms benefiting greatly and the bulk of beneficiaries having no discernible effect (González et al., 2005; Cunningham et al., 2016). More recently, Stucki (2019) found only the top 20% companies with the largest energy costs benefitted from investments in green energy technologies in Austria, Germany and Switzerland.

Successful policies require regulators' incentives be aligned with the public interest. Past experience shows initiatives with generous funds and uncertain outcomes leading to rent-seeking and lobbying (Foray et al., 2012). Transparency in decision-making and competition rules and regular program evaluations can mitigate such concerns. Providing support to whole sectors or sub-sectors, while encouraging competition within the sector, can ensure efficiency within the sector and limit rent-seeking by specific firms (Rodrik, 2014).

International coordination is another requirement for a successful energy transition. Countries have an incentive to freeride on each other's investments in new emission-limiting technologies. This can give a competitive edge in the present, but it leads to under-investment in green technologies. Such free-riding strategies are short-sighted, as investments in green technologies can be beneficial to all participants in a market, including the ones which took the lead and invested. For instance, investments in green technology may also create new markets, where early entry could be key to competitiveness. Taking the lead may or may not generate first-movers advantages. However, from an broader economic perspective, the worldwide substantial cost reductions of renewable energy sources are of great importance.

The energy transition also poses moral and equity considerations. A successful transition can avoid catastrophic climate change and associated huge economic costs, which would disproportionately affect poor communities which do not have the resources to adapt quickly (IPCC, 2014). Countries that do have the resources to invest in avoiding catastrophic scenarios could do so for both ethical and economic reasons. For instance, the Netherlands could take a leadership role in fostering the development, cost-reduction, and mass deployment of green technologies, so as to contribute to global climate targets. This leadership is important given that a radical energy transition is also needed in developing countries if global climate targets are to be met (IPCC, 2021).

4 Green innovation policy in the Netherlands

In this section, we briefly cover current government instruments that can affect green innovation in the Netherlands. We start with an overview of R&D spending in the Netherlands, cover instruments that affect incentives for basic research in the public sector, then public instruments encouraging later stages in the private sector (firms and individuals). We highlight the main policy instruments by budget and do not aim to cover all initiatives that can affect green innovation. [12]

4.1 The innovation environment in the Netherlands

Since 2019, missions play a role in the Netherlands' R&D strategy: the mission-driven top sector and innovation policy, which aims to consolidate the international competitive position in nine sectors (EZK, 2019). [13] The policy is structured around missions clustered in four themes: "Energy transition and sustainability", "Agriculture, water and food", "Health and care" and "Security" (see Appendix, Table A.1 for an overview). At least some of the stated environmental missions will require green innovation: a fully CO_2-free system of energy and building environment by 2050, an emission-free mobility system by 2050, a net climate

[12] Appendix Table A.3 offers an overview of many Dutch instruments that can affect green innovation in the Netherlands, including instruments with a small budget. Note that applied research (TO2) institutes are not included.
[13] The nine sectors are: horticulture and propagation materials, agri-food, water, life science and health, chemicals, high tech, energy, logistics and creative industries.

neutral system of agriculture and nature by 2050. Within each mission, companies and knowledge institutions are free to select research projects (CPB, 2020).

An important part of the innovation policy, however, is more general in nature. For instance, a large share of the innovation budget consists of tax credits, such as WBSO and innovatiebox (see below).

Spending on generic R&D in the Netherlands is in line with the EU27 average, but clearly below forerunners such as Sweden and Germany. In 2019, total R&D expenditures in the Netherlands amounted to 2.18% of GDP, which is slightly below the EU27 average of 2.23% (Eurostat, 2021) and below the Dutch government's own goal of 2.5%, Denmark's 2.93% and Germany's 3.17%. This suggests there could be room for an increase in total R&D spending (CPB, 2020). We are not aware of any breakdown regarding green R&D.

4.2 Policies affecting green innovation in the Netherlands

In the Netherlands, the overall portfolio of policies covers the stages of green innovation to a differing degree. Figure 2 provides a stylized presentation of the main instruments affecting incentives for green activities (left), innovation in generic activities (right), and innovation in green activities (intersection), in the Netherlands. As shown, many policy instruments act to support either green activities or innovation in general, whereas very few instruments specifically target innovation in green technologies. Table 1 provides the numbers behind Figure 2. It only includes instruments with a budget above € 100 million. A more comprehensive overview of instruments, including smaller ones, can be found in Appendix, Table A.3.

Figure 2 Stylized presentation of innovation policy instruments in the Netherlands that provide incentives for green activities (left), innovation in generic activities (right), and innovation in green activities (intersection) (budgets above €100 million).

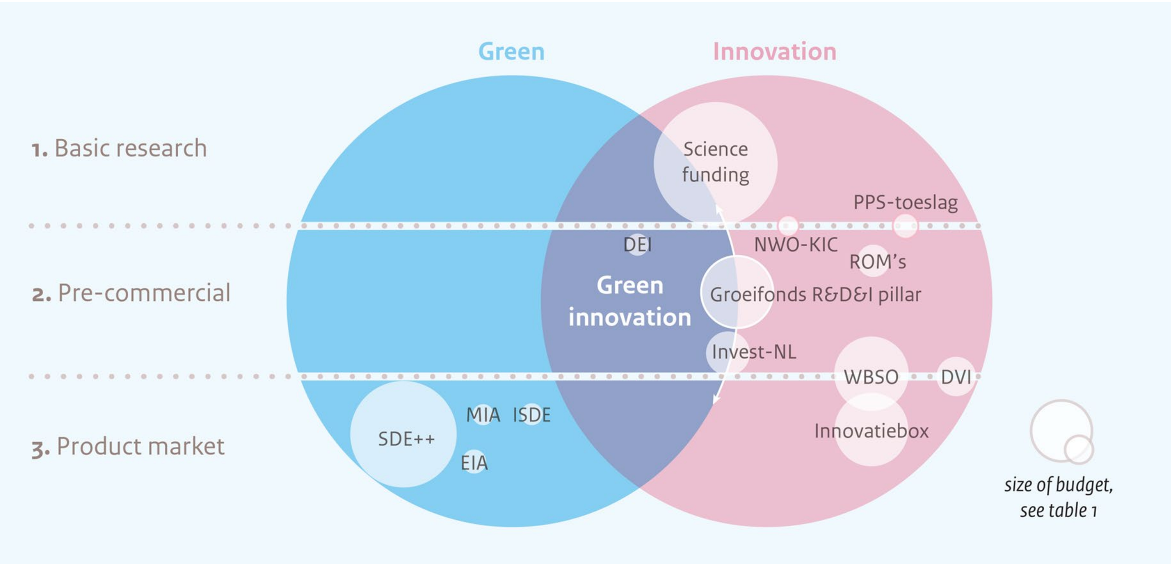

Table 1 Overview of largest innovation policy instruments in the Netherlands that provide incentives for green activities, innovation in generic activities, and targeting innovation in green activities (budget above €100 million)

Name	Description	Budget 2021 (€ mln)	Basic research	Pre-commercial	Product market
Incentives for green activities					
Stimulering duurzame energieproductie en klimaattransitie (SDE, SDE+, SDE++)	Subsidy for renewable energy production and CO_2 reduction.	2953 [14]			✓
Energie-investeringsaftrek (EIA)	Tax credit for investments in sustainable energy and energy efficiency covered by the Environment list (*Milieulijst*).	149 [15]			✓
Investeringssubsidie duurzame energie en energiebesparing (ISDE)	Subsidy scheme for home insulation and sustainable energy.	124 [16]			✓
Milieu-investeringsaftrek (MIA)	Tax credit for investments in goods and technologies covered by the Environment List (*Milieulijst*).	114			✓
Incentives for innovation					
Wet Bevordering Speur-en Ontwikkelingswerk (WBSO)	Tax credit covering social security contributions of employees involved in R&D activities.	1443		✓	✓
Innovatiebox (patent box)	Lower corporate income taxes for income deriving from intellectual property.	1410			✓
Dutch Venture Initiative (DVI)	Public co-investment in venture capital funds that target small and medium-size enterprises.	403 [17]		✓	✓
Regionale Ontwikkelings-maatschappijen (ROMs)	Regional development companies, investing in local companies active in energy transition and sustainability. 10% of budget goes to green projects.	271 [18]		✓	
PPS-toeslag	Fiscal program stimulating private-public partnerships between companies and research institutes.	172	✓	✓	
Incentives partly for green innovation					
University funding, NWO, and Horizon EU	Financing of scientific research.	~4000 [19]	✓		
Nationaal Groeifonds – R&D&I pillar	Public fund that provides subsidies to a variety of R&D and innovation projects, both green and non-green.	1354 [20]	✓	✓	✓
Invest-NL	State-backed VC fund acting as impact investor. Strong focus on sustainable energy and circular economy.	500 [21]		✓	✓
NWO-instrumentarium voor het Kennis- en innovatieconvenant (NWO-KIC)	Financing of basic and practical research in public-private cooperation. Some calls target green innovation.	118	✓	✓	
Incentives purely for green innovation					
Demonstratie Energie- en Klimaatinnovatie (DEI)	Subsidy scheme for early-stage innovation in carbon capture, energy efficiency, renewable energy, CO_2 reduction and local integration of large-scale wind and solar energy.	127		✓	

[14] In 2021, the SDE++ budget for the next 15 years was planned at €5 billion in total.
[15] Total budget available in 2021; actual use may vary.
[16] Total subsidy for households and companies.
[17] Total amount made available for two investment funds. Actual yearly investments can vary with availability of investment options and timing of promised investments.
[18] Total investment of ROMs in participation in 2020.

4.2.1 Basic research stage

The public sector encourages basic research mainly by funding universities and research institutes, with some funding targeting green innovation. Basic research is funded through standard university funding, competitive grants offered by the Dutch Research Council (NWO) and the Dutch Academy of Science (KNAW), as well as foreign sources such as the EU's Horizon 2020/Europe grants. NWO grants are a significant source of funding for research in the Netherlands: in 2021, total basic university funding for research is approximately €2.3 billion and the NWO disburses grants of about €1 billion. Similarly, the Horizon 2020 budget disbursed €4.5 billion to the Netherlands in the period 2014-2019, amounting to more than €700 million per year. At the moment, it is hard to assess the total amount of public funding going to basic research into green innovation, as not all grant calls can be clearly labeled. Starting in 2021, the EU's new Horizon Europe research program intends to spend at least 35% of its €95.5 billion budget on climate objectives.

In addition, the *Nationaal Groeifonds* (National Growth Fund) is also relevant for basic research as it targets all stages of innovation. This fund has three areas of interest: knowledge development, R&D and innovation (R&D&I), and infrastructure. The total fund size is €20 billion, planned to be used over a 5-year period, starting in 2021. For the first investment round for the subject R&D and innovation, a total of €1354 million has been (conditionally) allocated and reserved.

The Netherlands' use of a combination of university funding and competitive grants seems to be an effective instrument to foster innovation.

The Netherlands also features publicly funded applied research institutes (TO2 institutes), which aim to bridge the gap between purely theoretical research and private commercial research. Many of these institutes innovate in areas linked to environmental issues, such as agricultural sciences, water management and energy. Some policies, such as the public-private partnership (PPP) subsidy, called PPS-toeslag (*Publiek-private Samenwerking-toeslag*), encourage collaboration between companies and these research institutes. However, the efficacy of the PPP subsidy to promote innovation is unproven and the process of similar past policies was deemed cumbersome and ineffective (CPB, 2020).

4.2.2 Pre-commercial stage

Overall, the pre-commercial stage seems to receive less funding through targeted green instruments compared to the product market stage. We found one notable instrument specifically targeting pre-commercial green innovation, with a budget of €127 million in 2021. The DEI (*Demonstratie Energie en Klimaatinnovatie*) is a subsidy for pilot and demonstration projects in the area of energy (efficiency, use, storage, production), carbon capture and circular economy.

Targeted green support for the pre-commercial stage also seems more fragmented across various instruments compared to the product market stage (see Appendix, Table A.3). The DKTI-transport (*Demonstratie klimaat technologieën en -innovaties in transport*) is a scheme similar to DEI, which provides subsidies to pilot projects for sustainable transport. The MOOI (*Missiegedreven Onderzoek, Ontwikkeling en Innovatie*) is a subsidy scheme for mission-driven R&D in consortia working on climate-relevant themes (offshore wind, renewable electricity on

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[19] In 2021, total basic university funding for research was approximately €2.3 billion and the NWO disbursed grants of about €1 billion in 2020. Similarly, the Horizon 2020 budget disbursed €4.5 billion to the Netherlands in the period 2014-2019, amounting to more than €700 million per year.
[20] The total fund size is €20 billion planned to be used over a 5-year period, starting in 2021. For the first investment round for the subject R&D and innovation, a total of €1354 million has been used, of which €400 million being conditionally allocated, €121 million unconditionally allocated, and €833 million made as a reservation for projects that seem promising but require additional information; due to this last category, it is possible that the total funding for all subjects in 2021 will be below €4 billion (link).
[21] Around €500 million per year are planned for the set-up of Invest-NL, starting from 2019. Actual investment pledges amounted to €241 million in 2020 (Invest-NL, 2021).

land, built environment and industry), with a budget of €55 million in 2021. The HER+ (*Hernieuwbare Energietransitie*) is a subsidy scheme for businesses that aim to decrease their carbon footprint and has a budget of €32 million in 2021. The total budget for targeted green support for the pre-commercial stage (including DEI) is about €280 million.

Other instruments partly target green innovation, such as the National Growth Fund and Invest-NL. Invest-NL is a state-backed investment fund that acts as an impact investor on the private market. It is focused mostly on sustainable energy and circular economy investments and had a budget of €500 million in 2020, of which it invested €241 million. The NWO-KIC subsidy is partially targeted at green innovation: it organizes calls related to the top sectors, specifically encouraging collaborations and PPPs.

There are also general innovation instruments that aim to stimulate innovation in both the pre-commercial and the product market stage, such as the WBSO and the Dutch Venture Initiative (DVI). The former is a tax credit covering R&D workers' wage and income tax contributions. The DVI concerns public investment in VC funds that target small and medium-sized enterprises.

The literature suggests that government grants are especially effective in the pre-commercial stage, as companies and projects can fall through the cracks of current financing schemes. Given the relatively small size of instruments directly targeting green innovation in this stage, there could be more room for directly encouraging green pilot and demonstration programs.

4.2.3 Product market stage

We have found two instruments (partially) targeting green innovation in the product market stage, the National Growth Fund and Invest-NL. Also, many of the current programs on innovation and green activities would fit this stage. The programs usually target generic innovation (WBSO, Innovatiebox, DVI) or sustainability, usually through adoption subsidies, but do not specifically green innovation. Most are designed to ramp up in a cost-effective way technologies that have already proven feasible, rather than investigating new technologies.

The SDE++ aims to encourage private investment in sustainable energy, heating, gas and carbon capture. With a budget of almost €3.0 billion in 2021 and planned expenses in that year of over €5 billion over a period of 15 years, it is the largest program of green investment in the Netherlands. The SDE++ is a subsidy that covers the gap between the market unit price and the costs of energy and CO_2 emissions. Proposals that require lower subsidies have a higher probability of getting funding, which favors projects closer to commercialization and encourages short-term cost effectiveness. This mechanism does not seem meant for projects in earlier stages of innovation, which feature high uncertainty and costs. However, while the subsidy is not designed to encourage innovation directly, it might have positive side-effects of learning-by-doing.[22]

Households can also benefit from green adoption subsidies. Some schemes, such as the ISDE (*Investeringssubsidie duurzame energie en energiebesparing*), include detailed requirements about qualifying technologies in addition to minimum efficiency standards, which can limit the incentives to innovate. Others, such as the zero Value Added Tax for solar panels, can encourage further cost improvements in the technology, but do not necessarily encourage further innovation in other green technologies such as wind or heat pumps.

The Netherlands also features fiscal instruments for green investments which act as adoption subsidies for products in late stages of development. There are investment allowances such as MIA and EIA, as well as

[22] For an overview of learning by doing effects, see Thompson (2010).

smaller programs such as accelerated depreciation for specific green investments (Vamil: *Willekeurige afschrijving milieu-investeringen*). These green fiscal measures have smaller budgets than the SDE++ or innovation incentives, amounting to around €300 million in total in 2021. They encourage companies to invest in green goods and technologies that are present on the government's *Milieulijst*, a list of products and technologies that is updated yearly by the government. Since the list includes mostly proven green technologies, these measures would also fit as (very) late adoption subsidies.

4.2.4 Room for a green direction

The largest programs to encourage private R&D in the Netherlands do not specifically target green innovation. In fact, it is possible for companies to use generic innovation subsidies to invest in brown technologies. The two main such instruments, with a combined budget of €2.9 billion in 2021, are the patent box and the WBSO. The former allows a lower corporate income tax for income derived from intellectual property, while the latter is a tax credit covering R&D workers' wage and income tax contributions. Only the WBSO is likely to help increase liquidity in the early stages, as the patent box is applied to income that occurs only once innovation has been successful. Companies that are in the early stages of innovation tend to have small revenues and large costs, so profits-based instruments, such as the patent box, are unlikely to help with funding R&D in this stage.

Current innovation policies could be aligned better with environmental goals. This would mean more incentives occurring at the intersection of the Venn diagram above (Figure 2). Innovation schemes could be altered to target development of green technologies. Brown technologies could be specifically excluded from such innovation programs. Large subsidy schemes, such as the SDE++, are mainly targeted at adoption instead of development of new technologies. Currently, Dutch programs that fit firmly in the intersection of the diagram, such as DEI, DKTI-transport or HER+, are dwarfed in budget by generic subsidies such as WBSO and the patent box.[23]

Finally, the effective rate at which carbon emissions are being priced can be increased. In fact, fossil fuel technologies and products in the Netherlands receive substantial fiscal and financing support. Implicit fossil fuel subsidies are at least €4.5 billion in foregone government revenue per year (OECD and IEA, 2020). This amount is comparable to the expenditures planned in 2021 for the next 15 years for the SDE++, the largest subsidy for encouraging sustainable energy production in the country. Fossil fuel subsidies (whether implicit or explicit) have a negative effect on the environment, limited effects on employment (CPB and PBL, 2018) and further limit the incentives for green innovation.

5 Avenues for further research

This report provided an overview of the green innovation process and the government instruments that can be used to encourage it at the different stages. It also suggested that two lines of argument provide a foundation for green innovation support.

The literature provided some insights. Basic research tends to have the largest knowledge spillovers and relies mostly on public financing, usually in the form of university funding and grants. Direct R&D grants also seem

[23] Only DEI is shown in Figure 2, because the other schemes have a budget under €100 million.

to encourage green innovation in the second, pre-commercial stage, as they bridge the “valley of death” and provide companies with liquidity. For the third stage (product market) to proceed to the final stage of mass adoption, we have found evidence for the effectiveness of adoption subsidies, as well as some evidence on infrastructure and regulation.

Empirical evidence of the causal effects of public green innovation policies on private green innovation and economic activity more generally is limited (see Pless et al., 2020). Much past research has focused on the effects of generic public policies on green innovation and firm outcomes (most notably the Porter hypothesis). The relatively small number of policy evaluations could be explained by the heterogeneity in policy designs and the difficulty in finding good counterfactuals for current policies. Including evaluations in the design stage would mitigate such issues, encouraging learning among policymakers and the development of best practices. Empirical work is further hindered by difficulties in measuring innovation and distinguishing between general and green innovation. Furthermore, many green innovation policies are relatively new, so the period available for study is relatively short.

We see many questions that have yet to be answered. There seems to be little evidence on the effects of specific green instruments and their rankings in terms of effectiveness. Further research into the effectiveness of green public procurement for green innovation would be welcome. Another avenue is the design of contests and grants for specific green innovation stages, calculating the spillover effects caused by such programs and the importance of learning-by-doing. More information about the determinants of the adoption of green technologies would also provide valuable insights, for example the causal effects of infrastructure spending on green innovation. We also see scope for empirical evidence on the effectiveness of financial regulation reforms for green innovation.

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Appendix

Table A.1 Missions comprising the mission-driven top sector and innovation policy in the Netherlands[24]

Theme	Missions
Energy transition and sustainability	• Decrease national greenhouse gas emissions by 49% by 2030 and on the way to 95% by 2050, compared to 1990 • A fully CO_2-free electricity system in 2050 • A CO_2-free built environment in 2050 • A climate-neutral industry with re-usage of materials and products in 2050 • Emission-free mobility for people and goods in 2050 • A sustainable and fully circular economy in 2050, with a halving of raw materials use by 2030
Agriculture, water and food	• Reduction of raw materials and consumables in agriculture and horticulture by 2030. All end products and residual products to be brought to the highest possible value (circular agriculture) • Net climate-neutral system of agriculture and nature by 2050 • The Netherlands climate-proof and water-robust in 2050 • In 2030, the Netherlands will produce and consume healthy, safe and sustainable food; partners in the value chain, including farmers, will earn a fair price • A sustainable balance between ecological capacity and water management versus renewable energy, food, fishing and other economic activities. The balance must be achieved for marine waters in 2030 and in 2050 for rivers, lakes and estuaries • The Netherlands is and will remain the best protected and livable delta in the world, with timely, future-proof measures against manageable costs
Health and care	• In 2040, all Dutch people will live in good health for at least five years longer, and health differences between the lowest and the highest socio-economic groups will have decreased by 30% • In 2040, the burden of disease due to an unhealthy lifestyle and environment will have decreased by 30% • In 2030, care will by organized at least 50% more often in the own living environment, rather than in care institutions • In 2030, people with a chronic illness or lifelong disability will be able to better participate in society as they wish and are able to (+25%) • In 2030, the quality of life of people with dementia will have increased by 25%
Security	• In 2030, organized crime in the Netherlands will be too risky and poorly rewarding, due to greater insight into illegal activities and money flows • In 2035, the Netherlands will have the navy of the future. Able to respond flexibly to unpredictable and unimaginable developments • In 2030, the Netherlands will have operational space capacity for defense and security. • Cybersecurity. The Netherlands is able to secure economic and social opportunities of digitization • In 2030, the armed forces will work fully networked with other services and integrated with new technologies to be able to act faster and more effectively than the opponent • Supply and demand are brought together faster to implement short-cycle successful innovations. • In 2030, security organizations will collect new and better data, which makes them consistently one step ahead of threats • In 2030, the profession of safety professional will be one of the top 10 most attractive professions in the Netherlands

[24] Source: link.

Table A.2 Horizon 2020 Technology Readiness Levels (TRLs)

Level	Description
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	System prototype demonstration in operational environment
TRL 8	System complete and qualified
TRL 9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Table A.3 Overview of main innovation policy instruments in the Netherlands

Name	Description	Budget 2021 (€ mln)	Type	Basic research	Pre-commercial	Product market	Green activity	Innovation	Source
University funding, NWO, and Horizon EU	Financing of scientific research.	~4000 [25]	Subsidy	✓			Partly	Partly	Budget OCW, NWO, Rathenau
Stimulering duurzame energieproductie en klimaattransitie (SDE, SDE+, SDE++)	Subsidy for renewable energy production and CO_2 reduction.	2953 [26]	Subsidy			✓	Yes	No	Budget EZK
Wet Bevordering Speur- en Ontwikkelingswerk (WBSO)	Tax credit covering social security contributions of employees involved in R&D activities.	1443	Tax credit		✓	✓	No	Yes	Budget EZK
Innovatie box (patent box)	Lower corporate income taxes for income deriving from intellectual property.	1410	Lower tax rate			✓	No	Yes	Bedrijvenbeleidinbeeld
Nationaal Groeifonds – R&D&I pillar	Public fund that provides subsidies to a variety of R&D and innovation projects, both green and non-green.	1354 [27]	Subsidy	✓	✓	✓	Partly	Partly	nationaalgroeifonds
Invest-NL	State-backed VC fund acting as impact investor. Strong focus on sustainable energy and circular economy.	500 [28]	State VC fund		✓	✓	Mostly	Yes	Dutch Parliament
Dutch Venture Initiative (DVI)	Public co-investment in venture capital funds that target small and medium-size enterprises.	403 [29]	Financing		✓	✓	No	Yes	Bedrijvenbeleidinbeeld
Regionale Ontwikkelingsmaatschappijen (ROMs)	Regional development companies, investing in local companies active in energy transition and sustainability. 10% of budget goes to green projects.	271 [30]	Financing		✓		Partially	Partially	Bedrijvenbeleidinbeeld

[25] In 2021, total basic university funding for research was approximately €2.3 billion and the NWO disbursed grants of about €1 billion in 2020. Similarly, the Horizon 2020 budget disbursed €4.5 billion to the Netherlands in the period 2014-2019, amounting to more than €700 million per year.
[26] This figure concerns the subsidy budget for the year 2021. In 2021, the SDE budget for the next 15 years was €5000 million.
[27] The total fund size is €20 billion planned to be used over a 5-year period, starting in 2021. For the first investment round for the subject R&D and innovation, a total of €1354 million has been used, of which €400 million being conditionally allocated, €121 million unconditionally allocated, and €833 million made as a reservation for projects that seem promising but require additional information; due to this last category, it is possible that the total funding for all subjects in 2021 will be below €4 billion (link).
[28] €500 million per year is budgeted for Invest-NL. Actual investment pledges amounted to €241 million in 2020 (Invest-NL, 2021).
[29] Total amount made available for two investment funds. Actual yearly investments can vary with availability of investment options and timing of promised investments.
[30] Total investment of ROMs in participation in 2020.

PPS-toeslag	Fiscal program stimulating private-public partnerships between companies and research institutes.	172	Subsidy	✓	✓		Partially	Yes	Budget EZK
Energie-investeringsaftrek (EIA)	Tax credit for investments in sustainable energy and energy efficiency covered by the Environment list (*Milieulijst*).	149 [31]	Tax credit			✓	Yes	No	Dutch Budget
Demonstratie Energie- en Klimaatinnovatie (DEI)	Subsidy scheme for early-stage innovation in carbon capture, energy efficiency, renewable energy, CO_2 reduction and local integration of large-scale wind and solar energy.	127	Subsidy		✓		Yes	Yes	RVO
Investeringssubsidie duurzame energie en energiebesparing (ISDE)	Subsidy scheme for home insulation and sustainable energy.	124	Subsidy			✓	Yes	No	RVO
NWO-instrumentarium voor het Kennis- en innovatieconvenant (NWO-KIC)	Financing of basic and practical research in public-private cooperation. Some calls target green innovation.	118	Financing	✓	✓		Partially	Yes	NWO
Milieu-investeringsaftrek (MIA)	Tax credit for investments in goods and technologies covered by the Environment List (*Milieulijst*).	114	Tax credit			✓	Yes	No	Dutch Budget
Versnelde klimaatinvesteringen industrie	Support investment in cost-effective reductions of CO_2 emissions. Closer to an adoption subsidy.	82	Subsidy			✓	Yes	Mixed	Bedrijvenbeleidin beeld
Regeling groenprojecten	Tax reductions for individuals who invest in green projects.	81	Tax reduction			✓	Yes	Yes	RVO
MKB-Innovatiestimulering Regio en Topsectoren	Subsidy scheme to stimulate innovation for small and medium enterprises across regions.	66 [32]	Subsidy		✓	✓	No	Yes	Bedrijvenbeleidin beeld
Missiegedreven Onderzoek, Ontwikkeling en Innovatie (MOOI)	Subsidy scheme for cooperative integral projects on innovations supporting the Dutch Climate agreement.	55	Subsidy		✓		Yes	Yes	Budget EZK
Innovatiekrediet	Innovation credit for companies with strong business case, but not attractive enough for banks.	45	Financing		✓	✓	No	Yes	Budget EZK
DKTI-transport	Subsidy for green innovations in the area of transport.	37	Subsidy		✓		Yes	Yes	RVO

[31] Total budget available in 2021; actual use may vary.
[32] Granted subsidies in 2020.

Hernieuwbare energietransitie (HER+)	Subsidy scheme to reach the climate goals for 2030 in a more cost-effective way through innovative projects.	32	Subsidy		✓	✓	Yes	Yes	[Budget EZK]
Willekeurige afschrijving milieu-investeringen (Vamil)	Accelerated depreciation for investments that appear on Environment List (*Milieulijst*).	25	Accelerated depreciation			✓	Yes	No	[RVO]
Thematische Technology Transfer-regeling	Subsidy to encourage research organizations to cooperate in various sectors. Creation of funds that would provide risky capital for technology transfers.	24 [33]	Subsidy		✓	✓	Partially	Yes	[Bedrijvenbeleidinbeeld]
Techleap.nl (formerly StartupDelta)	Government-sponsored mentorship and networking programme, with a small incubator.	18 [34]	Network		✓	✓	No	Yes	[Bedrijvenbeleidinbeeld]
Topsector energiestudies industrie	Subsidy for feasibility studies of pilot or demonstration projects which cost-effectively reduce CO_2 before 2030.	15.5	Subsidy		✓	✓	Yes	Yes	[RVO]
Small Business Innovation Research (SBIR)	Contest-oriented procurement initiative to encourage innovative solutions to government-posed problems.	12.7 [35]	Subsidy		✓	✓	Partially	Yes	[Bedrijvenbeleidinbeeld]
Subsidie Topsector Industrie	Subsidy for companies that cooperatively research cheaper climate neutral or circular products or services to be used before 2030.	8.9	Subsidy		✓		Yes	Yes	[RVO]
Vroegefasefinanciering	Early-stage loan for innovative start-ups.	8.5	Financing		✓	✓	No	Yes	[Bedrijvenbeleidinbeeld]
Systeemintegratie	Subsidy for R&D in new products and services that can keep the energy system safe, reliable and affordable.	3.8 [36]	Subsidy		✓	✓	Yes	Yes	[RVO]
Innovatie Attaché Netwerk	Network for sharing information about innovation.	n/a	Network	✓	✓	✓	No	Yes	[RVO]
MVO Nederland	Network of companies interested in sustainability.	Project-funding	Network		✓	✓	Yes	Partially	[mvonederland]

[33] Budget for 2020. Up until end-2021, the scheme has been temporarily closed.
[34] Budget for the startup and scale-up agenda, which includes other initiatives and policies next to Techleap.nl.
[35] Tender budget for 2020.
[36] Budget for 2020. This subsidy scheme has been closed.

Table A.4 List of abbreviations

Abbreviation	Description
ARPA-E	Advanced Research Projects Agency–Energy
CEA	*Commissariat à l'énergie atomique et aux énergies alternatives* (Alternative Energies and Atomic Energy Commission)
CERN	*Conseil européen pour la recherche nucléaire* (European Council for Nuclear Research)
DARPA	Defense Advanced Research Projects Agency
DEI	*Demonstratie Energie en Klimaatinnovatie* (Demonstration energy and climate innovation)
DKTI-transport	*Demonstratie klimaat technologieën en -innovaties in transport* (Demonstrations of climate technologies and innovation in transport)
DVI	Dutch Venture Initiative
EIA	*Energie-investeringsaftrek* (energy investment deduction)
ESG	Environmental, Social, and Governance
EU	European Union
EU ETS	European Union Emissions Trading System
HER+	*Hernieuwbare Energietransitie* (Renewable energy transition)
ISDE	*Investeringssubsidie duurzame energie en energiebesparing* (investment subsidy for sustainable energy and energy savings)
ITER	International Thermonuclear Experimental Reactor
KfW	*Kreditanstalt für Wiederaufbau* (Credit Institute for Reconstruction)
KNAW	*Koninklijke Nederlandse Akademie van Wetenschappen* (Royal Netherlands Academy of Arts and Sciences)
MIA	*Milieu-investeringsaftrek* (environmental investments deduction)
MOOI	*Missiegedreven Onderzoek, Ontwikkeling en Innovatie* (Mission-driven research, development and innovation)
NWO	*Nederlandse Organisatie voor Wetenschappelijk Onderzoek* (Dutch Research Council)
NWO-KIC	*NWO-instrumentarium voor het Kennis- en innovatieconvenant* (NWO instruments for the Knowledge and Innovation Covenant)
PPP	Public-private partnership
PPS-toeslag	*Publiek-private samenwerking-toeslag* (public-private partnership subsidy)
PV	Photovoltaics
R&D	Research and development
R&D&I	R&D and innovation

ROM	*Regionale Ontwikkelingsmaatschappijen* (Regional development companies)
SBIR	Small Business Innovation Research
SDE	*Stimulering duurzame energieproductie en klimaattransitie* (Stimulus for sustainable energy production and climate transition)
SIB	State investment bank
SME	Small and medium-sized enterprises
TRL	Technology Readiness Level
US	United States
Vamil	*Willekeurige afschrijving milieu-investeringen* (Arbitrary depreciation of environmental investments)
VC	Venture capital
WBSO	*Wet Bevordering Speur- en Ontwikkelingswerk* (Tax credit for research and development)