EU innovation funding for climate neutrality

Case study: Innovation

Deliverable 4.2 – Four case study reports on innovation, infrastructure, investment & finance and integration

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Abstract

This report explores ways in which EU innovation funding for climate change mitigation – as a core climate policy instrument – can better support the transformation to climate neutrality. To do so, we focus on four important issues relating to the provision of public Research & Development (R&D) funding for innovation. First, we revisit the question of which level of government – EU, the member states, or regional governments – is best placed to provide this funding. Our analysis suggests that innovation funding aimed at early-stage technologies is more efficiently designed and implemented at the EU level, whereas policy supporting more mature innovations should favour a key role for the member states and regional levels of governments. Second, we estimate the need for public R&D funding within the European Union using existing Integrated Assessment Model estimates. Here our exploration suggests that within the European Union and the United Kingdom the need for public R&D funding for climate change mitigation technologies in 2025 is between 0.01% and 0.15% of Gross Domestic Product (GDP). Third, we map the existing EU innovation funding landscape, identifying 400 projects mobilising €4.9 billion from three main sources: Horizon Europe, the Innovation Fund, and the LIFE Programme, with a large percentage of that funding going to carbon capture and storage, carbon capture and utilisation, carbon dioxide removal, hydrogen, and energy storage. Finally, we explore the ways in which this landscape might evolve under four policy avenues, including the potential impacts of this evolution on innovation policy and the pathway to climate neutrality. We then make policy recommendations and provide suggestions for future research.

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List of Abbreviations

CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CDR	Carbon Dioxide Removal
CINEA	European Climate, Infrastructure and Environment Executive Agency
DT	Directed Transition (Policy Avenue)
EIC	European Innovation Council
EU	European Union
EV	Electric Vehicle
GDP	Gross Domestic Product
GEL	Green Economic Liberalism (Policy Avenue)
GHG	Greenhouse Gas
GIP	Green Industrial Policy (Policy Avenue)
IAM	Integrated Assessment Model
IEA	International Energy Agency
MFF	Multiannual Financial Framework
R&D	Research & Development
R&I	Research & Innovation
SD	Sufficiency & Degrowth (Policy Avenue)
TIP	Transformational Innovation Policy
TIS	Technological Innovation System
TRL	Technological Readiness Level
TIP	Transformational Innovation Policy

Executive Summary

Achieving the goals of the Paris Agreement will require a deep, rapid, and system-wide transformation of how society operates (Fazey et al., 2018; Termeer & Metze, 2019; Haddad et al., 2022). For this transformation to be successful, carbon-intensive technologies will need to be substituted by low-carbon alternatives. Some of these technologies can be replaced by existing ones, such as traditional solar photovoltaics and wind energy. But given the urgent need to reduce emissions, new technologies are also necessary and existing technologies need to be further developed (Blanco et al., 2022). Governments can accelerate innovation by eliminating or reducing the obstacles that impede it (Rienks, 2023). One key obstacle, especially for technologies that are in the early stages of development, is a lack of funding. Private investors are often hesitant to provide funding for such technologies, leaving the public sector as a vital source for financing (Polzin & Sanders, 2020). Therefore, public funding for technological innovation is a core instrument for climate mitigation policy.

In this report, we have examined four interconnected research questions related to innovation policy for climate change in the EU. Below, we reflect on each of these questions and then look forward to future research opportunities and policy recommendations.

Which level of government should be tasked with innovation policy?

Our theoretical framework regarding the appropriate level of government to design innovation policy is mainly based on the fiscal federalism literature. The key finding here is that, for technologies in the early stages of development, it is surprisingly difficult to find arguments relating to efficiency or effectiveness that support decentralization for climate-related R&D funding. This is in contrast to the arguments that support centralisation. Here, the incentives of a higher level of government – the EU – seem to be more aligned with stimulating climate change mitigation innovation, especially because it better internalises the positive cross-border externalities associated with innovation. Additional arguments for centralisation include reduced administrative costs for distributing and monitoring funds (economies of scale), reducing transaction costs related to cross-border cooperation, the avoidance of overlapping (duplicate) policies, increased potential for competition between innovative firms, and a reduction of political risk in case of failed innovation projects. For technologies that are more mature the arguments that support decentralisation become stronger. In these later stages of development, problems become less technical and more uncertain, making the context in which an innovation is used increasingly important. The relevance of policy learning/experimentation and jurisdictional competition increases, making the member state and regional levels of government increasingly efficient in designing and implementing innovation policy.

When comparing this to the actual innovation funding landscape within the EU, we find a very different picture. Historically, the EU noted that innovation policy was largely a member state responsibility and that the supranational level was largely about coordination (Reillon, 2016). And, despite growing, still only a small percentage of public R&D funding within the EU is provided by the EU, especially through the Horizon Europe and Innovation Fund. However, the bulk of funding is provided by member states. Based on the economic theories we discussed this would suggest that innovation policy within the EU can be made more efficient if member states move public funding from technologies with low TRLs towards technologies with high(er) TRLs. Alternatively, member states could also consider allocating their funds for technologies with low TRLs through EU institutions, such as Horizon Europe. It is important to note that our discussion focused on economic efficiency and thus ignored other criteria that might be used to determine the appropriate level of government for a certain task, such as, fairness.

How much public funding is required for climate change mitigation R&D?

Our theoretical reflection with regard to the required amount of public funding for climate change mitigation R&D is based on Integrated Assessment Models (IAMs). We begin this analysis by using the estimates from McCollum et al.'s (2018) IAM multi-model analysis of the required future low-carbon energy investments in the EU. Based on these estimates, we calculate a lower bound of required public R&D funding and a higher bound. The lower bound is based on research of Polzin et al. (2021) that calculates the average financing mix for different energy technologies over the period 2007-2016. The upper bound is based on the results of an expert survey in which experts were asked about the required financing mix (Sweatman et al., 2018). This explorative exercise suggests that in 2025 EU R&D funding aimed at climate change mitigation should be between 0.01% and 0.15% of GDP to be compatible with a 1.5 °C scenario.

Drawing on estimates from the IEA we find that public R&D funding devoted to clean energy in Europe was around 0.06% of GDP in 2021 (International Energy Agency, 2023). This suggests that actual public R&D funding within Europe falls within the estimated range of required funding but lies close to the lower bound. Because it lies close to the lower bound, we expect that there is still space for additional public R&D funding. Funding from Horizon Europe, LIFE, and the Innovation Fund (which we estimate between €3–8.7 billion) amounts to between .02% and .06% of GDP. This suggests that there is also space to increase government R&D funding at the EU level.

What does the current EU innovation funding landscape for climate mitigation look like?

The existing EU funding landscape is both extensive and complex. Our analysis identified three overarching programmes (Horizon Europe, the Innovation Fund, and the LIFE Programme) including nine sub-programmes that provide significant grants to early-stage, low-carbon innovation at EU level. Both have a focus on a number of early-stage technologies, including innovative solar, energy storage, carbon dioxide removal, and low-carbon industrial technologies. However, they differ in that Horizon Europe and LIFE are based on stable funding from the Multiannual Financial Framework, while the Innovation Fund gets its resources from auctioning revenue from EU ETS emission allowances – creating greater uncertainty and both potential upside opportunities and downside risks for the amount of money available.

We identified 400 projects related to climate mitigation and technological innovation that mobilised at least €4.9 billion from the EU funding landscape. We also identified 23 distinct technologies (e.g., solar, hydrogen) and topic areas (e.g., transport, maritime) that the 400 projects support. Despite this broad coverage, a few technologies stand out as attracting most of the support, with CCU/CCS/CDR, energy storage, and hydrogen alone attracting nearly 60% of available funding. The 23 large-scale projects in the Innovation Fund likewise account for around 60% of the €4.9 billion we have analysed.

How might the EU innovation funding landscape evolve under the four policy avenues? What are the impacts?

Our impact assessment of the potential direction of EU innovation policy under each of the four policy avenues, and the impacts this might have, yielded several cross-cutting findings. First, some avenues – especially Sufficiency & Degrowth – might be expected to push for greater decentralisation to better deal with regional/local issues, while the Green Economic Liberalism might be expected to take a flexible approach based on criteria similar to those, we derived from fiscal federalism above. In contrast, the Green Industrial Policy and Directed Transition avenues would be expected to lead to greater centralisation of innovation policy at EU level. Second, the Green Economic Liberalism avenue would prefer a strong degree of technological neutrality, whereas the other three avenues would likely see various levels of 'picking winners' when it came to innovation funding. Third, within the three avenues that would be more amenable to picking winners, priority areas would likely differ. For example, Green Industrial Policy and Directed Transition would be expected to prioritise technological solutions (such as CCS and hydrogen) while the Sufficiency & Degrowth avenue might see much greater focus on energy efficiency and social innovations related to lifestyle change.

Policy recommendations

Despite the large rise in public funds by the European Union in recent years, we find that there is still ample scope to increase public R&D funding for climate change mitigation technologies within the EU. But even when funding is not increased, our theoretical framework suggests that innovation policy within the EU could be made more effective when member states consider shifting their public R&D funds from technologies in the early stage of development, to technologies that are more mature. Simultaneously the EU could shift some of its funding from funds aimed at more mature technologies towards the Innovation Fund, and especially, Horizon Europe, to compensate for the funding changes by member states.

1. Introduction

Reaching climate neutrality in the European Union (EU) and pursuing the goals of the Paris Agreement will require broad, deep, and rapid transformations in how society operates (European Commission, 2019, p. 4; Intergovernmental Panel on Climate Change, 2018; Moore et al., 2021). Some of these transformations can be achieved with existing technologies and business models, such as traditional solar photovoltaics and wind energy. But given the urgent need to reduce emissions, new technologies will also be needed, and existing inventions will need to be demonstrated and then scaled up (Blanco et al., 2022). For example, the International Energy Agency has estimated that "…almost half of the emissions savings needed in 2050 to reach net-zero emissions rely on technologies that are not yet commercially available" (International Energy Agency, 2021, p. 30; see also European Commission, 2021c, p. 20). This need for green innovation goes beyond current EU policies, as the EU Fit for 55 package aims to reduce greenhouse gas (GHG) emissions to 55% when compared to 1990 levels, whereas research suggests a reduction of 64-77% by 2030 would be necessary to stay on track for the 1.5°C target (Climate Analytics, 2022). Developing the technologies for a climate neutral future requires substantial investments in innovation at a time when investments are also needed in other areas, such as infrastructure, to successfully reach climate neutrality (Klaaßen & Steffen, 2023).

Innovation policy – especially public funding for innovation – has taken on an increasingly important role in the EU's climate policy mix. Since 2010, both the EU and its member states have directed a growing amount of money, expertise, and time to innovation (European Commission, 2023b, p. 35; European Court of Auditors, 2022). Between 2021 and 2027, the EU plans to spend at least 35% of funding from Horizon Europe, the EU's framework for research and innovation (R&I), to research that contributes to climate objectives (European Commission, 2021b). Similarly, 30% of the EU's budget – the Multiannual Financial Framework (MFF) – is expected to be spent on climate-related measures in the same time period (European Commission, 2023a). This is on top of an earlier pledge for the 2014–2020 period to spend 35% of Horizon 2020 funding and 20% of the EU budget on climate action (European Court of Auditors, 2016).

This increasing focus on climate in EU R&D funding has been accompanied by the development of a large, increasingly complex funding landscape within the EU. Climate funding mechanisms and subsidies have proliferated. In 2009, the EU created the NER 300 programme, funded using €2.1 billion of revenue from selling allowances from the EU Emissions Trading System (ETS1), to support innovation related to carbon, capture and storage and early-stage renewables (see Boasson & Wettestad, 2014). In 2018, it created the NER 300's successor – the Innovation Fund – which adds support for industrial research and has a projected budget of €40 billion between 2020 and 2030 (European Commission, 2022b). Other important EU-level funding sources include the LIFE program and the InnovFin Energy Demonstration Projects loan programme supported by the European Investment Bank and the European Commission.

In this study, we focus on a core instrument in this landscape, namely EU funding for research, innovation, and demonstration of climate-related technologies in the early stages of development. Public funding is especially important in these early stages because it is where many innovations face challenges securing funding (Polzin & Sanders, 2020, p. 4). We map the current EU innovation policy landscape, focusing on Horizon Europe, the LIFE Programme, and the Innovation Fund. We compare this landscape with our theoretical insights about the allocation of government tasks and the need for green public funding. We do so by drawing upon the fiscal federalism literature, integrated assessment models (IAMs), and expert interviews. We find that, especially for low TRLs, more centralisation of public funds within the EU would be desirable. We also find that the available public funds for EU innovation fall within the range estimated by IAMs for required innovation funding but is very close to the lower bound of the estimate.

This report is part of Task 4.2 of the 4i-TRACTION project. As part of Work Package 4, it evaluates a core instrument of EU policy – public innovation funding for climate change mitigation – in the context of four *policy avenues*. These policy avenues have been developed in a co-creative process with a wide variety of stakeholders and explore how EU climate policy might evolve in the future under scenarios where four distinct policy paradigms are used to make decisions (see Section 6 and Görlach et al., 2022). The other three instruments studied under Task 4.2 are climate neutral public procurement, integrated infrastructure planning, and mandatory bank transition plans.

The rest of the report is organized as follows. In Section 2 provides background on innovation funding and explain the scope of the report and its methods. Section 3 focuses on which levels of governance are most effective for innovation policy related to climate change. Section 4 explores the amount of public innovation funding that is needed at EU level to support the transition to climate neutrality. Section 5 then maps the current EU innovation funding landscape, focusing on Horizon Europe, the Innovation Fund, and the LIFE Programme. It also compares existing levels of innovation funding to the analysis carried out in Section 4. Section 6 then presents a general, qualitative impact assessment about the ways in which EU climate-related innovation funding could be expected to evolve under four distinct policy avenues: Green Economic Liberalism, Green Industrial Policy, Directed Transition, and Sufficiency & Degrowth. Section 7 provides a summary of our findings and policy recommendations for the future of EU innovation funding for climate change.

2. Background and scope

2.1 Innovation and public funding

2.1.1 Transformative change and the innovation process

Achieving the goals of the Paris Agreement will require a deep, rapid, and system-wide transformation of how society operates (Fazey et al., 2018; Termeer & Metze, 2019; Haddad et al., 2022). For this brown or carbon technologies will need to be substituted by green technologies. Some of these green technologies are already mature whereas others still need to be discovered.

Because we focus on innovation aimed at a grand societal challenge, namely climate change mitigation, and on multi-level governance with the associated danger of policy miscoordination (Haddad et al., 2022), we use in this report the term transformational innovation policy (TIP), rather than just innovation policy. We do so for three reasons. First, innovation discussed in this report is aimed at a grand societal challenge, namely realizing a net-zero economy to mitigate climate change. Second, we focus on one key aspect of TIP, namely multi-level governance, and the associated danger of policy miscoordination (Haddad et al., 2022). Third, this report is part of a larger collection of reports, each of which focuses on a single core policy instrument. In isolation each of these policy instruments have limited transformational potential, but when used in a policy mix their transformative potential is increased. Nonetheless, because we focus mainly on technological innovation and focus on a single type of policy instrument (R&D funding) the difference between transformational innovation policy (TIP) and (non-transformational) innovation policy is limited, and many of the arguments presented in this report would also apply to (non-transformational) innovation policy.

Every innovation passes through several phases, from original inception to large-scale application. Innovations do not necessarily go through these phases in a step-by-step manner, and it is often difficult to sharply define when an innovation transitions from one phase into the next. Different researchers have different names for these phases. In the EU, it is common to think about this in terms of technology readiness levels (TRL). TRLs "[provide] a snapshot in time of the level of maturity of a given technology within a defined scale" (International Energy Agency, 2020, p. 67; see also Mankins, 1995). TRLs give the extent to which a technology is ready for commercialisation and diffusion. Table 1 gives an overview of the different TRLs and the innovation phases they fall under.

Table 1: Technology Readiness Levels (TRL)

TRL	Description	Innovation Phase
1	Basic principles observed	Discovery Phase
2	Technology concept formulated	
3	Experimental proof of concept	
4	Technology validated in lab	Development Phase
5	Technology validated in relevant environment	
6	Technology demonstrated in relevant environment	
7	System prototype demonstration in operational environment	Demonstration Phase
8	System complete and qualified	
9	Actual system proven in operational environment	Deployment Phase

Source: European Commission (2022a, p. 10).

2.1.2 Technological Innovation Systems

To accelerate innovation, governments must remove the obstacles that obstruct its development. These (potential) obstacles can be categorised using the Technological Innovation Systems (TIS) functions (Rienks, 2023). The TIS approach studies the development and diffusion of emerging technologies/products from the perspective that the determinants of technological change can be found in the broad social and economic structures surrounding innovations, the Technological Innovation System. A TIS is defined as "a set of networks of actors and institutions that jointly interact in a specific technological field and contribute in the generation, diffusion and utilisation of variants of a new technology and/or new product" (Markard & Truffer, 2008, p. 611). Actors within a TIS engage in a wide variety of activities that lead to the emergence of key innovation processes or system functions. Hekkert et al. (2007) have defined these system functions by mapping the activities that take place during the emergence and diffusion of technologies and products (see Table 2 for an overview of TIS functions). The TIS literature offers a well-developed basis for understanding how technologies mature.

Obstacles that impede innovation can occur with respect to every TIS function. The government can employ different policy instruments to remove obstacles and stimulate innovation (Borrás & Edquist, 2013). Examples of such instruments include regulatory instruments (e.g., rules on intellectual property), economic instruments (e.g., subsidies), and soft/voluntary instruments (e.g., voluntary agreements between governments and research organizations). However, overcoming obstacles that impede innovation is not only a matter of finding the right policies. The search for these policies and their implementation become much more effective when it is also done by the right level of government. Finding level of government – EU, national or regional – that is most effective in designing and implementing innovation policy is an important but somewhat overlooked question (Wanzenböck & Frenken, 2020; Cirera et al., 2020, p. 56). This question is especially pertinent in the context of large social transformations, with its emphasis on multi-level governance and policy coordination failure (Haddad et al., 2022).

Table 2: Technological Innovation Systems (TIS) functions

TIS function	Explanation
Entrepreneurial activities	The new (experimental and risky) activities entrepreneurs undertake which result in new products/services or adjustments to the production process.
Knowledge development	Activities aimed at learning.
Knowledge exchange	Activities aimed at sharing knowledge between actors.
Guidance of the search	Activities that make it clear what specific wants and requirements the technology needs to satisfy.
Market formation	Activities that help to bring together demand and supply.
Resource mobilization	Activities that help to ensure sufficient financial, human or raw resources.
Creating legitimacy and counteracting resistance to change	Activities aimed at increasing support for the innovation or at removing impediments related to formal or informal institutions.

Source: Based on Hekkert et al., 2007; Rienks, 2023.

Public funding as a policy instrument to stimulate innovation

Accelerating the development of an innovation can require the stimulation of many different TIS functions. However, in this paper we focus on **financial resources** (the resource mobilisation function), as an enabling condition for climate-related innovation, specifically public funding for low-carbon innovations at the early stages of development.

Public funding for innovation can take several forms, including grants or loans (Cirera et al., 2020, p. 90). Grants and loans can accelerate innovation if a lack of financial resources is an obstacle. For example, government loans can stimulate innovation if the financial sector does not provide sufficient lending opportunities. Grants offer additional incentives to entrepreneurs to undertake a project. Ideally, these policy tools support projects that would otherwise be financially infeasible, thus enabling the realisation of projects that would otherwise not happen or would only happen at a later date (Cirera et al., 2020, pp. 90–91). The reasons why these innovation projects were infeasible in the first place often relate to market, systemic, or transitional failures (Weber & Rohracher, 2012).

Public funding can stimulate innovation related to climate change mitigation (Brown & Hendry, 2009). Especially at the early stages of innovation, public grants are seen as being one of the few possible sources of funding for innovation (Polzin & Sanders, 2020, p. 4). Somewhat later in the innovation process, between invention and deployment, public funds are key to overcome the so-called 'valley of death', where many innovations fail to develop further because of a lack of investment (Auerswald & Branscomb, 2003). Innovation funding seeks to fill these gaps by providing government support for the invention and demonstration of promising technologies. Public innovation funding often also seeks to "crowd in" other public and private investment by requiring funded projects to secure a minimum percentage of their expected costs from other sources.

The degree to which public funding for innovation is effective depends, in part, on the need for such funding. Too much public funding might lead to the financing of low-quality innovation projects, and thus a waste of public funds. Too little public funding might lead to high-quality innovation projects not being executed (Ahlvik & den Bijgaart, 2022). In this report we explore the need for low-carbon public innovation funding by comparing the available amount of EU funding with the amount of public funds required, as estimated by Integrated Assessment Models.

2.2 EU funding for climate mitigation innovation

The EU has increasingly public funding to stimulate innovation. Beyond climate change, the EU's wider landscape of innovation funding is extensive and growing, stretching from sectors including agriculture, energy, and infrastructure to defence and space exploration. The instruments of support range from direct grants (Horizon Europe), to support for innovation-related infrastructure (Copernicus), and funding for the diffusion of existing technologies (the European Regional Development Fund). According to estimates by Rubio et al. (2019), between 2014 and 2020, much of the EU's innovation funding came directly from the EU budget: €150 billion or 14% of the budget. The biggest sources of this funding included the Horizon 2020 research programme (€61.8 billion) and the European Regional Development Fund (€53 billion), which together made up around 75% of estimated innovation spending from the EU budget.

Since 2018, EU-level innovation funding has increased substantially. This in a context where national innovation funding by EU member states is still recovering from declines after the 2008 financial crisis (European Commission, 2021a, pp. 9–10). Horizon Europe has a budget of €95.5 billion, a 19% increase from the Horizon 2020 programme. Climate innovation funding also comes from the Innovation Fund and the LIFE Programme, among others. Table 3 provides a general overview of EU funds that have an element of public funding for climate change mitigation technologies for low TRLs.

Table 3: EU funds for climate change mitigation technologies

Name	Amount	Funding source	Aim of fund	Eligible projects	Recipients
Innovation Fund (2020–2030)	Est. €40 billion	ETS1 auctioning revenue.	Commercial demonstration of innovative low-carbon technologies.	Commercial demonstration of: - Low carbon energy-intensive industry technology - CCS/CCU - Innovative renewables - Energy storage	Companies
Horizon Europe (2021–2027)	€33.5 billion to contribute to climate objectives	Multiannual Financial Framework	Framework for research and innovation funding in the EU.	- Research grants - Climate change adaptation - Climate change mitigation technologies, examples: hydrogen, transport, industry.	Companies, governments, academic institutions, other civil society.
RePowerEU (2023–2026)	€20 billion	ETS1 auctioning revenue up to €20 billion.	Reduce the EU's dependence on Russian fossil fuels.	- Energy infrastructure - Energy efficiency - Renewable energy - Zero emission transport - Green reskilling	Various (member states create plan).
LIFE Programme (2021–2027)	€1.95 billion for climate action	Multiannual Financial Framework	Contribute to the transition towards a more sustainable and climate-resilient economy.	- Climate mitigation - Renewable energy - Energy in buildings or industry - Climate adaptation strategies - Energy poverty	Various; mostly civil society or public organizations.
InvestEU (2021–2027)	EU guarantee of €26.2 billion	Multiannual Financial Framework	Contribute to climate action and environmental sustainability.	- Climate, energy transition, sustainable transport - Circular economy - Digital/data infrastructure - Social infrastructure - Space infrastructure	Companies, primarily SMEs.

2.3 Research Questions and Methods

This report is structured around four research questions. Our approach and methods for each of these topics is presented below.

RQ1: What level of government should provide innovation funding?

To examine which levels of government are most appropriate for providing innovation funding, we draw on the economics literature and the concept of fiscal federalism. This theoretical framework provides a starting point for discussing the trade-offs between centralisation (at EU level) and decentralisation (at member state and regional level) in relation to low-carbon innovation.

We complement this approach with five semi-structured expert interviews. All interviewees were currently working on EU innovation policy, being employed by either think tanks, consulting agencies, universities, the European institutions, or member states. The views of our experts are in no way representative of a larger population. Nor do our experts cover all aspects of EU innovation policy, although we did make sure to select at least one expert on the two main EU innovation funds, namely Horizon Europe and the Innovation Fund. These expert interviews are intended to give additional insights on how EU innovation policy works in practice.

Interviews lasted between 45 minutes and 90 minutes. Two interviews were held on location and three online. Interviews were semi-structured. Appendix A contains the layout of the semi-structured interviews. All interviews were recorded and after every interview a summary report was made. These reports were subsequently shared with the interviewee who were also invited to correct them.

RQ2: How much public innovation funding is needed for EU climate innovation?

To estimate the amount of funding required to support innovation and R&D sufficient to be compatible with a 1.5°C scenario, we draw on existing literature on the results of Integrated Assessment Models, as well as the estimated proportion of innovation funding that should come from government sources (based on the historical average financing mix and an expert survey). Like RQ1, we complement this approach with the same expert interviews with five participants (see above).

RQ3: What is the current size and technological focus areas of climate-related innovation funding at EU level?

We first identified a wide range of potential innovation funding mechanisms through a literature review and analysis of public EU documents. We chose a subset of these innovation funding programmes based on a set of five criteria (see Section 5). Data on individual projects were accessed from EU databases (CORDIS, 2023; CINEA 2023). Each project was then analysed according to whether it addressed both climate change mitigation and technological innovation. Those projects which addressed both topics were then categorised according to topical focus (Table 15). We also drew on insights from the expert interviews discussed under the RQ1 section above. Our findings are compared to the results of RQ3 on the required level of R&D funding to identify gaps and make recommendations about the development of future policy.

RQ4: How would EU innovation policy develop under the four policy avenues?

Drawing on the findings above, we explore how EU innovation funding for climate change could be expected to evolve under each of the distinct policy paradigms represented by the four policy avenues developed by Görlach et al. (2022): Green Economic Liberalism; Green Industrial Policy; Directed Transition; and Sufficiency & Degrowth. Our assessment focuses on the level of centralisation, the extent of technological neutrality, and the technological priority areas under each policy avenue.

3. Multi-level governance and innovation funding

3.1 Theoretical framework: Innovation policy and allocation of government tasks

Multi-level governance is a key characteristic of transformational innovation policies (Haddad et al., 2022). The sheer size and complexity of grand societal challenges, such as climate change, implies that they cannot be solved by a single level of government, scientific discipline, or sector. They go beyond market failures and also include so-called systemic and transformational failures (Weber & Rohracher, 2012). This necessitates flexibility and the inclusion of many different actors with different interests and problem perceptions. The EU, member states and regional governments are themselves key players in this transformation with different interests, traditions, and competences that, because innovations do not neatly follow jurisdictional borders, need to work together. For instance, policies in several jurisdictions involving the competences of different levels of government might need to be adjusted to facilitate innovation. This raises issues with respect to how to govern societal transformations (Bugge et al., 2018). We see this, for instance, in the electrification of road transport. Member states can provide tax incentives for electric vehicles (EVs), thus stimulating demand for EVs. Local governments, with their knowledge of local circumstances, are crucial for rolling out public charging infrastructure for EVs. Simultaneously, the EU can set dates to phase out the sales of cars with combustion engines, something that member states do not have the legal authority to do (Rienks, 2023).

To explore these issues, we revisit the literature on task allocation to different levels of government (Wanzenböck & Frenken, 2020), using a socio-technical perspective on transformation (Loorbach et al., 2017). We investigate which tasks should be centralised (i.e., allocated to a higher level of government) and which should be decentralized (i.e., allocated to a lower level of government). We do this by drawing upon the economics literature (especially fiscal federalism) and our expert interviews. Our research shows that task allocation involves trade-offs, making it necessary to weigh arguments on a case-by-case basis. However, the theory suggests that centralisation is more effective for lower TRLs whereas for higher TRLs the arguments for and against (de)centralisation become much more balanced.

Fiscal federalism is the most important economic theory about the optimal allocation of tasks to different levels of government (Ederveen et al., 2008; Baldwin & Wyplosz, 2019). This theory analyses when centralisation or decentralization of public economic functions improves welfare (Ederveen et al., 2008, p. 21). The theory of fiscal federalism assumes a benevolent policymaker, acting in the interest of its citizens, and assumes that the government pursues a uniform policy in all jurisdictions (Ederveen et al., 2008, p. 21). Subsequently it analyses three different key trade-offs, namely (Baldwin & Wyplosz, 2019; Ederveen et al., 2008):

1. **Diverging preferences.** When people living in different constituencies have different preferences, centralized decision making creates inefficiencies (preference matching). Therefore, lower levels of government can more effectively reflect the preferences of distinct groups. For instance, certain jurisdictions might have stronger preferences for (a certain type of) renewable energy or for public charging infrastructure.

2. **Economies of scale.** When the average cost per unit falls as quantity increases (e.g., more people using a certain service), decentralized decision making creates inefficiencies (*economies of scale)*. The idea is that through centralization, economies of scale can be realised. For example, if more citizens use public charging stations for EVs or a communal battery, average costs decrease.

3. **Spillovers.** When there are positive or negative (cross-border) spillovers, decentralised decision making creates inefficiencies. Positive spillovers would lead to an under provision of services, whereas negative spillovers would lead to an overprovision of services with respect to public welfare. For instance, innovation leads to positive spillovers, since firms in neighbouring countries can also benefit from it. However, these benefits obtained by other countries are not considered when countries decide how much to invest in innovation. So, rather than providing the socially optimal amount of innovation investment, countries will invest only so much as to maximize their own (individual) gains.

Ederveen et al. (2008) provide a functional subsidiarity test, based on fiscal federalism. This test consists of a decision tree made up of 3 questions to determine whether a certain task should be centralised or decentralised. These questions are (Ederveen et al., 2008; Pelkmans, 2006):

1. Do cross-border externalities or economies of scale justify centralisation?
2. Is credible voluntary cooperation possible?
3. At which level can policies be designed and implemented in a cost-minimising manner?

The first question is based the trade-offs related to economies of scale and spillovers. The second question explores whether it is possible to achieve the desired outcome without resorting to centralisation. The third and final question tests if, even if central decision making is necessary, the practical issues relating to the execution of the policy can be conducted at lower levels of government (Ederveen et al., 2008, p. 25).

Ederveen et al. (2008) also discuss what happens when the assumption of a benevolent policy maker is loosened. This leads to additional arguments relating to (de)centralisation in something which is also called the 'second generation theory of fiscal federalism' (Chandra Jha, 2015):

4. **Jurisdictional competition.** Decentralised policy can lead to a positive where different jurisdictions compete in a desirable 'race to the top' (this is also closely related to accountability) (Ederveen et al., 2008). For instance, citizens may move to another municipality when they feel taxes are too high, creating competition among jurisdictions. Municipalities might also compete with one another on the number of public charging stations for EVs they offer or on how business-friendly they are for certain innovative firms.

5. **Policy learning.** Both policy learning and experimentation are more effective when policy is decentralized. The reason is that decentralisation can create diversity in policies, which leads to experiences with policy in one jurisdiction that might benefit another. For instance, municipalities can learn from one another about the best way to write tenders for public charging infrastructure.

6. **Common pool problems**. Decentralisation can better address issues related to the incentive of member states to draw as much as possible from common budgets for projects that locally provide benefits. For example, member states might try to use EU innovation funding to fund innovation projects that mainly provide local benefits.

Ederveen et al. (2008) also discuss several problems for which centralisation or decentralisation do not provide a uniform solution. The most important of these is that of lobbying and government capture. The impact of lobbying on the decision to either centralise or decentralise will depend on the specific conditions, e.g., the level at which the lobby is organised.

Fiscal federalism and the innovation phases

In our discussion we find that issues related to preference matching, interjurisdictional competition, policy learning/experimentation, and common pool problems all serve as justifications for decentralisation. In contrast, cross-border externalities and economies of scale are seen as key justifications for centralisation. In addition, the importance of these trade-offs differs substantially depending on the innovation phase (discovery phase; development phase; demonstration phase; deployment phase, see Table 1). In the discovery phase, there are very few arguments for decentralisation, whereas for the deployment phase the arguments for and against decentralisation become much more balanced.

In the discovery phase, the arguments for decentralisation are weak: In this phase competition needs to take place among firms, not jurisdictions. Furthermore, since these technologies have not left the lab yet, policy experimentation and even preference matching are still premature. Finally, common pool problems seem to be less relevant because the benefits of projects in the discovery phase are not primarily local, although local benefits do exist, e.g., in local employment possibilities. In addition, the arguments for centralisation are strong. The economies of scale argument is not yet that important because of the limited quantities involved in this part of the innovation process, although it has some merit with regard to the administrative costs that governments must incur in order to allocate innovation funding and monitor its use. However, cross-border externalities are very important. In this phase the benefits of innovation are (in general) less internalised by the involved actors. That is, those who make the discovery often only internalize a fraction of the benefits of their invention, in contrast to the benefits of a more developed product. Because of this, lower levels of government are more likely to underinvest in basic R&D since they are less likely to internalise the benefits of innovation than higher levels of government. For instance, lower levels of government might be more inclined to protect (large) incumbent industries through regulation or by simply not funding R&D projects that might threaten these industries. At the EU level, the incentives thus seem more aligned to stimulate climate change mitigation innovation.

In the final phase of the innovation process, the deployment phase, the arguments for decentralisation gain more importance when compared to the discovery phase: In the deployment phase jurisdictions can engage in meaningful competition, for instance, by trying to make their cities more friendly to EV drivers. In this phase, policy experimentation and learning also generate tangible benefits. For instance, municipalities might experiment with different tenders for public infrastructure for EVs and learn what the best way to write such tenders is. Lower levels of government can play a key role in driving institutional and regulatory changes, thus stimulating behavioural change. In this phase preference matching also becomes important. For instance, cities whose citizens have a greater preference for EVs can roll out more public infrastructure for EVs than cities whose citizens have a weaker preference for EVs. In the deployment phase, the arguments in favour of centralisation are mixed. In this phase the number of units of an innovation that are deployed grows rapidly. This might enable economies of scale and thus be an argument in favour of centralisation. However, the cross-border externalities argument loses strength when compared to the discovery phase. When an innovation approaches market readiness, the (positive) effects are much more internalised by the product developer. In the deployment phase a technology has not only seen technological innovation but also business case innovation, which enables the seller or developer of a product to internalize much of its positive effects. This is also an important reason why it is often easier for technologies in the deployment phase to find private financing (rather than public financing).

These trade-offs strongly suggest that centralization is better for innovations in the low TRLs, i.e., the discovery phase. However, for higher TRLs, i.e., the deployment phase, arguments for decentralisation gain more importance. This seems to show some parallels with the argument of

Wanzenböck & Frenken (2020). They argue that decentralisation is more effective with wicked problems in which solutions are highly context dependent. The importance of context seems to be especially relevant for technologies at higher TRLs.

Practical reasons

Besides the theoretical reasons for (de)centralisation discussed above, the literature also considers several practical concerns. One important reason for centralsation is that lower levels of government, such as small municipalities, might simply lack the (financial) capabilities to design and implement innovation policies (Cirera et al., 2020, p. 56). Second, higher levels of government might lack the political will to develop a certain technology at a certain speed. For example, the city of Copenhagen planned to reach net zero in 2025 whereas Denmark plans to reach this goal only in 2045. Third, innovation processes do not always neatly follow jurisdictional borders. In such cases, coordination between governments at the same level becomes complicated and costly. Centralisation can help solve these coordination problems.

Expert interviews

Our experts are all convinced that a larger role for the EU in innovation policy is desirable. Such a consensus is interesting. However, all our experts also work within the EU policy space. Because of this their views might be more favourable towards the EU. Table 4 summarizes the views on this topic from a selection of our experts.

Table 4: Expert views on required EU funding for innovation

Interview Topic	Do we need to centralise or decentralise innovation policy in the EU?
Expert 1	Centralize. The EU can take more political risks compared to its member states. Furthermore, a single company will have less political influence in the EU, so the risk of government capture is smaller. Finally, EU-level funding also promotes competition. However, local presence remains important. Not all decisions should be made in Brussels.
Expert 2	Centralize. EU-level funding leads to a more level playing field between countries and promotes cross-border cooperation.
Expert 3	Centralize. Especially for lower TRLs. Climate change mitigation is also a research topic that serves the interests of all member states.

3.2 Which level of governance is best for climate innovation funding?

Innovation policy within the territory of the EU involves the European institutions, member states and regional governments. Individual member states are heavily involved in innovation spending, with amounts in bigger member states being comparable to those being spent at EU level. For example, between 2013 and 2021, EU member states reported spending €4 billion on climate-related R&D from their share of EU ETS auctioning revenues alone (European Commission, 2022c, p. 34). This is partly a result of the wide difference between the size of national budgets (e.g., government spending is around 60% of GDP in France) and the EU budget, which amounts to only 1% of the EU's GDP. Innovation policy is thus a shared EU and member state competence (Baldwin & Wyplosz, 2019).

Historically, the EU argued that innovation policy was largely a member state responsibility and that the supranational level was largely about coordination (Reillon, 2016). But since that time the EU's funding for research and innovation has continued to grow. Because of the principle of subsidiarity, the question of the added value of the EU programs for research and innovation has been an important topic of discussion within EU circles. The EU Framework Programs (e.g., Horizon) are designed to complement member state research programs. This made it necessary to define which activities would be better implemented and performed at the EU level in order to strengthen the European innovation ecosystem.

The EU uses several arguments to justify its involvement in innovation policy. One argument relates to cohesion and solidarity: there are major differences between member states in the percentage of GDP that is spent on research and development. The EU average is 2.3% of GDP, with the highest-spending member states (Sweden and Belgium at 3.5% of GDP on R&D) allocating a seven-times higher proportion than the lowest, Romania, at 0.5% (Eurostat, 2022). In this context, one aim of EU level innovation policies is to create funds that are available to companies and other actors throughout the member states, without being constrained by their geographical location (European Commission, 2022b, p. 16). Second, because of the investment needs of some of these larger projects, some can only be funded at the EU level or on the level of the largest member states (this was one justification for the NER 300, given the large size and capital intensity of carbon capture and storage projects). Third, when innovation projects require transnational cooperation, EU coordination is useful. This includes, e.g., different universities from different countries working together, but it may also occur when the value chain of a certain technology is transnational, in which case innovations in many locations can play an important role (Green, 2019; Nemet, 2019).

In line with these arguments, a comprehensive policy evaluation of Horizon 2020 and its predecessor (FP7) found that the key mechanism for realizing EU added value was the pooling of a critical mass of financial resources, research infrastructures, and expertise from different countries, sectors, and organisations (European Commission, 2017). The pooling of these resources allowed EU-level programs to support more complex and more expensive research activities than would have been possible at a national level. This EU added value was especially prominent in complex and highly resource-intensive research areas, such as nanoscience or space research. Other aspects of EU added value include the enabling of comparative cross-country research, the reduction of research risks through the size and composition of consortia (which enabled effective task sharing) and the EU 'brand' which signals quality to private investors (European Commission, 2017).

An evaluation focusing on the NER 300, the predecessor of the Innovation Fund, came to similar conclusions. It showed the EU value added of the program in terms of maximising innovation and decarbonisation benefits. The geographical and technological spread of innovative projects under NER 300, combined with the knowledge-sharing requirement for project sponsors, was likely to result in an effective knowledge spill-over throughout Europe (European Commission, 2015).

In Section 3.1, we briefly introduced a decision tree for (de)centralization based on the subsidiarity test of Pelkmans (2006):

1. Do cross-border externalities or economies of scale justify centralization?
2. Is credible voluntary cooperation possible?
3. At which level can policies be designed and implemented in a cost- minimizing manner?

The first question was already discussed in Section 3.1 and showed that for innovations in the discovery phase externalities and, to a lesser extent, economies of scale, justify centralisation. The other considerations introduced by Ederveen et al. (2008), such as policy learning or interjurisdictional competition, did not change this. It was interesting to note that later (EU) policy evaluations seem to confirm these benefits through empirical research (European Commission, 2015, 2017).

The second question is about voluntary cooperation. If voluntary cooperation between member states is possible, there is less reason to involve the EU. However, in the area of innovation policy, credible voluntary cooperation between member states is made difficult by coordination costs and the incentives that they have to free ride on the innovation efforts of other countries. This is especially a problem for technologies in the early stages of development.

The third question was mainly directed at the implementation of policy, which in some cases might be cheaper at the member state or regional levels. However, in the case of innovation policy, and especially innovation funding, it is rather straightforward that using the EUs administrative capabilities to allocate and monitor innovation funding is cheaper than doing this on the level of member states, primarily because at the member state level this involves duplication of efforts. It avoids every member state having to setup its own administration to allocate and monitor funds.

Conclusion

We have discussed the advantages and disadvantages of more centralised innovation policies within the EU drawing upon the fiscal federalism literature. Centralisation and decentralization come with trade-offs, making it difficult to make general statements. However, for technologies in the discovery phase there seems to be a strong case for centralization. In this phase the incentives of a higher level of government – the EU – seem to be better aligned with stimulating climate change mitigation innovation, especially because it better internalizes the positive cross-border externalities associated with it. Additional arguments for centralisation include reduced administrative costs for distributing and monitoring funds (economies of scale), reduced transaction costs related to cross-border cooperation, the avoidance of overlapping (duplicate) policies, increased potential for competition between innovative firms, and a reduction of political risk in the case of failed innovation projects. For technologies in the deployment phase the arguments for and against centralisation are much more balanced.

4. How much public funding is needed for EU climate innovation?

It is difficult to determine how much funding will be needed in the future for climate-related innovation. The required amount will depend on a variety of difficult-to-predict factors, including the specific technologies involved and their TRLs, the speed of technological development, government policies, the behaviour of firms, GDP growth, labour market developments, and developments in the costs of raw materials. Despite these uncertainties, researchers have made educated guesses on the required amount of funding. In this section we will draw upon the results of integrated assessment models (IAMs) and use them as an explorative indication for the total required low-carbon investments in the EU. Subsequently, we synthesize existing research to estimate a lower and upper bound for the required climate-related public sector R&D investments.

4.2.1 Integrated Assessment Models (IAMs)

There is a long tradition of analysing the expected impacts of climate change and energy policies using economic modelling, including the DICE model (Nordhaus, 1992) and the IMAGE model. These models are also called integrated assessment models (IAMs), i.e., the integration of human activities and natural systems in an economic modelling framework. They are widely used by policymakers to gain insight into the costs of climate change on the one hand and the costs of mitigating climate change on the other (Arigoni Ortiz & Markandya, 2009). These dynamics are difficult to elucidate since they influence one another, for example, an increase in global temperatures will impact GDP growth, whereas GDP growth influences GHG emissions and thus climate change.

The general equilibrium model framework is used for most existing IAMs, as it can represent the whole economy, including capital accumulation and labour change over time, as well as accommodating the interactions of these aspects with the natural environment. This includes the effects of the accumulation of greenhouse gases and an assessment of the subsequent damages. IAMs model these dynamics through equations such as production functions of different sectors, utility functions of different consumers, and the market equilibrium condition. IAMs are usually calibrated using large databases that contain data on transactions between actors, such as trade between countries (the Social Accounting Matrix). These equations represent key processes in the economy and the environment and can subsequently be used to study different scenarios and their effects. For instance, one might compare the effects of different policies or different levels of global warming using IAMs. As with all models, IAMs are a simplified version of the real-world, and their predictions contain substantial uncertainty (Zhu, 2004).

It is common to analyse an issue using a single IAM, which makes the analysis more vulnerable to the specific assumptions of the particular IAM employed (McCollum et al., 2018; Bertram et al., 2021). McCollum et al. (2018) use a multi-model analysis, i.e., several IAMs[1] to estimate the required low carbon investments both globally and regionally. They focus on the investments needed for energy efficiency, electricity transmission and distribution (T&D), electricity storage, non-bio electricity renewables (wind; solar; hydro; ocean; geothermal), nuclear, biomass (including with carbon storage), and carbon storage. They take the year 2015 as their starting point and use it to calibrate the IAMs, making sure that they generate similar results to the actual available data from the International Energy Agency (IEA). Subsequently, they estimate how these investments might develop from 2015 to 2100 under three different scenarios. The estimates for later years are less reliable than those for earlier years and in our analysis, we will focus on the years up to 2040. The first (baseline) scenario models the required investments if countries limit their actions to their 2015 efforts to mitigate climate change (the 2015 Policy Scenario). In the second scenario, required investments are estimated that are compatible with a maximum increase in global average temperatures to 2°C (above the pre-industrial level) over the course of the 21st century with >66% likelihood (the 2°C Scenario). In the third scenario, the required investments are estimated to limit the increase in global average temperatures to 1.5 °C with >50% likelihood (the 1.5°C Scenario). To model these different scenarios, a common set of assumptions relating to population and socioeconomic development is used, drawing upon the 'middle of the road scenario' of the IPCC, also referred to as a Shared Socioeconomic Pathway (McCollum et al., 2018).

Table 5 and figure 1 show the required investments for key climate change mitigation technologies for the EU27 and the United Kingdom. Note that the scenarios also foresee a substantial disinvestment in carbon-based technologies, which is not shown in the table. Table 5 shows the required low-carbon investments in billion 2015 USD as the average of the 5 IAMs. Within square brackets, both the minimum and maximum IAM values are shown. The table shows that more ambitious climate change mitigation targets require more investment. In the 1.5°C Scenario, twice as much low-carbon investment is needed in 2040 as in the 2015 Policy Scenario. Table 5 also shows that, depending on the IAM, the required investments can vary by 10-fold.

[1] The IAMs included in this analysis are: IMAGE; MESSAGEix-GLOBIOM; POLES; REMIND-MAgPIE; WITCH-GLOBIOM. Note that McCollum et al. also use a sixth IAM, but the results of this IAM were not disaggregated for the EU and are thus excluded from our analysis.

Table 5: EU27/UK: Required public and private low-carbon investments

A) Billion 2015 USD

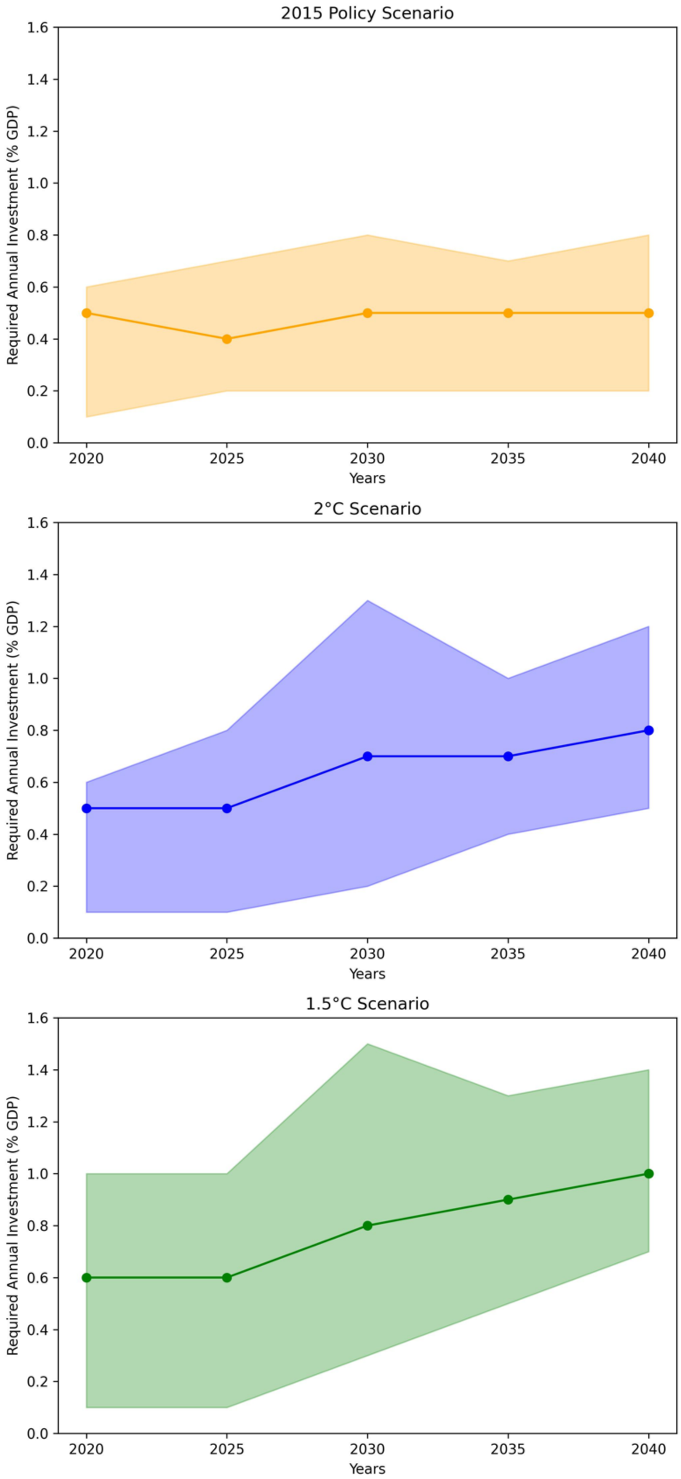
Scenario	2020	2025	2030	2035	2040
2015 Policy Scenario	91 [28–131]	95 [43–146]	114 [53–203]	120 [61–183]	137 [69–225]
2°C Scenario	97 [24–131]	108 [22–173]	155 [47–308]	173 [93–259]	231 [150–352]
1.5°C Scenario	113 [21–202]	124 [19–217]	191 [61–360]	228 [120–349]	276 [192–404]

B) % of GDP

Scenario	2020	2025	2030	2035	2040
2015 Policy Scenario	0.5% [0.1%–0.6%]	0.4% [0.2%–0.7%]	0.5% [0.2%–0.8%]	0.5% [0.2%–0.7%]	0.5% [0.2%–0.8%]
2°C Scenario	0.5% [0.1%–0.6%]	0.5% [0.1%–0.8%]	0.7% [0.2%–1.3%]	0.7% [0.4%–1.0%]	0.8% [0.5%–1.2%]
1.5°C Scenario	0.6% [0.1%–1%]	0.6% [0.1%–1%]	0.8% [0.3%–1.5%]	0.9% [0.5%–1.3%]	1% [0.7%–1.4%]

Source: McCollum et al., 2018. Average values of the five IAMs. Lowest and highest IAM estimate in brackets.

Figure 1: Average required EU/UK low-carbon investments (% GDP)



Source: McCollum et al., 2018.

4.2.2 Lower bound estimate: Historical average financing mix

The next step is to calculate which share of these total investments should take the form of government R&D investments. There are no IAMs that directly estimate the required financing mix in this way. However, Polzin et al. (2021) have developed a workaround to address this issue. They calculate an 'average' financing mix for energy technologies. To calculate this average, they use historical data collected by Bloomberg New Energy Finance that shows the financing mix for different energy technologies over the period 2007–2016.[2] Using this data they calculate the average financing mix for these technologies. Table 6 gives an overview of the average investment mix for these technologies over the period 2007–2016.

Table 6: Average investment mix for selected energy technologies

Investment category	Examples & definitions	Share
Government R&D	Grants or public procurement for research and development	1.87%
Corporate RD&D	Corporate expenditures on research and development, such as labs or salary costs of researchers	1.59%
Venture capital	Early-stage investors invest institutional money into a portfolio of start-ups	0.81%
Private equity	Capital investments that are not publicly traded	1.15%
Public markets	Selling company stocks or bonds	4.21%
Asset finance	Debt and equity provided by institutional investors, e.g., banks	66.89%
Reinvested equity	Reinvesting dividends, interests, etcetera into the firm	0.97%
Small, distributed capacity	Investments by households through, for example, mortgages or leasing	22.52%

Source: Polzin et al., 2021.

For our purposes, we are mainly interested in the first category: government R&D. The Polzin et al. (2021) methodology assumes that one can derive the required financing mix by taking a

[2] They use the following technologies: solar power; wind power; bio-power; hydropower (<50 MW); biofuels; geothermal; ocean energy. To calculate their averages, they examine the financing mix between 2012 and 2016. In contrast, we use the entire period 2007–2016 for our calculations.

constant share of the total investments. Polzin et al. (2021) readily admit this is a strong assumption since these shares differ over the life cycle of a technology. In the early stages of developing a technology the share of government R&D is generally higher than in the later stages (Polzin & Sanders, 2020).

Using the estimates in Polzin et al. (2021), we multiply the average government R&D investments with the results of the IAM models. This provides a preliminary indication of the required government R&D financing for climate change mitigation technologies within the EU27 + UK, as shown in Table 7. This approach estimates that in 2025, the EU and UK should provide $2.32 billion in government R&D investments to stay on a 1.5°C pathway. In the table the share of R&D increases over time rather than decreases. This is because the IAMs estimate that the total investments in green power technologies increases over the period 2020–2040. And because we assume that the required government R&D remains constant, i.e., 1.87%, this share also increases over time.

Table 7: EU/UK: estimate of low-carbon government R&D (based on historical financing mix)

A) Billion 2015 USD

Scenario	2020	2025	2030	2035	2040
2015 Policy Scenario	1.71	1.79	2.14	2.24	2.56
2°C Scenario	1.79	2.03	2.91	3.24	4.33
1.5°C Scenario	2.11	2.32	3.57	4.27	5.17

B) % of GDP

Scenario	2020	2025	2030	2035	2040
2015 Policy Scenario	.01%	.01%	.01%	.01%	.01%
2°C Scenario	.01%	.01%	.01%	.01%	.02%
1.5°C Scenario	.01%	.01%	.01%	.02%	.02%

Source: Own analysis, based on: Polzin et al., 2021; McCollum et al., 2018.

The numbers in Table 7 provide our lower-bound estimate of the required government R&D investments in climate change mitigation technologies in the EU and UK. In the next section, we will turn to another methodology to estimate the required financing mix, namely expert surveys, which will provide us with an upper bound estimate.

4.2.3 Upper bound estimate: Expert survey

A second method that has been used to investigate the required amount of R&D financing for innovation in low-carbon technologies is expert surveys. In 2017 Climate Strategy & Partners conducted a survey among 50 experts from 38 organisations (Sweatman et al., 2018). In their expert survey, they asked about the required financing mix for the necessary innovation investments (see Table 8). This survey leads to a markedly different financing mix when compared to those in Table 5. Comparing the financing mix of Polzin et al. (2021) and Sweatman et al. (2018) is not straightforward since the financing categories do not fully align. However, we are mainly interested in government R&D. In the early stages of innovation this will mainly take the form of grants (Polzin and Sanders, 2020) and public sector grants are one of the financing categories used by Sweatman et al. (2018).

Table 8: Average investment mix for selected energy technologies

Investment category	Share
Public sector grants	26%
Private equity	12%
Private sector debt, including green bonds	31%
Risk sharing instruments	14%
Public soft loans	17%
Total	100%

Source: Sweatman et al., 2018: p. 29.

In Table 9, we multiply the share of public sector grants (26%) reported by the experts in Sweatman et al. (2018) with the results of the IAM models reported in McCollum et al. (2018). The figures in this table represent our upper-bound estimate in climate change mitigation technologies in the EU and UK.

Table 9: EU/UK: estimate of low-carbon government R&D (based on expert survey)

A) Billion 2015 USD

Scenario	2020	2025	2030	2035	2040
2015 Policy Scenario	23.79	24.82	29.71	31.18	35.57
2°C Scenario	24.89	28.20	40.40	45.10	60.14
1.5°C Scenario	29.31	32.21	49.60	59.40	71.84

B) % of GDP

Scenario	2020	2025	2030	2035	2040
2015 Policy Scenario	0.12%	0.11%	0.12%	0.12%	0.13%
2°C Scenario	0.12%	0.13%	0.17%	0.17%	0.21%
1.5°C Scenario	0.14%	0.15%	0.21%	0.23%	0.26%

Source: Own analysis, based on: Sweatman et al., 2021; McCollum et al., 2018.

We might see the estimates in Table 7 as representing a lower bound for the required government R&D finance, and the estimates in Table 9 as representing an upper bound. The main reason why the calculation based on Polzin et al. (2021) can be seen as a lower bound is because it insufficiently takes into account the fact that that the financing mix can differ during the life cycle of a technology. Especially in the early stages of that life cycle, government R&D is more important. The main reason to see the survey results of Sweatman et al. (2018) as an upper bound is that the experts they survey often work within the green technology sector. They thus may have an interest in overstating the importance of government grants.

Note that our estimates focus on R&D while ignoring the needed investments for higher TRLs. As such, they do not provide the entire story. To illustrate: Baccianti (2023) estimates the EU public investment needs for the deployment of clean energy, resource, and energy efficiency technologies while explicitly excluding R&D. He bases his estimates on the National Energy and Climate Plans and finds an EU public spending need of 0.8% of GDP.

4.2.4 Expert interviews

We also used semi-structured in-depth interviews to ask experts if there is sufficient EU funding available. Their views vary from 'there is sufficient funding available' to 'much more funding is necessary". The experts all agree that more (innovation) funding from both public and private sources is necessary. However, they disagree on whether public funding should be increased. The discrepancy in views mainly depends on whether private and public funding are seen as substitutes of one another or complementary to one another. If an expert is of the opinion that increasing public funding is a good way to attract more private funding, they generally find that more EU grants are necessary. However, when they feel that public funding crowds out or substitutes for private funding, they say that there is already sufficient public funding available. In Table 10 below a selection of these expert opinions is summarized.

Table 10: Expert views on required EU funding for innovation

Interview Topic	Is the current EU funding for R&D in climate change mitigation technologies sufficient?
Expert 1	Largely sufficient for early-stage TRLs. Rather than increasing the size of funding, make more efficient use of current funds. The goal is to establish a 'fertile ecosystem' for innovation. An important challenge is to crowd-in private capital.
Expert 2	We need more public and private investments in innovations relating to climate change mitigation. The closer an innovation comes to market readiness, the more money is necessary and an increasingly large share of this must be provided by private investments. At the research phase (i.e., TRL 1-3) we need more public funding, e.g., quadruple Horizon funding. At TRL 4-6 we need more public and more private money. Public and private money are not substitutes but rather complementary to one another. To increase funding here we could, for example, increase the Innovation Fund or we could increase equity financing, i.e., the state operating as a venture capitalist with a long-term vision.
Expert 3	For the Innovation Fund: if the goal is just to support demonstration projects, there is sufficient money. However, given the new goal of also supporting market deployment, more money is required. This is also necessary if the EU wants to compete with the innovation subsidies of the US.

5. The current EU climate innovation landscape

5.1 Overview and scope

Given the complexity of the EU innovation funding landscape, we chose to focus our analysis according to five criteria. Our first criterion is that the funding needs to be **focused on climate change mitigation**. For example, we did not focus on funding for climate change adaptation – which has been an increasing focus of EU activities in the adaptation issue area (especially in Horizon Europe). Second, we focus on **currently active funding programs** – excluding those that have been discontinued (e.g., the NER 300). See Appendix B for an overview of EU innovation funds between 2014 and 2020 (based on Rubio et al., 2019).

Third, the funding needs to be **innovation-related**, i.e., our analysis does not include climate funding that focuses on investment in existing technologies. For example, the Modernisation Fund is one of the EU's largest climate funding mechanisms, but it is largely focused on upgrading electricity generation infrastructure in Central and Eastern Europe by supporting the deployment of existing technology. It was therefore excluded from our analysis. Fourth, we focus on funding programmes that **provide support for technologies between TRLs 1 and 6**, spanning the innovation lifecycle from the creation of the basic concept (TRLs 1–2) to early-stage demonstration of the concept in a relevant testing environment (TRL 6). Fifth, we examined **programmes which distributed grants**.

Based on these criteria, the analysis below focuses on three innovation-related funding programmes: the Innovation Fund, the LIFE Programme, and Horizon Europe – which includes the European Innovation Council and Pillar II clusters (Horizon Climate, Horizon Energy, and Horizon Transport). These three programmes arguably form the core of EU-level funding for early-stage climate change innovation and have grown in importance in the previous decade. Therefore, to understand the current policy landscape and make recommendations for it is improvement, understanding these funding mechanisms is key.

5.2 Horizon Europe

The Horizon programmes (formerly the Framework Programmes) are a core part of the EU's research and development policy. They are funded through the EU's main budget – the Multiannual Financial Framework. Starting in 2013, the EU set itself a target of using 35% of this funding – at the time under the Horizon 2020 programme – for climate action.[3] However, in this period, the programme undershot this target: from 2014 to 2017 the percentage was estimated at 24% (European Court of Auditors, 2016, p. 36). Horizon 2020 faced significant implementation challenges, given the bottom-up nature of a large percentage of projects. This implementation gap then drove changes in the programme that redirected money towards systems that would allow its strategic use for climate action. The EU increased funding levels and shifted funding from bottom-up projects that did not need a specific focus (such as climate) to more directed, mission-oriented funding, especially under Horizon Europe.

Because it is funded directly from the Multiannual Financial Framework negotiations, the level of funding and its timing are more predictable, allowing policymakers to plan for and the entire funding period – a benefit over the ETS-funded model of the Innovation Fund. A downside is that this funding would be less likely to be increased with, e.g., inflation, an especially pertinent issue after Russia's full-scale invasion of Ukraine in February 2022.

Table 11: Overview – Horizon Europe

Name	Horizon Europe (Includes European Innovation Council, European Missions, European Partnerships)
Legal Basis	Regulation (EU) 2021/695
Time Period	2021–2027
Funding Source	Multiannual Financial Framework
Funding Amount	€33.5 billion to contribute to climate objectives.
Aims	Framework for research and innovation funding in the EU.

[3] Regulation (EU) 1291/2013

Funding Eligibility	Climate change adaptation. Climate change mitigation technologies, examples: hydrogen, transport, industry.
Recipient Types	Companies, governments, academic institutions, other civil society.

Horizon Europe is a diverse programme, funding collaborative research in Pillar II (Global Challenges and European Industrial Competitiveness, Cluster 5: Climate Energy & Mobility), which includes European Missions and European Partnerships. In the European Missions, the most relevant programme is focused on climate neutral and smart cities. Horizon Europe also funds the European Innovation Council, which aims to provide financial support for proof of concept to early commercial stage, as well as for market deployment (EIC Pathfinder, EIC Transition, EIC Accelerator).

5.2.1 Horizon Climate, Horizon Energy, and Horizon Transport

The European Climate, Infrastructure and Environment Executive Agency (CINEA) implements Horizon Europe's Pillar II programmes under Cluster 5 on Climate, Energy, and Mobility. Under Horizon Pillar II, in 2022 and 2023, 493 projects have been funded in CINEA-coordinated clusters: Horizon Climate (110 projects), Horizon Energy (205 projects), and Horizon Transport (178 projects). An analysis of these three clusters suggests that Horizon Energy and Horizon Transport have a much stronger focus on technological innovation related to climate mitigation, than Horizon Climate, which allocates a substantial portion of its funding to other topics, such as climate adaptation and policy-oriented modelling, including econometrics and Integrated Assessment Models (for an overview, see Table 14 below). Horizon Energy includes 147 mitigation/innovation projects, representing 72% of funded projects and 70% of money allocated. Prominent areas of research include battery storage, innovative solar PV, and technologies related to the electricity grid. In comparison, Horizon Climate includes only 11 mitigation/innovation related projects, representing 10% of funded projects and the same percentage of money allocated. In the projects that focus on mitigation innovation, a common focus is Carbon Dioxide Removal technologies.

5.2.2 European Innovation Council

The European Innovation Council (EIC) includes three major sub-programmes. The EIC Pathfinder programme focuses on invention and proof of concept (TRL 1 to 4), providing grants of up to €3 to €4 million. The EIC Accelerator programme provides further grants for scaling up (up to €2.5 million, TRL 5-8), as well as equity investment for deployment (up to €15 million, TRL 9). Finally, the EIC Transition programme focuses on TRL 5/6 as well as business development, with up to €2.5 million grants.

Table 12: EIC funding for technological innovation and climate mitigation (2020-2023)

Programme	Total projects funded	Climate mitigation/ innovation projects	Total allocated amount	Allocated amount (mitigation/ innovation)	Mitigation/ innovation funding (% of total)
EIC Pathfinder	147	16	€448 million	€48 million	11%
EIC Transition	62	6	€139 million	€15 million	11%
EIC Accelerator	260	49	€595 million	€110 million	19%
Total	**469**	**71**	**€1.2 billion**	**€173 million**	**14%**

Source: Own analysis, based on CORDIS, 2023.

Table 12 presents the overall data for climate projects and funding under the EIC. Pathfinder and Accelerator are larger programmes overall, and so account for most of the relevant projects and funding, with Accelerator giving nearly twice its funding (in percentage terms) to climate projects than the other two programmes. Low-TRL Pathfinder projects are heavily focused on hydrogen (8 projects, 50%). Accelerator projects are focused on energy storage, transport, heating/cooling, and hydrogen. Transition projects are more diverse (the most common is hydrogen with two projects). An overview of technology focus for the EIC as a whole can be found in Table 15.

5.3 Innovation Fund

The Innovation Fund draws its financial resources from the auctioning revenue of the EU Emissions Trading System for fuel combustion, energy-intensive industries, aviation, and the maritime sector (ETS1).[4] Although the Innovation Fund's financial resources come from the ETS auctioning revenues, these resources are considered part of the EU budget and defined as external assigned revenue (European Court of Auditors, 2023, p. 24). As a result, unlike the related Modernisation Fund, decision making is more heavily influenced by the European Commission and subject to oversight by the European Parliament and the European Court of Auditors.

The Innovation Fund has its roots in the NER 300, the first large-scale ETS-funded mechanism for supporting early stage innovation. The NER 300 was created as part of a major reform of the ETS1 under the 2009 ETS Directive (Åhman et al., 2018; Eikeland & Skjærseth, 2020, pp. 45–46). The NER 300's strongest advocates were companies – especially in CCS-related industries – and it aimed to support demonstration projects in this area. Renewables were added to the list of

[4] The newly created EU ETS for buildings and transport (ETS2) directs a portion of its auctioning revenues to the Social Climate Fund.

targeted projects because advocates for the fund needed to gain more member state support in the Council of Ministers (Boasson & Wettestad, 2014). The European Commission was initially opposed to the idea and pushed for smaller amounts of funding to be allocated to the NER 300 from ETS1 auctioning revenue. At this time, ETS1 auctioning was very limited and implemented at the member state level, and there was a high level of uncertainty about carbon prices.

The NER 300 was allocated significantly fewer allowances than the Innovation Fund (300 million vs. 450 million). However, the main difference between the two was the price of allowances when they were auctioned. In the NER300's case, 300 million allowances raised approximately €2 billion (at an average allowance price of €6.67). If the same price existed now the Innovation Fund's original allocation would be worth only €3 billion. Indeed when the Innovation Fund was set up it was projected to total €10 billion based on the price at the time of approximately €20/tonne (Pickstone, 2019). But because the current allowance price sits at €80, a multiple of 12 compared to the NER300, the Innovation Fund was able to disburse funding equal to 60% of the NER300's total budget in just the first call for projects (European Commission, 2022b, p. 9). Overall, total Innovation Fund calls at the time of writing totaled €5.8 billion, €5.5 billion for large-scale projects and €300 million for small-scale projects.

The Fund was originally allocated the auctioning revenue from 450 million emission allowances. As part of the 2023 ETS Directive, it is estimated it will receive an additional 165 million allowances that would otherwise have been allocated for free to energy-intensive industries (Council of the European Union, 2023, p. 5). Finally, as part of the RePowerEU Regulation, an amount of allowances from the Innovation Fund equal to €12 billion will be used to fund 60% of RePowerEU spending – funding that will be partially replaced by an additional 27 million allowances from other sources.[5] This complex, multi-stage process means that the Innovation Fund is currently expected to be funded by the allowance revenue from 642 million ETS allowances, minus the €12 billion for the RePowerEU programme. The European Commission currently estimates that the Innovation Fund will be able to draw on €40 billion during its first decade. Unlike the Horizon Europe and LIFE Programme, the final amount available is highly dependent on uncertain allowance prices over the decade.

Table 13 Overview – Innovation Fund

Name	Innovation Fund
Legal Basis	Directive 2003/87/EC (ETS Directive) as modified by Directive (EU) 2018/410 and Directive (EU) 2023/959. Implemented by Commission Delegated Regulation 2019/856.
Time Period	2020–2030
Funding Source	EU Emissions Trading System (ETS1) auctioning revenue.
Funding Amount	Estimated €40 billion. €5.8 billion allocated for first three calls.

[5] Emission allowances in the Market Stability Reserve that would otherwise be cancelled (see Article 5, RePowerEU Regulation).

Aims	Commercial demonstration of innovative low-carbon technologies.
Funding Eligibility	Commercial demonstration of: • Low carbon energy-intensive industry technology • CCS/CCU • Innovative renewables • Energy storage • Green hydrogen production (deployment/CCfDs)
Recipient Types	Companies

The Innovation Fund has a relatively wide scope of eligible projects: carbon capture and storage, carbon capture and utilisation, innovative renewables, energy-intensive industry technologies for low-carbon production and energy storage (European Commission, 2022b, p. 17). Within these eligibility criteria, the process for selecting projects is generally 'bottom-up', i.e., submissions are judged equally on the selection criteria: effectiveness of greenhouse gas emissions avoidance; degree of innovation; project maturity; scalability; and cost efficiency.

As allowance revenue from the ETS1 increased beyond initial projections, the Commission has increased the size of calls (e.g., for large-scale projects, from €1 billion in the 1st call to €3 billion in the 3rd call). It has also focused parts of funding calls on specific technology groups. In its 3rd call for large-scale projects (European Commission, 2022d), the Commission divided the funding between an open call (€1 billion), electrification in industry and hydrogen (€1 billion), clean tech manufacturing (€700 million), and "mid-sized pilots", i.e., "projects for validating, testing and optimising highly innovative solutions" (€300 million). In addition, in 2023 the EU will fund Carbon Contracts for Difference to support hydrogen production using approximately €800 million from the Innovation Fund (European Commission, 2023c, pp. 6–8).

Financial support from the Innovation Fund is both larger and longer-term than that found in the other programmes. A single large-scale CCS project, Kairos-at-C, is funded with €356 million over 15 years, double the amount allocated for all projects funded by the European Innovation Council. Overall, 23 large-scale projects are funded for more than €50 million each, and the average length of both small-scale and larget-scale projects is 8.7 years. Nearly half of the funding so far (€1.47 billion) has gone to projects related to carbon dioxide removal, as well as carbon capture and storage/utilisation. Other major focus areas include hydrogen (18% of funding), biofuels/biorefineries (6%), energy storage (5%), and solar energy (4%) (see Table 15).

5.4 LIFE Programme

The LIFE Programme – and its sub-programme for climate action – is a relatively small EU-level fund focused on disbursing grants to support demonstration, best practice diffusion, and upscaling for technologies, approaches or policies (European Commission, 2018, pp. 5–6). Although LIFE documentation mentions innovation, an analysis of funding disbursed in the current funding period shows that only €17.9 million (7%) was spent on projects focused on both climate mitigation and technological innovation, as shown in Table 14. The LIFE Climate sub-programme funded 42 projects, allocating a total of €115 million. Eight of these projects addressed climate change mitigation and technological innovation (€16 million, 14% of total funding allocated). The LIFE Clean Energy Transition sub-programme funded 73 projects, disbursing a total of €122 million. Only one of these projects addressed climate mitigation and technological innovation (€1.9 million, 2% of total funding allocated). Overall, LIFE funding accounts for less than half of one percent (0.37%) of the funding analysed in this section. Within these projects, LIFE focused on agriculture, biofuels/biorefineries, the electrical grid, and solar energy (Table 15).

5.5 Summary: A map of EU climate innovation funding

Our mapping of existing EU innovation funding for climate mitigation has revealed a growing, complex policy landscape which encompasses nine programmes (including the three EIC sub-programmes), 400 distinct research projects, and provides financial support for a wide range of climate-related technologies. The programmes presented in Table 14 vary significantly in size (from €2 million in the LIFE Clean Energy Transition programme to €3.1 billion in the Innovation Fund) and in the extent to which they focus on technological innovation for climate mitigation (from 2% of projects in LIFE Clean Energy Transition, to 68% in Horizon Energy and 100% in the Innovation Fund).

Table 14: EU funding for technological innovation and climate mitigation (2020-2023)

Programme	Total projects funded	Total allocated amount	Projects on climate mitigation & innovation	Allocated amount (mitigation + innovation)	Mitigation + innovation project funding (% of total)
Horizon Climate	110	€740 million	10	€73 million	10%
Horizon Energy	205	€1.3 billion	144	€893 million	68%
Horizon Transport	178	€1.2 billion	97	€655 million	56%
European Innovation Council	477	€1.2 billion	71	€173 million	14%
Innovation Fund	69	€3.1 billion	69	€3.1 billion	100%
LIFE Climate	42	€115 million	8	€16 million	14%

LIFE Clean Energy Transition	73	€122 million	1	€2 million	2%
Total	**1154**	**€7.8 billion**	**400**	**€4.9 billion**	**62%**

Source: Own analysis, based on data from CINEA, 2023; CORDIS, 2023.

We also identified 23 distinct technologies (e.g., solar, hydrogen) and topic areas (e.g., transport, maritime) that the 400 projects support (Table 15). Despite this broad coverage, a few technologies stand out as attracting most of the support, with CCU/CCS/CDR, energy storage, and hydrogen alone attracting nearly 60% of available funding. The 23 large-scale projects in the Innovation Fund likewise account for around 60% of the €4.9 billion we have analysed.

Table 15: Innovation funding for climate mitigation, by fund and topic (million €)

Topic	EIC	HE P-II	IF	LIFE	All Funds	% of funding
Agriculture	1.9	17.9	7.1	1.8	28.7	0.6%
Bioelectricity	4.9	1	-	-	5.9	0.1%
Biofuel/refineries	-	86.7	187.5	2.3	276.5	5.6%
Buildings	5	54.6	-	0.1	59.7	1.2%
CCU/CCS/CDR	-	86.6	1,470	-	1,556.1	31.8%
Cement	2.4	-	-	-	2.4	0.05%
Energy storage	26.9	405.6	166.4	-	598.9	12.2%
Geothermal	3	12.1	96.1	-	111.2	2.3%
Grid	2.3	149.5	12.1	3	166.9	3.4%
Heating/cooling	14.4	5.7	-	-	20.1	0.4%
Hydrogen	35.5	94.9	561.6	1	693.0	14.1%
Lighting	4.4	-	-	-	4.4	0.1%
LULUCF	4.6	-	-	2.5	7.1	0.1%
Maritime	4.9	65.1	4	-	74.0	1.5%
Mining	1.7	-	-	-	1.7	0.03%
Nuclear	2.5	-	-	-	2.5	0.1%
Ocean	2.5	13.1	-	-	15.6	0.3%
Other	14.3	86.4	169.1	5	274.8	5.6%
Renewable/other	3	22.2	-	-	25.2	0.5%

Solar	9	130.5	125.9	2.4	267.8	5.5%
Transport	15.6	260.6	80.2	-	356.4	7.3%
Waste	7.2	-	110.8	-	118.0	2.4%
Wind	4.9	123.2	105.4	-	233.5	4.8%
Total	**173**	**1,616**	**3,096**	**18**	**4,900**	

Source: Own analysis, based on data from CINEA, 2023; CORDIS, 2023. Each project was classified under one category according to primary focus. Technology categories (hydrogen, solar) signify a project which primarily focused on that technology. Sectoral categories (e.g., transport) focused on that sector rather than one technology. EIC: European Innovation Council. HE P-II: Horizon Europe Pillar II (Horizon Climate, Horizon Energy, and Horizon Transport). IF: Innovation Fund. LIFE: LIFE Programme.

5.6 Is EU climate-related innovation funding sufficient?

In Section 4, we presented estimates for the annual EU/UK climate R&D funding that would be necessary to be compatible with a 1.5°C scenario. Those estimates suggested that in 2025, EU R&D funding for clean energy should be between 0.01% and 0.15% of GDP. Total European R&D funding in 2021 was €328 billion or 2.27% of GDP, with 0.76% of GDP coming from public sources and the remainder from the private sector (Eurostat, 2022). This 0.76% of GDP includes R&D on all topics, and it is not clear what percentage of this is spent on climate change mitigation technologies (Sweatman et al., 2018). However, the IEA estimates that in 2021 EU energy R&D investment was $11.7 billion, of which around 80% ($9.36 billion) was devoted to clean energy. This amounts to roughly €8.15 billion in 2021 Euros (.06% of GDP).[6] These clean energy investments include low-emission fuels, carbon capture and storage/utilisation, nuclear, battery storage, electric vehicles, grids, energy efficiency, and renewable power (International Energy Agency, 2023, p. 134). Although this does not cover all climate change mitigation technologies, it does make up a substantial part of it. Our back-of-the-envelope calculations suggest that public R&D funding for clean energy within Europe is around 0.06% of GDP. This is within the lower bound estimated by the IAMs for 2025, namely 0.01% of GDP (Table 7). However, it falls markedly short of its upper bound, which was 0.15% of GDP. This suggests that there is space to increase public funding for climate change mitigation R&D within the EU.

This also becomes clear when we focus on the innovation funding mapped in Section 5.5. For Horizon Europe for the period 2021–2027, €33.5 billion has been allocated to contribute to climate objectives. If we assume this funding is evenly spread out over the period, this amounts to €4.8 billion per year. For the Innovation Fund for the period 2020–2030 an estimated amount of €40 billion is allocated (€3.6 billion per year). For the LIFE programme for the period 2021–2027 an amount of €1.95 billion has been planned (€280 million per year). Together this estimate amounts to €8.7 billion. This should be considered an upper-bound estimate for these programmes given

[6] With an average dollar to euro exchange rate in 2022 of 0.951 (Exchange Rates UK, 2023) and with a Euro annual inflation rate in 2022 of 9.2% (Eurostat, 2023).

that some of them (especially LIFE) devoted only a small percentage of their funding to mitigation-related technological innovation between 2020 and 2023 (Table 14). As an illustration, Horizon Europe, the Innovation Fund, and the LIFE programme together provided €3 billion worth of funding to projects that began in 2022. Funding from these programmes (between €3–8.7 billion) therefore amounts to between .02% and .06% of GDP. This suggests that there is also space to increase government R&D funding at the EU level.

6. Impact assessment: Policy avenues and innovation funding

In the previous sections, we identified various ways in which EU innovation funding can be improved. Depending on the design principles that policy makers follow, policy makers will come up with different concrete policies. Görlach et al. (2022) identify four policy avenues based on distinct policy paradigms. These four policy avenues are: Green Economic Liberalism; Green Industrial Policy; Directed Transition; and Sufficiency and Degrowth. In this section, each policy avenue will be shorty introduced. Subsequently, we discuss how each policy avenue might impact the way that EU innovation policy is designed, and what that mean for the path toward climate neutrality.

6.1 Green Economic Liberalism

6.1.1 Overview

The Green Economic Liberalism (GEL) policy avenue values economic efficiency and markets. It thus prefers market-based policy instruments, especially carbon prices, to reach climate neutrality. The core instruments in this avenue are the EU Emissions Trading Systems covering fuel combustion and energy-intensive industries such as steel (ETS1), the ETS2 that will cover transportation and buildings, and a third, future ETS3 to cover land use, agricultural, and forestry emissions.

In this context, the higher prices for carbon-based products caused by the emissions trading systems play a key role in driving innovation. They internalize or attribute the costs for emitting greenhouse gases to the respective goods and services (i.e., operationalising the 'polluter pays' principle) and thus give actors a strong incentive to innovate. This process would give firms an incentive to innovate technologically and consumers an incentive to buy greener products, thus also creating opportunities for business model innovation. Nonetheless, public funding plays an important role for early-stage technologies that would otherwise find it difficult to secure sufficient financing.

6.1.2 Impacts on innovation funding

In this policy avenue, there is a clear need for innovation funding. Market failures lead to under investment in innovation and there is thus a clear rationale for public innovation funding. The GEL policy avenue also places a high value on economic efficiency. As such, the arguments discussed in Section 3 related to the best level of governance to support innovation would carry considerable weight. Policies and funds for the lower TRLs (basic R&D) would be more strongly centralized at EU level. However, (classical) liberalism is also strongly associated with small and less powerful governments, so for higher TRLs, as markets become more effective and the local context becomes increasingly important, this policy avenue would advocate for more involvement of the private sector and national/regional governments. In practice this would mean that Horizon would become much more important. However, funds for higher TRLs, such as later-stage European Innovation Council support or some projects in the Innovation Fund, would see more involvement by national and regional governments.

The strong emphasis GEL places on emissions trading – along with the assumption that combined these systems would have lower caps to reach climate neutrality by 2050 – could imply a greater potential pool of revenue from allowance auctioning to fund innovation projects, as is currently done with the Innovation Fund. However, the question is if this avenue – strongly valuing economic efficiency – would foresee these additional revenues going into early-stage innovation funding or other areas, such as a reduction in distortionary taxes. This is especially the case if strict caps aimed at climate neutrality lead to a high carbon price – which in this scenario would be assumed to drive a significant share of required innovation. Given these two contrary tendencies, i.e. an increase in revenues but also a greater concern for providing too much money for innovation and thus funding low-quality projects, we argue that EU innovation funding will remain on its current trajectory. However, as already discussed, we do see a shift of funding away from the higher TRLs towards the lower TRLs.

Concerns about inefficiency, such as funding the wrong technologies, and the trust they have in markets, also has consequences for the directionality of innovation policy. Rather than picking winners, GEL would prefer a more technologically neutral innovation policy. In practice this would mean more technologically neutral topics within Horizon Europe and the Innovation Fund, as opposed to more mission-oriented funding that focuses on specific technologies. Policymakers will also place greater weight on efficiency (e.g., the "cost efficiency" criterion used to select Innovation Fund projects).

6.2 Green Industrial Policy

6.2.1 Overview

Innovation funding is at the core of the Green Industrial Policy (GIP) policy avenue. The avenue assumes expanded, large-scale research and development funding to both support breakthrough innovations and strengthen the deployment and scaling up of existing solutions (Görlach et al., 2022, pp. 40–42). Incorporated into this view of policy is an assumption that governments, including the EU, will play an active role in directing technological change, "picking winners" by directing funding to specific technologies and sectors that are seen as especially important to the transition to climate neutrality. This also implies that – unlike carbon prices – this type of funding is not technologically neutral and, as noted in the previous sentence, there are clear winners and, consequently, the need to pick losers where some sectors and technologies are not funded (and others are actively phased out). With that said, carbon prices and the emissions trading systems are still foreseen to play an important role, both as a policy tool and as a source of funding for innovation subsidies.

Another core element of the GIP policy avenue is that funding will be more intensively coordinated from the EU level in so-called innovation "missions" that focus on concrete goals and coordinate actors from various sectors around core innovation processes. It also assumes that innovation funding will be implemented in conjunction with performance standards, product standards, and technology phase out requirements (e.g., exnovation/phase-out requirements).

6.2.2 Impacts on innovation funding

With the emphasis the GIP policy avenue places on planning and coordination, a further shift of competences to EU level is likely. This would not only apply to the lower TRLs but for all TRLs. Such centralization of discretionary powers does not necessarily mean that the execution of policies also happens in Brussels. National and regional governments still play a key role in implementing policy. It remains an open question whether or not something as complex as the energy transition can be managed so centrally. And a major challenge to overcome within this policy avenue is how to sufficiently consider local interests and local knowledge.

Within the GIP we foresee a significant scaling up of innovation funding, greatly increasing the size of related programmes. We also foresee a streamlining of the funding landscape, either by the merging of multiple funds, such as the Innovation Fund and the Modernisation Fund, or by increased central coordination between different funding sources via the enhanced Climate Missions Framework. Given the focus on "mission-oriented funding" in this avenue, policy makers would likely expand the climate-related European Mission programmes under Horizon Europe beyond their current focus on climate adaptation, climate neutral cities, and healthy oceans. More generally, this avenue would see increased funding across the innovation landscape, from the Innovation Fund to the LIFE Programme, Horizon Europe, Repower EU and InvestEU. There would potentially be less pressure to keep innovation funding narrowly focused or within strict time limits. The percentage of project costs that would be covered may also be increased to make more marginal and risky projects financially feasible.

In this context, where innovation funding is so central to policy goals, the source and stability of funding budgets would become especially important. With the parallel ambitious regulatory standards in place, policymakers may be able to rely on continuing high carbon prices in the ETS1 to provide resources for innovation funding. However, given that such funding would be "too important to fail", it is likely that additional sources of funding would be explored. This might include the creation of additional funding in the Multiannual Financial Framework, funded by European Union bonds or from greater diversion from existing funding sources, such as the revenue from the Carbon Border Adjustment Mechanism.

Increases in the EU budget could be used to scale up programs that are currently funded by budgetary resources – such as Horizon Europe, where the mission-focused innovation is currently centred in the European Missions and European Partnerships. In addition, EU budgetary funds could be used to "top up" funding instruments currently resourced from ETS allowances, such as the Innovation Fund and RePowerEU. Increased budgetary resources could be used both to plan long-term funding plans for these funds, but also to top up or react to lower-than-expected carbon prices, i.e., the budget could be automatically increased if those prices fell below a certain threshold.

6.3 Directed Transition

6.3.1 Overview

The Directed Transition (DT) policy avenue centres its policy mix on a comprehensive framework of ambitious, stringent targets and standards which limit the amount of greenhouse gases that can be emitted and progressively ban certain technologies such as internal combustion engines. In this avenue, carbon prices, while still existing, are not seen as an essential driver of the transition to climate neutrality. Instead, standards agreed at EU level put hard limits on emissions, which progressively tighten to drive a shift to low-carbon technologies.

6.3.2 Impacts on innovation funding

In the DT policy avenue, regulatory and market-pull effects would be expected to help crucial low-carbon technologies succeed. The fact that businesses and other actors are subject to stringent standards to reduce greenhouse gas emissions and required to phase out certain technologies makes replacement technologies and business models indispensable. However, there is a risk of a mismatch between these standards and the existing technologies – that is why the DT policy avenue also foresees an important role for the early-stage invention and deployment funding that this report focuses on. Deliverable 4.1 therefore sees "high volumes of capital" needed for invention and deployment support for new technologies (Görlach et al., 2022, p. 58).

The DT policy avenue would need to spend planning time on picking the technologies that policy makers believed were required to make standards feasible, especially where the standards require the phasing out of specific technologies – leaving a technological gap that must be filled. For standards where the metric is reduction in greenhouse gas emissions per e.g., kilometres driven for cars, then funding could be less centrally directed, and perhaps be more efficiency focused (similar to the Green Economic Liberalism policy avenue).

6.4 Sufficiency and Degrowth

6.4.1 Overview

The Sufficiency and Degrowth (SD) policy avenue differs in significant ways from the other three avenues. Those avenues are all in different ways strongly represented in the EU's existing climate policy mix. In contrast, the SD avenue foresees a radically new path for public policy to reach climate neutrality. In this avenue, it is assumed that policy makers and society chose to reduce material and energy use, potentially including via a developmental path that leads to economic degrowth: the planned reduction in economic activity and/or GDP. It also assumes a general policy scepticism to both market-based policies and economic efficiency, and to GDP as a flawed measure of well-being. As far as concrete policy goals, there is a focus on changing behaviour and lifestyles and limiting "demand for emission-intensive goods and services" (Görlach et al., 2022, p. 65). This implies for example, broader social changes such as a dietary shifts, less use of cars or airplanes, etc.

6.4.2 Impacts on innovation funding

Another implication is about the targets of innovation. It is unlikely that innovation funding in this avenue would be directed toward fossil fuels or nuclear power. More attention (and funding) would be directed toward innovation related to low-consumption lifestyles, business model innovations that supported them, and potentially social innovation, supporting new economic or social models with a smaller economic and climate footprint. This could be redirected from existing funding sources like the Innovation Fund, or also from other places such as the Social Climate Fund. Another key point would be the greater decentralisation and localisation of innovation planning and funding, potentially making them more democratic and better able to deal with the complex, wicked issues brought up by simultaneous climate mitigation and social change/innovation (Wanzenböck & Frenken, 2020).

Under the SD avenue, a key issue would be the amount of funding that would indeed be available for innovation. Given the general scepticism to market-based instruments under this avenue, it is not clear to what extent auctioning revenue from emissions trading systems would be available, and if those systems are deemphasized or if their scope is reduced, that could also create challenges for revenue. In addition, reduction in economic activity could create problems for general tax revenues, affecting the possible replacement for these funding sources.

7. Conclusions

Achieving the goals of the Paris Agreement will require a deep, rapid, and system-wide transformation of how society operates (Fazey et al., 2018; Termeer & Metze, 2019; Haddad et al., 2022). For this transformation to be successful, carbon-intensive technologies will need to be replaced by low-carbon alternatives. Some can be replaced by existing ones, such as traditional solar photovoltaics and wind energy. But given the urgent need to reduce emissions, new technologies are also necessary and existing technologies need to be further developed (Blanco et al., 2022). One key obstacle to developing new solutions, especially for technologies that are in the early stages of development, is a lack of funding. Private investors are hesitant to provide funding for such technologies, leaving the public sector as a vital source for financing (Polzin & Sanders, 2020).

In this report, we have examined four interconnected research questions related to innovation policy for climate change in the EU. Our analysis of the **most effective levels of government** for innovation policy found a varying picture: in the early stages of technology development (especially the discovery phase), the arguments for centralisation at EU level are strong, because it would better internalise positive cross-border externalities, reduce administrative costs, avoid policy duplication, increase competition, and reduce political risk. For more mature technologies, the arguments that support decentralization become stronger. In these later stages of development, problems become less technical and more uncertain, making the context in which an innovation is used increasingly important. The relevance of policy learning/experimentation and jurisdictional competition increases, making the member state and regional levels of government increasingly efficient in designing and implementing innovation policy.

Our assessment of the **required level of EU R&D** drawing on Integrated Assessment Models (IAMs), suggests that in 2025 EU R&D funding aimed at climate change mitigation should be between 0.01% and 0.15% of GDP to be compatible with a 1.5 °C scenario. Drawing on estimates from the IEA we find that public R&D funding devoted to clean energy in Europe was around 0.06% of GDP in 2021 (International Energy Agency, 2023). This suggests that actual public R&D funding within Europe falls within the estimated range of required funding but lies close to the lower bound. Because it lies close to the lower bound, we expect that there is still space for additional public R&D funding. Funding from Horizon Europe, LIFE, and the Innovation Fund (which we estimate between €3–8.7 billion) amounts to between .02% and .06% of GDP. This suggests that there is also space to increase government R&D funding at the EU level.

Regarding the **existing EU funding landscape**, our analysis identified three overarching programmes (Horizon Europe, the Innovation Fund, and the LIFE Programme) supporting 400 projects related to climate mitigation and technological innovation that mobilised at least €4.9 billion from the EU funding landscape. We also identified 23 distinct technologies (e.g., solar, hydrogen) and topic areas (e.g., transport, maritime) that the 400 projects support. Despite this broad coverage, a few technologies stand out as attracting most of the support, with CCU/CCS/CDR, energy storage, and hydrogen alone attracting nearly 60% of available funding. The 23 large-scale projects in the Innovation Fund likewise account for around 60% of the €4.9 billion we have analysed.

Our examination of the **impacts on EU innovation policy of each of the four policy avenues** yielded several cross-cutting findings. First, some avenues – especially Sufficiency & Degrowth – might be expected to push for greater decentralisation to better deal with regional/local issues, while the Green Economic Liberalism might be expected to take a flexible approach based on criteria similar to those that we presented in Section 3. In contrast, the Green Industrial Policy and Directed Transition avenues would be expected to lead to greater centralisation of innovation policy at EU level. Second, the Green Economic Liberalism avenue would prefer a strong degree of technological neutrality, whereas the other three avenues would likely see various levels of 'picking winners' when it came to innovation funding. Third, within the three avenues that would be more amenable to picking winners, priority areas would likely differ. For example, Green Industrial Policy and Directed Transition would be expected to prioritise technological solutions (such as CCS and hydrogen) while the Sufficiency & Degrowth avenue might see greater focus on energy efficiency and social innovations related to lifestyle change.

Policy recommendations

Despite the large rise in public funds by the European Union in recent years, we find that there is still ample scope to increase public R&D funding for climate change mitigation technologies within the EU. But even when funding is not increased, our theoretical framework suggests that innovation policy within the EU could be made more effective when member states consider shifting their public R&D funds from technologies in the early stage of development, to technologies that are more mature. Simultaneously the EU could shift some of its funding from funds aimed at more mature technologies towards the Innovation Fund, and especially, Horizon Europe, to compensate for the funding changes by member states.

Future research

Future research on these EU innovation funding for climate mitigation could usefully go in several directions. It could explore questions related to the most effective level of government for innovation policy by further developing the theoretical approach to the topic (e.g., by incorporating concepts from other literatures such as on governance) or carrying out empirical case studies of individual high-priority technologies to explore the trade-offs between centralised and decentralised innovation funding. Research on the required level of R&D funding at EU level could be advanced by incorporating insights from a wider array of sources (e.g., additional IAMs or updated data). Analysis of the EU's current innovation funding landscape could be extended further into the past to create a longitudinal analysis of the development of EU-level funding or explore related topics such as the governance system which supports this complex landscape. Finally, analysis using the policy avenues could be built on to further explore how EU innovation policy should be improved to put the EU most effectively on track for climate neutrality.

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Appendices

Appendix A: Questions for semi-structured interviews

Current EU innovation funding for climate change mitigation

1) What are the biggest bottlenecks or obstacles to climate change innovation in the EU?

2) Is a lack of financial resources a key obstacle or bottleneck to developing climate change innovations?

3) Currently we are focusing on the following grants and loans for EU innovation for climate change mitigation: Horizon and Innovation Fund. To a lesser degree LIFE and InvestEU (climate and infrastructure); RePowerEU also plays a role. Did we miss anything?

If the interviewee is specialized in a specific fund, they can answer these questions for that fund (rather than for the more general funding landscape).

4) How are these funds performing in your opinion? Have you identified any problems with these funds or did you hear any complaints about them? More specifically:
    a. Are these funds spent at the most effective level of government? Could MS and/or local governments spent these funds more effective?
    b. Is the total size of these funds sufficient?
    c. Are these funds aimed at the right technologies?

5) Fund specific question: Do the right companies receive funding?

Future EU innovation funding for climate change mitigation

6) How do you expect current EU-level grants and loans for innovation for climate change mitigation to develop the coming years?

7) What discussions are currently in progress in this area?

8) Which funds do you expect to arise? E.g., the Sovereignty Fund.

What would your ideal innovation funding landscape look like?

9) How do you think the current and projected EU funding landscape for direct investments in RD&I can be improved? Specifically related to:

    - Would you want to centralize funding for innovation more at the EU level or would you want to decentralize it more?

- The amount of funding available. Would it need to increase or decrease?
- The source of funding (e.g., emissions trading allowances, EU budget)
- The policy instruments (grants, loans, contracts for difference)
- The technologies/actives at which these funds are targeted.

10) Are there any other countries (e.g., the US) that the EU can learn from when it comes to effectively supporting innovation?

Further research

11) Which people would you recommend that we speak to?

12) Do you have any further questions or suggestions for us?

Appendix B: EU innovation funds period 2014-2020

This table is based on Rubio et al. (2019).

Name	Amount	Type of policy instruments used	Aim	Technology
Horizon 2020	€61.8 billion	Direct support to RD&I projects; Support to innovative firms; Support knowledge and information exchange, research infrastructure, human capital, and policymaking.	Contribute to building a society and economy based on knowledge and innovation across the Union by leveraging additional research, development, and innovation funding.	Technology neutral.
European Regional Development Fund (ERDF)	€53.4 billion	Support diffusion of innovations, innovative firms, knowledge and information exchange, research infrastructure, human capital, and policymaking.	Reducing the disparities in the level of economic development among EU regions by investing more heavily in the less developed ones.	Largely technology neutral (some advantages for technologies that contribute to low-carbon economy).
European Fund for Strategic Investments (EFSI)	€9.1 billion	Demonstration projects; knowledge & technology diffusion.	Finance projects of strategic importance, which otherwise would not have been financed by private or public actors.	Cross sectoral.
Connecting Europe Facility (CEF) Telecom	€900 million	Support diffusion of innovations.	Support trans-European networks and infrastructures in the telecommunications sector.	Digital services & broadband infrastructure.
Competitiveness of Enterprises and Small and Medium-sized Enterprises (COSME)	€600 million	Support innovative firms.	Strengthening the competitiveness and sustainability of EU enterprises, specifically SMEs.	Cross sectoral.
Euratom	€1.6 billion	Direct support to RD&I projects.	Fund research on nuclear safety, radioactive waste management, and fusion energy.	Nuclear energy.
NER 300	€2.1 billion	Direct support to RD&I projects	Support commercial demonstration of carbon capture & storage (CCS)	CCS & renewable energy.

			and renewable energy technologies.	
CEF Transport & Energy	€3.7 billion	Direct support to RD&I projects; Support to diffusion of innovations	Support trans-European networks and infrastructures in the transport and energy sectors.	Various, but explicit attention is given to low-carbon technologies and clean energy.
International Thermonuclear Experimental Reactor (ITER)	€2.9 billion	Direct support to RD&I projects	Demonstrate feasibility of nuclear fusion.	Nuclear fusion.
LIFE	€1.8 billion	Direct support to RD&I projects	Support projects related to the environment, resource efficiency, nature/biodiversity, environmental governance, climate change mitigation & adaptation.	Mostly resource efficiency & nature management, but also climate action-related innovation.
Cohesion Fund	€800 million	Support to diffusion of innovations	Reduce disparities and promote sustainable development in the EU.	Low-carbon energy and transport infrastructures.
European Agricultural Fund for Rural Development (EAFRD)	€1.7 billion	Direct support to RD&I projects	Promote sustainable rural development & sustainable management of natural resources.	Agriculture, food production & forestry.
European Maritime and Fisheries Fund (EMFF)	Not disclosed	Development & introduction of innovative products or techniques.	Support sustainable & competitive fisheries and aquaculture.	Fishery & aquaculture.
Copernicus	€4.3 billion	Support research infrastructure, human capital and policy-making	Monitoring the Earth, using satellites and ground-based monitoring. Data is processed into information services on e.g., atmosphere monitoring.	Most funding goes towards innovation in space technologies.
Galileo	€7 billion	Direct support to RD&I projects	Galileo is a navigation system operating 24 satellites. The project itself can be considered an innovation.	Space/satellite navigation.
Preparatory Action on Defence Research (PADR)	€90 million	Direct support to RD&I projects	Support research, development, and acquisition of military equipment.	Defense equipment.

Asylum, Migration and Integration Fund (AMIF)	Not disclosed	Funds are mostly used to finance the actions of member states, or to finance transnational activities.	Efficient management of migration flows and policies on asylum and integration. Innovation is not a key objective and seems to be marginal.	Migration & integration.
Internal Security Fund (ISF)	Not disclosed	Development of new methods/technologies with a high potential for transferability; diffusion of methods/technologies.	The ISF implements the Internal Security Strategy. Furthermore, the fund promotes cooperation between law enforcement agencies and funds (external) border management.	Security & border management.
European Social Fund (ESF)	€3.6 billion	Direct support to RD&I projects	The goal of the fund is to improve labour market access, education & training, as well as reducing poverty and social exclusion.	Social innovation, in particular social inclusion.
Employment and Social Innovation (EaSI)	€80–100 million	Direct support to RD&I projects	Modernization of social and employment policies; increase job mobility; promote social entrepreneurship.	Social policy, job mobility & social entrepreneurship.
Erasmus+	Not disclosed	Mobility grants; knowledge exchange networks.	Promote cooperation between organizations involved in the areas of education, training and youth; support mobility of individuals in these areas; support policy reform in these areas.	Education, training and youth. Innovation is supported through the sharing of best practices.
Health Programme	€30 million	Support to diffusion of innovations	The goal is to support the health policies of Member States, among others through encouraging innovation in health systems.	Technologies and policy approaches related to health.

About the project

4i-TRACTION – innovation, investment, infrastructure and sector integration:
TRAnsformative policies for a ClimaTe-neutral European UnION

To achieve climate neutrality by 2050, EU policy will have to be reoriented – from incremental towards structural change. As expressed in the European Green Deal, the challenge is to initiate the necessary transformation to climate neutrality in the coming years, while enhancing competitiveness, productivity, employment.

To mobilise the creative, financial and political resources, the EU also needs a governance framework that facilitates cross-sectoral policy integration and that allows citizens, public and private stakeholders to participate in the process and to own the results. The 4i-TRACTION project analyses how this can be done.

Project partners

Ecologic
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University of Eastern Finland
Wageningen University & Research
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