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Assessing the adequacy and impact of research and innovation policy towards a climate neutral economy

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1 Introduction

Climate change is one of the biggest global challenges that certainly calls for governmental action in many respects. In its roadmap for global climate neutrality by 2050, the International Energy Agency (IEA, 2021) emphasises the key role of technologies that are still in the development phase. These are expected to contribute more than 40% to the reduction of CO_2 emissions between 2020 and 2050. As key technologies, the IEA identifies further developments in batteries, electrolysers to produce green hydrogen and the direct extraction of CO_2 from the atmosphere as the most promising fields of innovation and sees measures to promote these and other environmental innovations at the heart of global energy and climate policy.

Other studies calculate the huge investments needed to reach climate and emission reduction targets. Boston Consulting Group (2021) estimates that in Germany alone cumulative 860 billion Euro need to be invested between 2021-2030 to reach the goal of climate neutrality by the year 2045. Krebs and Steitz (2021) estimate that the German public financial sector needs to invest 460 billion Euros between 2021-2030. The German Council of Economic experts calculates for the period till 2045 an investment need of up to 607 billion Euros (Sachverständigenrat, 2023). The EU plans to mobilise 1 trillion Euro from the EU budget and other public and private sources by the year 2030 earmarked for climate-relevant support. The USA Inflation Reduction Act includes 370 billion Euro in particular for a big investment and subsidise programme for the climate protection industry. Demary and Neligan (2018) conclude that worldwide an investment of up to 7 trillion USD annually is required for fulfilling the Paris climate target.

In the context of climate policy, economists strongly argue for (carbon) emission pricing to directly penalise the negative consequences that the emission of CO_2 and other greenhouse gases (GHG) imply through their contribution to global warming (see e.g. Carbon Pricing Leadership Coalition, 2019). There is ample evidence that higher energy prices or directly targeted carbon pricing induces emission or energy-saving innovations (see e.g. Popp, 2002; Teixidó, Verde and Nicolli, 2019; Ren *et al.*, 2022). Yet, there are also valid arguments that call for additional governmental support for Research and Innovation (R&I) activities (Cervantes *et al.*, 2023). Such arguments are diverse positive externalities and other market failures in the innovation process. The most commonly discussed domains are insufficient consideration of reduced environmental degradation, knowledge spill-overs, cost reductions through learning-by-doing or learning-by-using, network effects from the expansion of technology infrastructure from which all market participants can profit, path-dependencies, incomplete information, market entry barriers and incomplete capital markets (see Meißner, Peterson and Semrau (2023) for a review of the literature).

In this context, governments are, or should be, concerned with the adequacy and optimal design of their measures. Related to adequacy the question is what role public R&I support should play in the policy mix and more precisely, in which form, for which technologies and to what degree it is needed. There are certainly cases where other measures, like carbon prices inducing privately funded innovation, would be more successful than government-funded R&I. In this context, the next section summarises key rationales of governmental R&I policy and its role in the climate policy mix. Although, this is not the focus of the paper, it provides the background for assessing governmental R&I measures. One would for example like to know how a certain R&I activity contributes to emission reductions, what other major impacts a certain measure has, the drivers of this impact and how one can maximise it. While it is still relatively simple to assess impacts of a specific technology support on the product or service level – be it lower emission intensities or lower production cost – assessing impacts on the societal level is very complex, and in many cases even not possible. A key source is the complexity of the interaction between R&I funding and other societal and economic processes. Moreover, as common for any innovation process, there is a high level of uncertainty of its outcome, considerable time lags, cumulative causation making attribution difficult and trade-offs between different impact dimensions.

Against this background, we shed light on the complex interactions and key components of an impact assessment and establish a methodological framework to describe and - as far as possible - assess the adequacy and impacts of R&I policy. Given the described complexities such an assessment is in many dimensions at most qualitative and a quantification is often not feasible. The described framework strongly builds on (Miedzinski *et al.*, 2013) and we use the German Federal Climate Change Act (Bundes-Klimaschutzgesetz - KSG[1]) and the Climate Action Programme (Klimaschutzprogramm – KSP) to provide examples and sketch a specific application of the rather broad framework. With this Act, the German government has set binding climate protection targets for Germany. By 2030, greenhouse gas emissions (GHG emissions) are to be reduced by at least 65% compared to 1990 levels. At the same time, research and innovation measures play a decisive role in bringing Germany's transformation onto a target-compliant course.

The paper proceeds as follows. Section 2 addresses the question why, where and when governmental R&I policy is justified. Section 3 discusses the general approach to link governmental R&I to climate change related impacts. In Section 4, we provide a first applied approach on linking F&I indicators with GHG emission indicators to generate an insight into the climate effects generated by public R&I measures.

2 The rationales behind R&I policy

Research and Innovation (R&I) policy supports a very broad range of activities from funding blue-sky, basic or applied research not necessarily only on technologies but also governance, acceptance and more broadly social issues over providing direct and indirect support for technology diffusion or educational programmes to measures to support system changes in relevant areas such as individual mobility.

Within the German Climate Action Programme (Bundesregierung, 2019, 2023), e.g. the German Federal Ministry of Education and Research mostly funds applied research for specific technologies but also several network and consolidation projects, as well as research on social and governance issues to address climate change in its entire breadth. The programme lists 24 different areas and focuses particularly on the energy sector, mobility, and industry policy. It, e.g. supports different technologies along the hydrogen supply chain (solar cell-based electrolysis, transport of hydrogen, hydrogen-based methanol production), several battery related projects, research on synthetic fuels, research on preventing process-based emissions in industry and on carbon capture and storage (CCS).[2] Yet, the programme also supports mobility related projects focusing on urban and spatial planning as well as education projects, related e.g. to vocational education, early childhood development and provides scholarships to young people engaged in climate protection.

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[1] The German KSG (Bundes-Klimaschutzgesetz, engl. Federal Climate Protection Act) was passed in 2019 and aims at ensuring the achievement of national and European climate protection targets. For the first time, this act legally enshrines sectoral targets to be met. The law mandates a reduction in greenhouse gas emissions by at least 65% compared to 1990 levels by 2030 and by at least 88% by 2040. Additionally, it sets the goal of achieving net greenhouse gas neutrality by 2045.

[2] The government established the new German Climate Action Programme 2023 in October 2023. It includes about 130 measures including measures aiming at R&I activities (Expertenrat für Klimafragen, 2023).

In this paper, we focus on technology support, even though the approaches discussed in the next chapters can be transferred, at least partially, to assess other types of governmental R&I support as well. When assessing governmental R&I programs, it is important to clarify the rationales behind the support measures. For technology support the rationales are in particular

- the presence of market and system failures in the R&I process,
- higher political support for green R&I policies compared to other climate polities such as carbon pricing,
- industrial policy targets.

Rational (1): The presence of market and system failures in the R&I process

Related to the first rationale, there is broad agreement that diverse positive externalities and other market failures in the innovation process lead to private underinvestment in such activities compared to the social optimum (e.g. Grossman and Helpman, 1991; Jaffe, Newell and Stavins, 2005; Acemoglu et al., 2012; Aghion et al., 2016; Cervantes et al., 2023). Figure 1 illustrates four different domains of market and system-related failures justifying green R&I support.[3]

Figure 1 Different domains of market and system-related failures justifying green R&I support

Double externality	Dynamic increasing returns	Path dependency	Other market imperfections
• Knowledge creation • Reduced environmental degradation	• Learning by using • Learning by doing • Network externalities	• Market size effect • Price effect • Network effect • Costs of delay	• Uncertainties in investment costs • Financial constraints • Market entry

The creation of environmental innovations (EIs) creates two socially desirable outcomes which are not sufficiently considered in the innovation process of the private sector, known as the double externality problem. First, EIs generate positive knowledge spill-overs since knowledge is non-rival and often non-excludable, the benefits extend beyond the innovating firm (Grossman and Helpman, 1991). Second, EIs contribute to reduced environmental degradation, such as decarbonisation (Rennings, 2000; Jaffe, Newell and Stavins, 2005; Popp, 2006). This market failure, characterised by both knowledge and environmental externalities, justifies policy interventions to encourage green investments.

The second domain relates to dynamic increasing returns in the adoption of EIs. Learning-by-using involves the dissemination of knowledge as adopters showcase a new technology, creating positive externalities by revealing information about its characteristics and success (Jaffe, Newell and Stavins, 2005). Learning-by-doing, on the other hand, focuses on supply-side aspects, with production experience leading to cost reductions, e.g. already observable in the early stages in the take-off of solar photovoltaics (Nemet, 2006). Finally, network externalities amplify technology value with user numbers (Berndt, Pindyck and Azoulay, 2003; Jaffe, Newell and Stavins, 2003). Governments may justify over-proportional subsidies for costlier technologies, anticipating knowledge spill-overs through learning-by-using, long-term cost

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[3] See Meißner, Peterson and Semrau (2023) Section 2 for detailed discussion of justifying factors for governmental green R&I support.

reductions through learning-by-doing or to avoid a path dependency induced by low numbers of users compared to environmentally less friendly but already established technologies (Aghion *et al.*, 2019).

Next, path dependencies in innovation are evident in both clean and dirty production, as demonstrated empirically by Aghion *et al.* (2019) in the automotive sector. Regions and firms specialised in dirty patenting exhibit lower future activities in green patenting, indicating a path dependency in both directions. Market size effects guide innovation toward sectors with larger input markets, while price effects direct innovation towards sectors with higher prices. Both effects favour established dirtier technologies. Aghion *et al.* (2019) discuss network effects as an additional source of path dependency. There is an incentive to deploy innovations that use existing infrastructure, e.g. patrol stations vs. charging stations for electric vehicles. In addition, innovations unfold higher payoffs with complementing technologies, e.g. renewable energies show a higher payoff complemented by storage capacities. Acemoglu *et al.* (2012) emphasise the need for governmental intervention to avoid technological lock-ins in dirty production, as such lock-ins could lead to environmental disasters. An optimal policy comprises a policy mix of market-based instruments, e.g. carbon tax, and governmental R&I support. Delaying the implementation of such a climate policy mix substantially reduces the cost efficiency of climate policy (Acemoglu *et al.*, 2016).

The last domain comprises other market imperfections. Uncertainties surrounding investment costs and the returns to innovation create a disparity between innovators, who possess a more comprehensive understanding of risks and opportunities in new green technologies, and investors, who face incomplete information. Investors, seeking compensation for uncertainty, demand a risk premium, leading to a reduction in socially desirable R&I activities (Jaffe, Newell and Stavins, 2005). Moreover, financial constraints significantly impede R&I investments, especially affecting young and small companies. The lack of access to external funds hampers innovation, with newer companies typically driving radical innovations while older ones focus on incremental changes. Venture capital serves as a crucial mechanism for facilitating risk-taking and unlocking the innovative capacity of these companies (Bond, Harhoff and Van Reenen, 2005; Cervantes *et al.*, 2023). Finally, a lack of business dynamics can hinder innovation activities, e.g. missing market entry opportunities for new, innovative firms (Cervantes *et al.*, 2023).

Recognising the existence of market imperfections hampering EI activities justify that governments step-in to support the take-off of EIs. Missing governmental support can result in less than socially desirable green R&I and system failures impeding creativity, effectiveness and efficiency of R&I systems (Miedzinski *et al.*, 2013). In line with this, there is a broad consensus in the literature that R&I support is part of an optimal climate policy mix. The relevance of policy mix goes back to the Tinbergen (1952) rule, which advocates for a specific policy instrument for each addressed market failure. In a stylised setting for electricity production e.g. Fischer & Newell (2008) show that the optimal governmental policy includes a carbon price, a subsidy for R&I into renewable energy to correct for knowledge spill-overs and a production subsidy for renewable to correct for learning-by-doing effects. Along the same lines, Acemoglu et al. (2012) emphasise that a mix of environmental regulation, such as carbon pricing and R&I support, can redirect technical change to clean technologies and overcome path dependencies. Yet, such findings say little about the level or specifics of needed R&I support. Although market-based approaches should be in the forefront of a cost-efficient policy mix, governments might favour R&I support because of its popularity among voters as discussed next.

Rational (2): Higher political support for green R&I policies

The second rationale relates to the observation that climate policies providing incentives for private related R&I efforts - including especially carbon pricing - might be politically difficult to implement, while R&I support receives more acceptance (Jaffe, Newell and Stavins, 2005; Dechezleprêtre *et al.*, 2022). Yet, there is ample evidence that stringent climate policy is the most important driver of private investment into relevant private R&I (Jaffe, Newell and Stavins, 2005) and thus governmental R&I policy alone will not ensure the necessary level of innovation and diffusion of it. In other words, there is the danger that for acceptance reasons, policy is relying too heavily on such R&I support, while from a societal standpoint, a policy mix with market-based regulations in its centre would have been more effective and efficient. Moreover, assessment of R&I policies is even more difficult since it is not clear if other possibilities for raising private R&I funds are feasible or not. An example where acceptance reasons play a key role is the recent US "Inflation Reduction Act" (IRA), through which the Biden Administration hopes to foster emission reductions in a setting where carbon pricing, still mentioned in the campaign for the presidency (Davenport and Glueck, 2019), is not politically feasible. The name of the policy package also indicates the target of reduced energy prices through R&I. This is most likely relevant for acceptance and political feasibility but also international competitiveness of US firms, pointing to rational (3).

Rational (3): Green industrial policy

More broadly the rational (3) of industrial policy relates to different aspects of fostering the competitiveness, development, and growth of domestic industries. While for some time scepticism about specific industrial policy dominated, it is now again highly on the political agenda. The recent wave of industrial policies is centralised around subsidy policies and is primarily driven by advanced economies. China, the European Union and the United States account for 48% of all industrial policy-related measures. Beyond strategic competitiveness as the dominant motive, other objectives like climate change, resilience and national security are rising (Evenett *et al.*, 2024).

In this paper, we focus on the assessment of R&I with respect to its contribution to climate neutrality, but there are also aspects that overlap with industrial policy targets. This is particularly the issue of carbon leakage: If domestic industries relocate abroad or if domestically produced products are substituted by foreign products with higher carbon content, emissions are partly shifted abroad and not avoided (Copeland and Taylor, 2005). Hence, the result of carbon leakage can be an offset of domestic emission savings and higher worldwide emissions (Aichele and Felbermayr, 2015). In addition, carbon leakage has negative economic consequences for the country undertaking stringent climate policy. A way to reduce or even avoid carbon leakage can be to reduce costs for domestic firms – e.g. lowering domestic input prices, pricing emissions in globally sourced inputs or supporting innovation activities – and thus remain more competitive on world markets. This would call for R&I efforts especially related to industries that face high international competition.

Given that rationale (1) leaves it mostly open what exactly should be supported and how much and given that rationales (2) and (3), though valid, only lead to second best policies or can be criticised for good reasons, it is advisable to not blindly call for R&I support wherever some technological developments play a role but to critically think about the overarching instrument mix in which R&I funding is only one option. Some conclusions from the literature can help in the discussion about when R&I policy should be undertaken and how it should be designed.

For technologies close to the market, deployment support can reduce production costs, e.g. supporting learning-by-doing by implementing feed-in-tariffs or auctions. However, a technology-push induced by public R&I support is crucial for clean technologies which are still in the early stages of development, as this will help to neutralise the base advantage of the older and dirtier installed technologies and helps the clean technologies to "move down the learning-curve". Analysing political support of clean technologies, Cervantes *et al.* (2023) reveal a strong emphasis on deployment policies rather than supporting immature technologies. They show that in the US, Japan and the EU public support for R&I measures related to renewable energies (solar and wind) where only a tiny fraction of support for the deployment of these technologies, e.g. in the EU 458 million USD on public R&I support vs. 78.4 billion USD on deployment in 2018. Comparable arguments also imply that it can make sense to support different technologies to different degrees, even though on the first sight, supporting, e.g. originally more expensive solar energy more than wind energy leads to a higher-cost solution at least in the short term.

Derived from this, scenarios about which technologies have to be used to reach net-zero targets and the development stage of these technologies can indicate where governmental support is most needed. As mentioned in the introduction, the IEA (2021) estimates that especially from 2030 technologies that are only in the development phase and where only demonstration projects and prototypes exist are needed to reach net-zero. It identifies further developed batteries, electrolysers to produce green hydrogen and the direct extraction of CO_2 from the atmosphere as most promising fields of innovation in this respect. The most recent IPCC (2022) report on climate mitigation compares the levels of mitigation costs across technologies which highlights where cost reductions are most relevant. These includes especially many technologies in the energy and industrial sectors (bioelectricity, geothermal energy, CCS, fuel switching in industry to natural gas, electricity, bioenergy or hydrogen, material and energy efficiency). Specific country-studies, such as the so-called "Big-5 Studies" on how Germany can reach its net-zero target for 2050 (see Kopernikus-Projekt Ariadne, 2021) can give further insights into which technologies are most relevant in this context.

It is also clear, that R&I policies interact with all types of other policy instruments. Most prominently, the direct emission effect of an R&I policy is zero if emissions are caped e.g. through a cap-and-trade system. Yet, in this case R&I support reduces the costs of meeting the given target and can make such a policy more acceptable (see Fischer, Hübler and Schenker, 2021; Dechezleprêtre *et al.*, 2022), politically enable stricter targets in the future and also reduce carbon leakage and thus indirectly lead to less global emissions.

3 Linking R&I policy to climate change related impacts

The aim of this section is to set-up an impact assessment (IA) framework that supports the assessment of specific R&I policies with respect to their impact on climate neutrality. The framework heavily draws on (Miedzinski *et al.*, 2013). While it contains some general elements that are both relevant for an ex-ante and an ex-post assessment, the framework is mainly targeted at the former. Put differently, the framework is designed to assess the potential impact of R&I measures on GHG-emission mitigation, mitigation costs and contribution to climate neutrality more generally before they are implemented.

3.1 From inputs to impacts - an evaluation and impact assessment framework

As discussed, a first question in any policy assessment should be, why this instrument is needed in the first place and whether there are, or would have been, better alternatives. Furthermore, it should be assessed whether a specific instrument could be optimised and designed in an even better way. In the following, though, we focus on impacts of R&I policies independent of the question whether these policies are the optimal instrument and whether other instruments would have been better.

Public intervention in R&I then takes place in a broader setting including diverse macroeconomic, sectoral and climate policies but also market forces and further framework conditions that affect the impact of R&I interventions. A common assessment framework to analyse social consequences of a project (see e.g. Taylor and Bradbury-Jones, 2011; Belcher *et al.*, 2019), that is rather similar to the one used for policy assessment in Miedzinski et al. (2013), distinguishes between inputs, activities, outputs, outcomes and impacts that are influenced by these multiple determinants. Complexity increases with each step.

Inputs describe the resources needed to undertake R&I activities including personnel, overheads, infrastructure, machinery, etc. These can typically be monetarised and added up. For example, the research project on the synthetic fuel Namosyn within the German KSP 2030[4] has a volume of 20 Mio. Euros (Dechema, 2023). Or the KlimPro project, which focus on process emissions and their elimination in basic industries, such as steel and iron production, the cement industry or the chemical industry, is supported with 30 Mio. Euro (FONA, 2023).

Inputs are used to undertake activities or actions conducted by the project which can be related to classical technological development but also for a broader set of projects like in the German KSP 2030 activities can include project design, literature review, fieldwork, planned communications and/or engagement with stakeholders, etc. (Belcher *et al.*, 2019). From a different point of view, activities and actions are necessary steps to reach the project goals (McLaughlin and Jordan, 1999).

Outputs are the direct results of R&I activities in the form of for instance patents, publications, knowledge about products and services or more broadly new concepts and processes. They are often described to manifest in the shorter term, but this does not need to be the case. Popp (2016), for example, shows for US governmental R&I support that “USD 1 million in additional government funding leads to one to two additional publications, but with lags as long as ten years between initial funding and publication”. It then takes further time for these publications to be cited in patents. Thus, even outputs can occur only after a significant time lag. Generally, they are intended to lead to results and contribute to intended long-term impacts. Examples could be knowledge about the optimised process to avoid process emissions in the cement industry, the development of a new battery with a longer lifetime and better recycling options, new bio-based products or knowledge about the acceptability of new urban mobility concepts. Outputs are rather controllable since they depend mostly on internal capacity (competence of the research team, access to equipment and good management).

Outcomes are more broadly the result of policy intervention or in our case R&I support contributing to achieving their overall objectives. In line with Taylor & Bradbury-Jones (2011), outcomes describe why the outputs are important and their implications in our case for firms, individuals or society. According to Millar et al. (2001), output is what an activity, programme or policy produces and the outcomes are what it seeks to accomplish. Outcomes are more strongly influenced by external factors than outputs and are, thus, less controllable. Or as Belcher *et al.* (2019) formulate it: “(T)he project cannot control what happens, but it can exert influence in many different ways.” Outcomes (as outputs) are typically classified also as short-term but can, as argued before, be rather long-term. For an innovative product, short-term outcomes could be the customer benefits and intermediate outcomes the result of the use and application of the short-term outcomes (McLaughlin and Jordan, 1999). More specifically, a laboratory prototype for an energy-saving technology could be the short-term outcome, while the intermediate outcome could be the scaling in production. The distinction between outputs and outcomes is not always clear. One could say that only the patent for the prototype

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[4] Differences among the KSP 2030 established in 2019 and KSP 2023 established in 2023 are not considered in this chapter. An insight on the differences is given by Expertenrat für Klimafragen (Expertenrat für Klimafragen, 2023).

would be the output and the prototype based on the patent itself already a short-term outcome, but one could also see the prototype as a direct output of R&I funding. Therefore, it makes sense to group both as in Miedzinski et al. (2013). In the context of the German KSP 2030, the medium-term outcome of supported activities could be that the chemical industry uses new processes with less process emissions, the use of new batteries reduces resource use through recycling, biobased products are gaining market share or new urban mobility concepts are implemented. Furthermore, what e.g. Millar et al. (2001) and McLaughlin & Jones (1999) term long-term outcomes are termed impacts in other approaches like in Miedzinski et al. (2013).

Impacts, finally, are typically defined as long-term changes a policy intervention contributes to or, in the case of new products and services, the following results from the application. Impacts often occur at the level of the economy or society in which policies are just one driving force and they are even less controllable as outcomes. In the framework of Miedzinski et al. (2013), there is a further step to relate socio-economic impacts to the targeted environmental pressures. In our case, this implies deriving how the impacts contribute to climate neutrality. In the example of the new energy-saving prototype, the impact (or long-term outcome) would be a cleaner environment (McLaughlin and Jordan, 1999) and in the case of many measures of the German KSP 2030, lower emissions, lower costs of reaching given emission targets and/or greater acceptance of climate policy. This shows, again, that the contribution to climate neutrality does not always need to be a certain emission reduction and there can be both socio-economic impacts and resulting environmental impacts. Beyond the contribution to climate neutrality, it still makes sense to also assess other environmental pressures to identify potential trade-offs and unintended side effects.

Inputs, activities and direct outputs are commonly closely monitored by funding agencies that require regular reporting and are, thus, also to some degree controllable. This is much less the case for outcomes and impacts. Generally, already outputs but even more so outcomes and impacts of R&I policies depend on many external factors that can support or hinder intended impacts and can also lead to unintended side-effects.[5] They are mostly outside the scope of R&I support and thus not controllable and also uncertain. A framework like the PEST (political, economic, socio-cultural and technological) approach from business analysis to assess external factors as part of strategic management (Aguilar, 1967) can help for a structured assessment of such determinants.[6]

Relevant political factors include the legal system, diverse standards and norms, the roles for intellectual property rights, fiscal policies, but most of all, the existing climate policy framework that sets incentives for the diffusion of new technologies and practices. The climate policy framework determines whether such diffusion will mainly lead to cost savings at the national level (if a cap-and-trade system is present) or can also lead to overall emission reductions. Related to this, there is ample literature on the interplay of R&I policy and other types of policies. Fischer et al.(2017) and Gerlagh et al. (2009) e.g. analyse this interplay theoretically and stress the role of carbon pricing. Gerlagh et al. (2009) finds that R&I support should focus on sectors with little carbon pricing. Popp (2019) summarise the empirical research examining links between environmental policy and environmentally friendly innovation. Examples are the

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[5] The stated result is frequently initiated by rebound effects. Research in the automotive sector has reduced emission per HP in cars by 50% in the period 1990 – 2019. However, at the same period the average HP per car doubled.

[6] Others, like Miedzinski et al (2013) add "environment" as a further component and talk of a "STEEP framework" (Social, Technological, Economic, Environmental, Political). Yet, their examples for environmental determinants like access to material or natural resources can also be subsumed under economic determinants.

regulations by the ReFuelEU Aviation law that generate a strong incentive for research in synthetic fuels for airplanes.

Economic factors such as demand for certain goods and services, competition framework, resource costs, access to capital, etc. also determine e.g. the diffusion of a new technology or product. Howell (2017) e.g. finds that support for start-ups is more effective for more financially constraint firms.

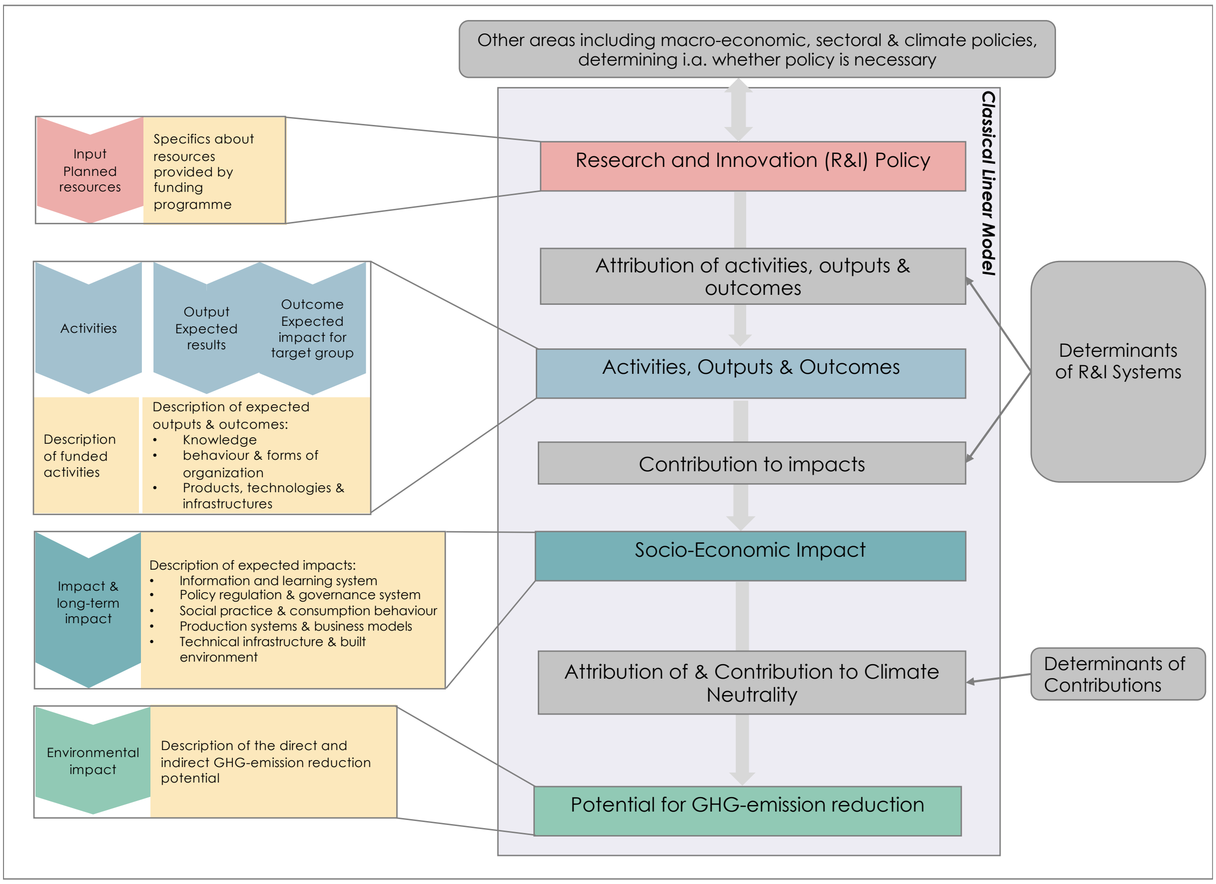
Social-cultural factors e.g. determine the impact of educational projects or the degree to change behaviour towards e.g. less carbon intensive mobility.

Technical and technological determinants include the quality of technical infrastructure. The literature also shows that the success of an R&I support depends on the stage of the supported technology. The IPCC (2022) discuss that issue in detail.

A so-called Impact Assessment (IA) approach puts all these components together. It starts from a certain R&I policy measure and attributes, in the first step, activities, outputs and outcomes, taking other policy areas and the determinants of the R&I system into account. The next step is to identify the type of impacts and contribution to the targeted variables – in our case climate neutrality – taking again relevant determinants into account. In some cases, it might also be possible to quantify impacts to some degrees but given the described complex interactions this is very difficult. This is intuitively clear for R&I measures such as educational programmes or mobility concepts, where it is not clear to which degree they are adopted. But also for some very relevant technologies like batteries or hydrogen the impacts are highly unclear, since the first technology is part of a net-zero electricity system, but does not save emissions directly and the latter can be used in several different sectors and applications each within a different setting and environment.

Figure 2 summarises this IA framework. The left part of this figure structures the evolution of the effects in levels, building upon each other and indicating possible diffusion pathways of R&I policy induced outputs. These diffusion pathways are often operationalised through linear models (also called ‘logical models’), which focus on outcome-oriented impacts. They intend to build causal relationships between funding program (inputs), research activities (process), and impacts (outputs). Traditionally, these models focus on so called “paybacks”, aiming to identify where the funding line materialised into measurable outcomes (Donovan and Hanney, 2011). In the context of our impact assessment, this framework can be adapted towards environmental impacts. Furthermore, in line with Miedzinski et al (2013) the relevant determinants of the activities, output, outcomes, and impacts need to be added to the linear model.

Figure 2 Model to assess governmental R&I support towards climate neutrality



3.2 Classifying outcomes and impacts of R&I Policy towards climate neutrality

To assess the impacts of R&I Policy towards climate neutrality, it is helpful to further classify outcomes and socio-economic impacts as well as contributions to climate neutrality.

To group outcomes we follow the Oslo Manual 2018 for recording innovations (OECD and Eurostat, 2018). In addition to product innovation, business process innovation, which includes process, marketing, and organisational innovation, is also relevant. We divide business process innovation into knowledge-based and behaviour-based innovations. This distinction is not necessarily trivial, outputs can sometimes be associated with different outcomes. Nevertheless, it is helpful to differentiate which modes of action are represented by an overall portfolio of R&I measures and to define their innovation and output characteristics are:

- Type 1: New or modified <u>knowledge (competencies)</u>, which can be either applied or theoretical, codified and transferable or tacit and have medium-term effects on the level of knowledge, the knowledge structure, and the knowledge management of the R&I sector.
- Type 2: <u>Behaviour, organisation, and intangible infrastructure.</u> These outputs have medium-term effects on social, economic and political behaviour and on organisations, their structure and working methods as well as on intangible infrastructure (e.g. financial infrastructure, information, networking).
- Type 3: New or modified <u>products, technologies, or physical infrastructures</u> where outcomes can include testing new prototypes, enhancing market readiness or diffusion. These outputs have medium-term effects on products (e.g. the (further) development of a product), technologies (e.g. scaled market launch of new technologies) and physical infrastructure.

The projects within the KSP 2030 address typically type 1 outcomes plus either type 2 or type 3 outcomes but sometimes also a mixture of all three types.

Following Miedzinski et al. (2013) we then group socio-economic impacts into five categories. The first category "Information and learning system" is a rather vague concept of changes in the system in which the interplay of public and private actors generates new knowledge. The impact indicators are based on the following:

- Information and learning system: Interdisciplinary research programmes and educational initiatives that focus on understanding and raising awareness of climate change and its impact on emissions. Such programmes could include, for example, the analysis of emission trends, research into the impact of different emission sources and the development of emission reduction strategies. These educational and research endeavours will raise general awareness of the urgency of reducing emissions and create a sound knowledge of the links between human activity and climate change.
- Policy regulation, and governance system: R&I support can influence public strategies, regulations and policies related to climate neutrality. This is especially likely for funding for socio-economic research. As part of the KSP, the ARIADNE project (https://ariadneprojekt.de/) for example directly addresses political frameworks and instruments. Modified or new policies will in turn influence the pathway to climate neutrality in manifold ways.
- Social practice and consumption behaviour: This relates to impacts on individual and social practice and consumption patterns in society (Miedzinski *et al.*, 2013). In our context, examples are that new products can change consumption patterns or new urban mobility concepts can change mobility practice.
- Production system and business models: Impacts in this category can be the diffusion of new low- or zero-carbon technologies, products and services and the degree to which they substitute existing services or product-services systems (e.g. in the mobility or heating sector).
- Technical infrastructures and built environment. This area is introduced since infrastructures and the built environment and the energy use and carbon footprints are very relevant for carbon neutrality, e.g. in the electricity, mobility, building and heating sector. Also related to e.g. negative emission technologies infrastructure is important.

The outcomes and socio-economic impacts then result in impacts on climate neutrality can be on very different levels and related to different types of contributions. The most natural contribution are emission reductions – be it the reduction of direct emissions or embodied emissions to account for full carbon footprints. Emissions can be affected at the product and service level, at the level of consumers, households, or single institutions, at the level of whole industries or sectors, at the level of a country, or even at the global level, which is the level that finally matters for climate change. Another second relevant contribution are reduced costs at the different levels (products, services, households and so on). Costs are driving the use of different technologies and in systems with fixed emissions (such as an emissions trading system), R&I will not affect emissions at the national or sectoral level but reduce the costs of reaching the target levels. Costs also relate to acceptance and burdens for households where lower costs of low-carbon products/ services, or the reduced carbon footprint of products/ services lowers the costs of carbon taxes. On the industry level costs determines competitiveness of low-carbon products but also the danger of carbon leakage leading to less emissions savings on the global level.

Further contributions are less easy to define but relate more broadly to network and system effects. For example, the effects of both green hydrogen and batteries can only be assessed at the system level. This makes a detailed impact assessment in terms of emission and cost impacts very difficult (see section 3.4.) but certainly constitutes a contribution to climate neutrality.

Furthermore, it should be accounted for at which level impacts occur. Most of the impacts within the causal chain pictured in Figure 2 take place at the micro and meso-level, i.e. at the product and service level, at the consumer, household, and organisational level, or at the level of industries. Thus, the impact model takes account of changes that occur at a small scale technological, process or social practice level and transform into higher level impacts once their effects on the different sectors is accounted for.

Table 1 summarises the main contributions of R&I on climate neutrality, where we group the impacts following Miedzinski et al. (2013) into micro-, meso- and macro-level.

Table 1 Main R&I contributions to climate neutrality

	Micro-Level		**Meso-Level**	**Macro-Level**	
	Products/ Services	**Consumers/ HH/ Organisations**	**Industries/ sectors**	**Countries/ regions**	**Supernational/ Global**
Direct / Embodied **Emissions**	Direct / Embodied GHG emissions per unit of good or service	Direct GHG emissions / GHG footprint per household	Direct GHG emissions / GHG footprint per unit of output and overall, by industry/ sector	National territorial GHG emissions / GHG footprints	Global Emissions
Cost-Reductions	Production cost per unit of output of cleaner technology	Cost per household, …. for specific services/ products	Competitiveness of industry	Reduced cost to achieve given emission reduction/ target Reduced carbon leakage	Reduced costs to reach given emission reductions
Network / System effects	Contributions to a net zero economy on different level, only indirectly reducing emissions or (system) costs, including both tangible and intangible contributions.				

The mentioned PEST-framework can then help to structure also the determinants of contributions. Yet, these are highly case and technology specific. For instance, in the energy sector the evaluator should consider the CO_2 intensity of the electricity mix. Many low-emission technologies and processes that emerge from R&I policies rely to a certain degree on the input of electricity. However, if the grid's electricity is produced carbon intensively, the emission reduction potential of the new technologies and processes might be at stake. Also, the development of the energy infrastructure is decisive for the emission and costs impact of the outputs of R&I policies. In the absence of a sufficient energy infrastructure, the supply of the new technology, process, or product might be insufficient and will therefore not be established on the market. In the industry sector impacts of R&I policies might depend on carbon leakage. Industries with low fixed costs of production might shift their production to non-EU countries instead of conducting abatement measures like adopting low-carbon alternatives that might evolve from the R&I policies. Energy prices matter as well. With low energy prices, the industries are less prone to switch to technological alternatives emerging through R&I. Besides those sector specific determinants, many there are many cross-sectoral factors, such as again the EU ETS coverage and certificate price or the cross-price elasticity between fossil-based and equivalent low-emission products that becomes relevant for the adoption when R&I policies reduces the prices of low-emission technologies and products.

The categories and lists of determinants and influencing factors can help to establish a customised impact assessment for a given R&I policy or funding program which provides certain inputs to undertake activities.

Since this is of special importance, we next want to provide a short review of existing work related to the impact of R&I measures on greenhouse gas (GHG) emissions. And while an indicator system to categorise the climate policy impact of future R&I measures does not exist to date, this work contributes to develop our indicator system in Chapter 4.

3.3 Status quo of indictors for the relation between R&I measures and GHG emissions

Theoretical and empirical considerations on the connection between R&I and GHG emission indicators are made from different perspectives. Fundamental work on the relationship is based on the model of an environmental Kuznets curve. The original Kuznets curve states that the inequality of income distribution first increases with rising per capita income before it eventually decreases again (Kuznets, 1955). Decades later it was found that also pollution increases with rising per capita income and declines above a certain level of prosperity (Grossman and Krueger, 1991). This led to the hypothesis that the increase in research-induced innovations, at least in OECD countries, leads to declining GHG emissions from a certain level of per capita income growth (Leal and Marques, 2022). Relevant indicators used here were the changes in gross domestic product and the pollution levels measured in pollution values of the pollution object (Thompson, 2014).

While the indicators based on Kuznets' hypothesis are certainly empirically relevant for locally anchored environmental damage, such as water pollution, they have long been highly controversial for non-local environmental damage such as GHG emissions. Even if numerous macroeconomic ex-post studies support the hypothesis of a positive influence of growing income on lower GHG emissions (Awaworyi Churchill *et al.*, 2019), the results of these ex-post studies depend to a large extent on the assumptions made in the modelling. More critical studies on Kuznets' impact model tend to assume an N-shaped relationship between per capita income and GHG emissions, which calculates a renewed increase in GHG emissions for rising per capita incomes above a certain income level (Levinson, 2002).

Ex-post studies analysing the regional correlations between R&I and GHG emission reductions come to similar critical conclusions. These studies show that the relationship between R&I and GHG emissions is not clear. For some R&I activities, decreasing GHG emissions are identified, for others increasing emissions occur (Li and Wang, 2017).

The ex-ante relationship between economic policy measures and GHG emission reductions has been the subject of intense debate in climate policy discussions for several years (Schlomann et al., 2022). In these approaches, indicator systems are developed that analyse the impact of economic policy measures that are close to their application, as is done, for example, in the projection reports of climate reporting (Harthan and Förster, 2023). The indicators used here aim to determine the impact of economic policy measures on GHG emissions by modelling changes in primary or final energy consumption or in costs. The modelling is often carried out with the aid of **life cycle analysis (LCA) models**, which attempt to determine the impact of R&I on the technology paths of the applications under consideration (NPM, 2021). The LCA models are used to identify technological and innovative development trends within the considered pathways that lead to GHG emission reductions. Restrictive assumptions about the effects of the R&I measures are made in all of these models so that the future event space becomes manageable. It should be emphasised that LCA models have proven their worth for tangible applications initiated by research and innovation policy. For example, in the projection reports on climate reporting, which are essentially based on "total cost of ownership" models (Moawad et al., 2023), analyses based on LCA models are carried out in the analysis of GHG emission reduction pathways in order to determine parameters for technical and innovative developments and their future influences on GHG emission trends. Yet, the LCA methodology sometimes is also more critically discussed (IPCC, 2022).

Especially in the context of intangible innovations and in systemic analyses that include scale, spill-over or rebound effects, the possibilities of LCA models are limited. These studies do not provide a more intensive analysis of the relationship between R&I measures and GHG emission changes (Rüter, 2023).

Such approaches are more likely to be found in innovation policy studies that deal with ex-ante evaluations of technology and innovation policy programmes. Initial work in this direction has been undertaken in Austria, for example, for tangible applications (Gallauner, Ibesich and Kampel, 2014). Working Group 3 of the IPCC has also addressed this issue (IPCC, 2022). IPCC has started to create an initial systematisation of the relationship between R&I systems and GHG emission trends. This is based on an indicator model with the following indicators: Knowledge Development, Knowledge Diffusion, Guidance of Search, Resource mobilisation, Entrepreneurial Activities, Market Formation, Creation of Legitimacy.[7] However, the IPCC does not carry out any ex-ante modelling of the impact of R&I measures, particularly intangible ones, on GHG emissions. Rather, the IPCC also refers to the methodological challenges of an ex-ante assessment of the relationship between R&I measures and GHG emissions.

3.4 Limits of an impact assessment

Before we develop an exemplary more detailed impact assessment in the context of the German KSP 2030 we want to briefly summarize the limitations of any impact assessment which we have touched upon already at different points. Identified limitations of the R&I impact on GHG emission mitigation and more generally climate neutrality results mainly from following effects:

1. **Indirect impacts** of R&I activities that make a linear allocation and thus quantification of GHG emission mitigation impossible.
2. **Technological interrelatedness** and **rebound effects**.
3. **Timeline** spreads between R&I activities and resulting impacts.

R&I processes frequently show nonlinear or even probabilistic as well as unintended attitudes as result of **indirect impacts**. That generates a lack in identifying links as presumed in the linear assessment model. When looking at Figure 2, under that assumption an assessment gets more difficult when moving from one component of the linear assessment model to the next. Inputs and activities are usually well-known and e.g. part of project applications and project reports. Already outputs but even more so outcomes and impacts of R&I policies depend on diverse and very individual external factors (the determinants in Figure 2) that influence intended impacts in manifold ways and can also lead to the mentioned unintended side-effects. They are mostly outside the scope of R&I support and thus not controllable. Furthermore, they are also often highly uncertain. Any assessment of these determinants and their consequences needs to be tailored for the R&I measure in question and will still remain limited. Accordingly, also the potential to quantify GHG emission potentials of R&I projects and measures is limited. The challenge of validating the impact of measures on emissions is most obvious in the analysis of the KSP 2023 impact assessment. As discussed by the Expertenrat für Klimafragen (2023) a clear qualitative or quantitative impact on GHG-emissions is not feasible for a majority of the

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[7] , Table 16.7.

measures listed in the programme. In particular, R&I measures that aim at intangible activities belong to that group of measures.

Beside indirect impacts **technological interrelatedness** as well as **rebound effects** limit the validity of quantified GHG emission effects but also more general impacts on climate neutrality. Mitigation contributions are less easy to define but relate more broadly to network and system effects. In section 3.1. we have already briefly mentioned that hydrogen is part of a net-zero economy but can be used in several different sectors and applications where the impact of hydrogen on a net-zero economy is interrelated with other technologies, so that the impact of e.g., improved solar cell-based electrolysis depends on where the produced green hydrogen is finally used and requires a system-level analysis. Similarly, the development of batteries is decisive for an energy system based on renewables, and the emission and cost effects of batteries can again only be assessed at the system level. Even for a project like green steel production where it is possible to calculate the emission reductions per tonne of steel compared to an old technology (following e.g. the guidelines of the EU for projects funded under the Innovation Fund (European Commission, 2021). it is not clear how much emissions are ultimately saved, since the amount of produced steel is not fixed and depends on the competitiveness of the green steel production in the longer run and available substitutes. An "optimal" net zero scenario might for example include a stronger use of wood in the building sector, lighter cars and overall, less steel production than today, so that emission savings would be overestimated when simply calculating the difference in emissions per ton of steel and multiplying it by today's steel production.

System effects also become relevant for intangible outcomes like better mobility concepts or increased knowledge about climate change in the society. As already indicated with these examples, the policy framework will strongly influence how product/ service level impacts translate into household, industry, sectoral, national, and global impacts. Furthermore, other determinants are also gaining importance when moving to the next level. In our example of green steel, emissions in steel industry might still go up because output increases (called rebound effect), or emissions at the EU level stay unchanged because steel industry is part of EU emission trading system with fixed cap. As another example, more efficient batteries provide downward pressure on electricity price, but overall electricity prices go up because of more demand from other sectors (e.g., e-mobility or heating). Beside those effects based on technological interrelatedness rebound effects limit the mitigation effects. As an example, the German automobile industry managed to cut emission per HP by 50% from 1990 to 2019 but at the same time the average HP per car more than doubled. Accordingly rebound effects lead to higher GHG emission than in the pre-innovation stage.

Frequently the **timeline** for R&I projects regarding GHG emission mitigation is not consistent. The research on the fusion reactor ITER illustrates the problem. Even so establishing nuclear fusion on earth will strongly enhance the production of renewable electrical current, the expected time of the introduction of nuclear fusion as a commodity has changed regularly and it is still not clear when and if at all this technology will be applicable on larger scale. Accordingly, the point in time as well as the GHG emission mitigation provided is not quantifiable. The impact of R&I supports thus very much depends on the progress of research in nuclear fusion. However, since the GHG emission mitigation concept is based on a budget approach where the realised emissions at a certain point of time (n) in the future is less of interest than cumulated GHG emissions from today to point (n) in the future.

Given the discussed complexities an impact assessment of R& I fundings on GHG emission mitigation but also more general impacts on climate neutrality is often quantitatively not feasible.

However, in opposite to quantitative assessments a qualitative validation of impacts is often still realisable. Qualitative assessments allow qualified validations by experts who are able to e.g., qualify impacts of R&I activities on GHG emission mitigation. Those validations might be able to develop a range of impacts of R&I projects on GHG mitigation. In opposite to a quantitative impact assessment the results do not show the amount of reduced emissions but a more vague assessment of mitigation ranges and potential. Because of the difficulties with quantitative indicators, we propose a system of qualitative indicators that establish a qualitative assessment of R&I support. This approach is illustrated in the following chapter.

4 Deriving ex-ante indicators for the qualitative assessment of the climate policy impact of R&I by funding institutions

Based on the impact assessment model developed in the previous chapter, we now present a concept that allows a qualitative ex-ante indicator model of the climate policy impact of future R&I measures. With the help of such an indicator system, it will be possible to anticipate the climate policy relevance of political R&I measures.

4.1 Methodological approach

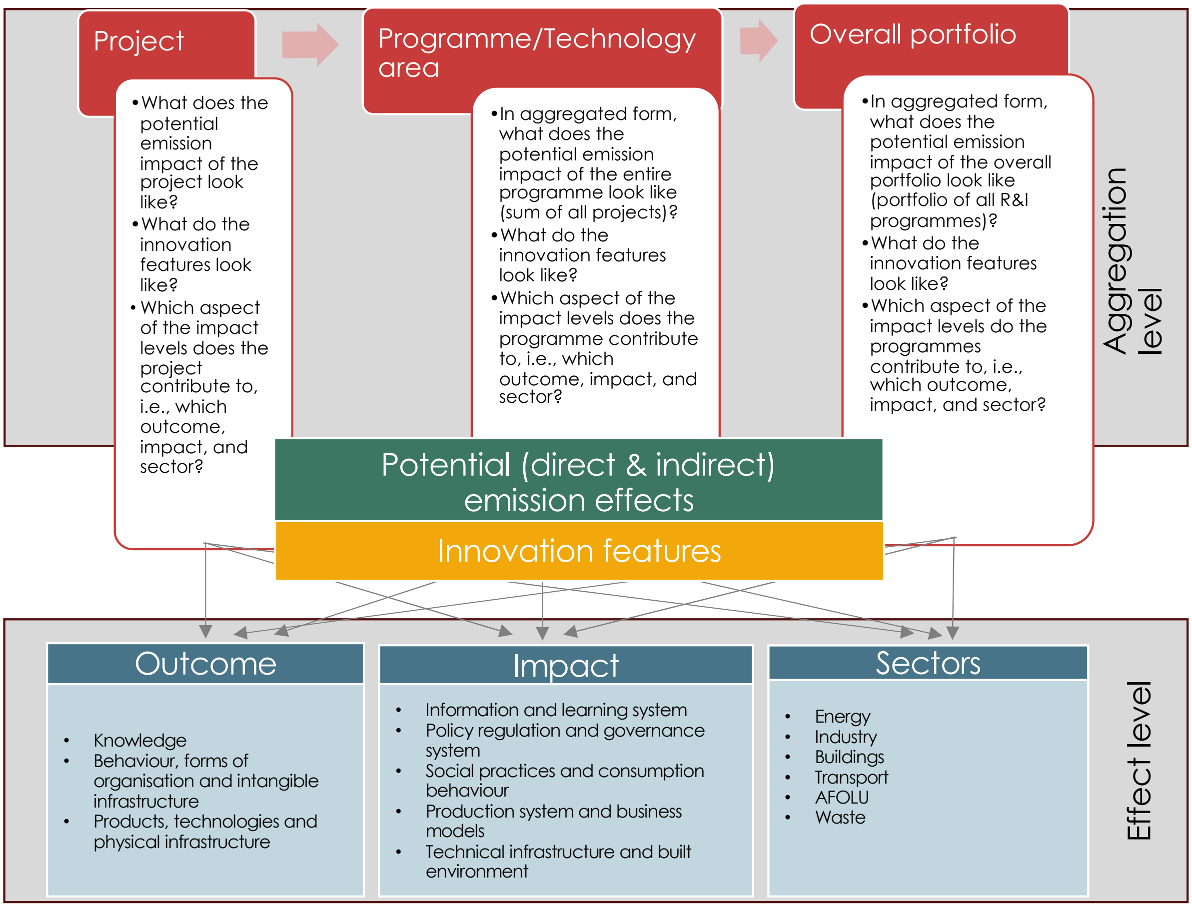
The literature review in Section 3.3 has made clear that at present, a qualitative or even quantitative ex-ante evaluation of the climate impact of specific R&I measures not to speak of an overall portfolio of such measures targeted at funding institutions such as the German Federal Ministry of Education and Research does not exist. On the one hand, as discussed above, developments in the field of R&I are uncertain due to their novelty value and therefore climate-relevant effects are difficult to predict. On the other hand, the effects of successful R&I measures are usually too complex in their interactive and indirect impact chains to reliably predict their influence on GHG development. A qualitative or quantitative ex-ante evaluation of the climate policy effects of R&I measures has therefore not yet been developed in a scientifically sound or practically usable way.

In order to solve this problem of not being able to assess the impact of R&I measures on GHG emissions directly, we propose a bottom-up approach based on data from the initial phase of R&I measures. Although this does not allow the ex-ante evaluation of an R&I measure itself to be realised prior to its establishment, at least the data set can be collected at the start of the first project proposals, which enables a statement to be made on the GHG emission effects. It should be emphasised here that – as Section 3.4 has discussed - a quantitative assessment of the effect of an R&I measure on GHG emissions is not possible.

The proposed ex-ante indicator system is therefore aimed at a **robust but purely qualitative orientation** of the impact of the R&I measure. As part of a bottom-up approach, the first step is to collect information from the funded projects at the application stage. In the second step, this information can be aggregated across all funding projects of an R&I measure. In a third step, the qualitative GHG emission effects of R&I measures can be aggregated across individual areas so that, for example, the effect of the R&I measures located in one area on the GHG emission values can be qualitatively estimated. As discussed, a quantitative link between outcomes of R&I measures and GHG-emission reduction is not feasible. However, based on the data provided by the bottom-up selection can be qualified into categories of impact on GHG emission.

Figure 3 illustrates how the collected data can be used. The innovation and GHG emission-saving potentials are broken down, presented, and aggregated according to projects, programmes, and the overall portfolio. Considering three different impact levels allows to analyse the potential of the projects, programmes and the overall portfolio of a classic evaluation approach, which runs through the input-output-outcome-impact stage sequence in Figure 2 and, due to the assignability, sectors (which are in our examples below the sectors of the German Klimaschutzgesetz – KSG). This enables, for example, an assessment of the emission and innovation potential of the programmes for an individual sector or for a specific impact category.

Figure 3 Ex-ante indicator system



This structured and comprehensive assessment enables a systematic and explicitly categorised understanding of the potential effects of climate-relevant R&I measures on GHG emission reductions and potentially also other impacts related to net-zero. This understanding, in turn, can have a positive impact on the decision-making ability and adaptive flexibility of a resort and its project sponsors. In the long term, it may thus be possible to align the resort's R&I policy more effectively not only with R&I-specific challenges but also with climate policy challenges by using more climate-sensitive measures.

4.2 Empirical implementation of the model

For the empirical application of these indicators, which are based on a bottom-up approach, funding agencies can ask applicants for funding to provide condensed information on targeted questions as part of e.g., a short digital questionnaire. The collected information can then be flexibly aggregated to show, for example, the innovation and GHG emission reduction potential of R&I measures overall and at individual impact levels. Our approach aims to provide graphs, that are easily interpretable, while these are to be created automatically by a tool which uses the data gathered by the applicants' responses. Thus, no major effort is needed from the provider of the R&I programmes. In the following we continue to use examples from the German Climate Action Programme (2030).

4.2.1 What are the benefits and use of ex-ante indicators?

The advantage of an indicator system that establishes the link between R&I indicators and GHG emission indicators is available at both the political and the governance levels. At the political level, it helps a ministry to estimate the impact of funded projects on GHG emissions - both for individual projects and aggregated at the level of individual measures, groups of measures and an entire ministry. Overall, the indicator system helps to increase climate policy awareness in a ministry, the orientation of funding policy towards GHG emission reduction potentials and the analysis of the climate policy orientation of individual funding areas.

At the governance level, such an indicator system helps with fine-tuning both within a funding measure as well as across funding measures to carry out climate policy monitoring in the accompanying analysis of the impact of funding measures. This is particularly important for funding measures that focus directly on achieving climate policy goals.

Finally, the indicator system helps the applicants for funding to reflect on the impact of their activities on GHG emission targets and, if necessary, to focus on a more climate-sensitive task.

4.2.2 What Is collected?

The indicator system aims at indicators from both the R&I-system and the GHG-emission section. The indicators thereby cover the innovation chain while also providing an insight into the potential GHG emission reduction potential. Accordingly, the system starts with a specific input information that specifies the following:

Under which R&I programme is the project being applied for?

The information ensures that all future projects in a programme can be collected and aggregated.

Indicator categories

In our categorisation of impacts we follow the framework in Section 3.1.

Output

Definition: Outputs are the direct, measurable results of project activities. Several outputs can be assigned to a project. These are collected to record the specific results of a project in a differentiated manner so that more precise statements can be made about their impact. **Example:** Development of a constantly updated, interactive map showing the value chains of green hydrogen and the stock of all German Power-to-X plants.

Characterisation of the variable

As the outputs can have very different characteristics, it does not seem useful to categorise them here. Instead, a free text field is provided to briefly describe the expected output. This information can therefore not be included in aggregated form in the creation of the graphs, as shown in **Error! Reference source not found.** but provides an insight into which specific outputs can be expected at the individual project level.

Significance of the determined value

No value is determined here and therefore the output can only be assessed qualitatively.

Outcomes of the R&I policy

Definition: Outcomes refer to the medium-term effects triggered by the outputs of the project.

These outcomes relate to three dimensions. These are recorded to understand the general mode of action of the project, i.e., the leverage of the R&I measure. For example, is the project primarily knowledge-based (e.g., education programme) or does it focus on a technology (e.g.

research into new batteries)? As described in Section 3.1. we differentiate between three types.

- **Knowledge (competencies)**: The outputs of the programme have medium-term effects on the level of knowledge, the knowledge structure, and the knowledge management of the R&I sector.

  Example: Development of an updated, interactive map showing the value chains of green hydrogen and the inventory of all German Power-to-X plants has an impact on the knowledge structure and thus on the way this knowledge is handled.
- **Behaviour, organisation, and intangible infrastructure**: The outputs of the programme have medium-term effects on social, economic, and political behaviour and on organisations, their structure and working methods as well as on intangible infrastructure (e.g., financial infrastructure, information, networking).

  Example: The development and implementation of a new concept for energy management in companies. This could include a system that monitors and optimises energy consumption and thereby reduces emissions.
- **Product, technology & physical infrastructure**: The outputs of the programme have medium-term effects on products (e.g., the (further) development of a product), technologies (e.g., scaled market launch of new technologies) and physical infrastructure.

  Example: The development of a new generation of solar cells that are more efficient, cost-effective, and environmentally friendly than current models.

Characterisation of the variable

Applicants can select among the three categories described above if the outcome is expected for the respective project. It is possible to select more than one category. This allows aggregating the outcomes at the programme level/technology area or regarding the overall portfolio (cf. Figure 3).

Significance of the determined value

As with the outcomes, no quantifiable value is determined at this stage.

Socio-economic impacts of R&I policy

Definition: Impact refers to the long-term changes or final effects that are partly caused by the outcomes and can also go beyond the original scope of the programme (e.g., positive external effects, economies of scope). These are classified as belonging to one of the five categories described in Section 3.2. to analyse which aspect of the project contributes to which of its potential outcomes.

- **Information and learning system**: Interdisciplinary research programmes and educational initiatives that focus on understanding and raising awareness of climate change and its impact on emissions. Such programmes could include, for example, the analysis of emission trends, research into the impact of different emission sources and the development of emission reduction strategies. These educational and research endeavours will raise general awareness of the urgency of reducing emissions and create a sound knowledge of the links between human activity and climate change.

- **Policy regulation, and governance system**: Legislation to reduce CO_2 emissions in industry and transport, such as emissions trading systems or stricter emission limits for motor vehicles. These political measures steer innovation and research in the direction of low-emission technologies and drives.
- **Social practices and consumption behaviour**: R&I-driven initiatives to promote public transport and reduce individual car use, leading to a reduction in (urban) emissions. R&I-based findings on how people can be encouraged to adopt more sustainable behaviour can also contribute to optimised awareness raising for sustainable consumption and also to a reduction in the individual CO_2 footprint.
- **Production system and business models**: Development and use of low-emission production processes, such as the use of renewable energies in production or the implementation of circular economy models that increase resource efficiency and reduce emissions or initiate business start-ups.
- **Technical Infrastructure and built environment**: Research and development in the green building industry, including energy-efficient building technologies and environmentally friendly building materials. Such innovations can lead to a significant reduction of emissions in the construction sector by minimising the energy consumption of buildings and promoting sustainable construction practices.

Characterisation of the variable: As with the outcomes, it is also possible to select several categories if impacts are expected in more than one category. This information can again be used to aggregate at the programme level/technology area or overall portfolio (cf. Figure 3).

Significance of the determined value: As with the outcomes, no quantifiable value is determined here either.

Target sectors: Which sectors of the funding program, in our example, the KSG does the project target? Energy, industry, buildings, transport, AFOLU (agriculture, forestry and other land use) and waste management. This serves to aggregate the projects at the sector level and ultimately allows to create the outputs, that is to aggregate potential impacts of various projects on certain sectors. It is also possible to select several sectors if a new technology promises impacts in more than just one sector.

Validation of the R&I and emission indicators

Degree of Innovation

The effect of an R&I measure on GHG emissions or costs savings largely depend on its degree of innovation. For example, a product that is widely applicable and already demonstrably functional under real conditions can develop its emission- or cost-reducing effect more easily in the medium term than a product that only works under laboratory conditions. The degree of innovation of the R&I measure is therefore offset against the potential emission effect to obtain a more realistic estimate of the actual effect.

- **Innovation leap**: 1 = minor portfolio optimisation, 2 = major portfolio optimisation, 3 = substantial product development, 4 = new development.
- **Applicability**: 1 = niche, 2 = small application in some sectors, 3 = broad application in some sectors, 4 = broad application in (almost) all sectors.
- **Application status** (Technology Readiness Level, TRL): 1 = Proof of the functionality of a technology (TRL = 1-3), 2 = Test setup in the laboratory or in the application environment (TRL = 4-5), 3 = Prototype in use (TRL = 6-7), 4 = Qualified system with proof (TRL = 8-9).

- **Impact on framework conditions and non-technical (intangible) infrastructure:** 1 = low, which is defined as hardly any impact on a specific product, process or business model innovation, 2 = moderate, which is defined as an impact on generic attributes of the innovation process as f.i. clusters, 3 = high, which is defined as a strong impact on the innovation process itself as establishment of specific actions like green finance schemes, 4 = very high which is defined as a fundamental impact on the generation of an innovation as f.i. financing patent enrolments.

Contribution to reducing emissions

The indicator "GHG-Emission reduction potential" analyses the impact of the measure/project on GHG mitigation. As discussed above (Chapter 3.3) there is no simple link between the socio-economic impact of a R&I-project and its impact on emission mitigation. In addition, the time perspective of the impact is of importance. It makes a difference if the emission indicator targets a period up to 2030 or up to 2100. For our example of the Climate Action Programme 2030 of the German Federal Government, GHG-emission reduction potentials in the short term are differently handled than those to be expected in the long term. Accordingly, short-term GHG-emission reduction potentials have to be validated higher in the indicator model than long-term potentials. By validating the time perspective, the indicator helps to qualify the impact on the budget-based climate track agreed on in the Paris Agreement.

The indicators reflect two distinct effects of R&I measures on GHG emissions. On the one hand, R&I measures are expected to have **direct GHG emission reduction potentials**. By this, we mean measures that are aimed at targeted tangible technological processes, such as the optimisation of production of batteries or fuel cells. The stronger the objective of the measure/project aims at shaping the GHG emission reduction potential the stronger the expected impact value is.

On the other hand, **indirect GHG emission reduction potentials** must be recorded by the indicators. This includes funding measures that aim, for example, at improved R&I infrastructure (e.g., establishment of clusters, financial instruments), the formation of an overarching competence structure, or cost optimisation of products or processes. The more indirect GHG emission reduction actions are targeted by the measure the higher the indicator is valued.

We therefore propose to cluster the GHG-emission impact based on the following concept shown in Table 2.

Table 2 Proposal for an Indicator Typology for GHG-Emission Impact

	Direct Emission Reduction Potential		**Indirect Emission Reduction Potential**	**Time Perspective**
Definition	Project/programme targets aim at systematic emission reduction	Scope[8] of expected GHG emission reduction potential	Project/programme targets on emission reduction by: a. Improved infrastructure (Financing, cluster etc.) b. Generic competence building c. Cost optimisation in production or processes	Time perspective validates the time span till the emission reduction might be established

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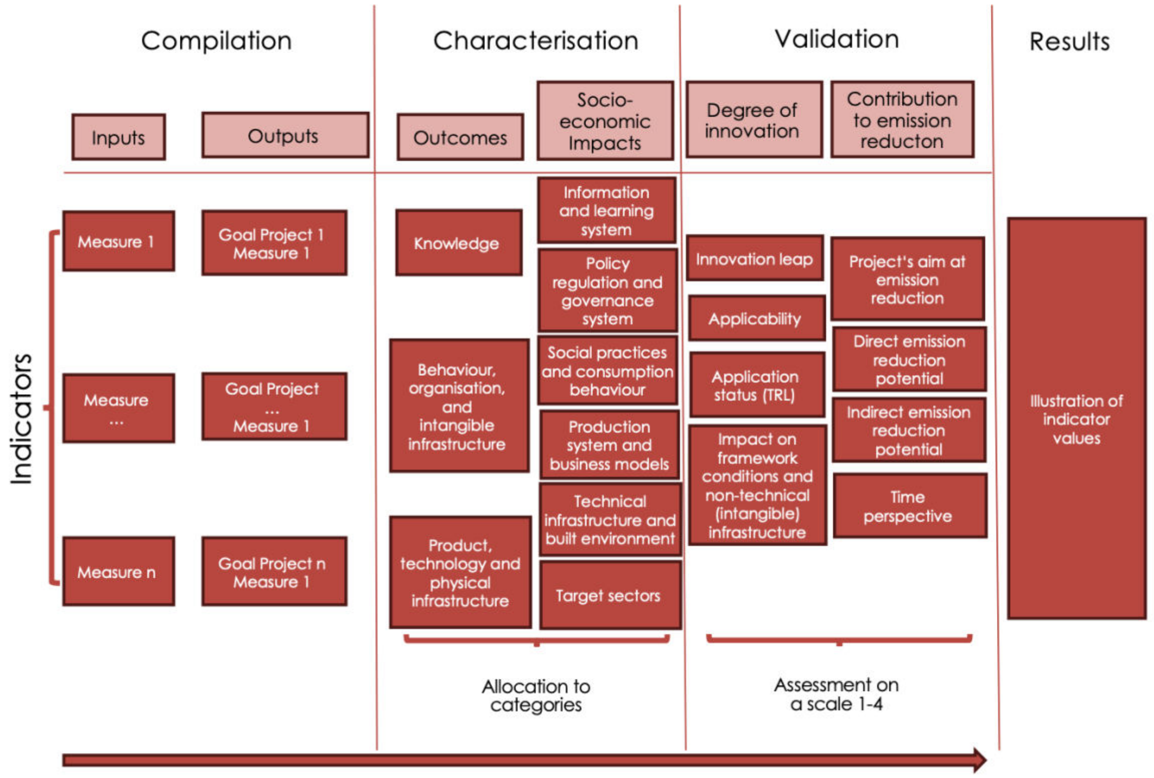
[8] The definitions used here are: (1) hardly any: The impact on GHG emission reduction is neglectable; (2) Some: The impact on GHG emission reduction is very limited to a single product or process; (3) Strong: The impact on GHG emission reduction is covering a group of products or a sector; (4) Very much: The impact on GHG emission reduction ranges across the whole economy.

	Direct Emission Reduction Potential		**Indirect Emission Reduction Potential**	**Time Perspective**
Value 1	No GHG emission reduction objective	Hardly any	No focus on any of the 3 indirect GHG emission reduction objectives	More than 15 years after measure/ project started
Value 2	GHG emission reduction objective as a sub target	Some	Focus on 1 out of the 3 objectives	About 15 years after measure/project started
Value 3	Strong focus on GHG emission reduction	Strong	Focus on 2 out of the 3 objectives	About 10 years after measure/project started
Value 4	GHG emission reduction as the major objective	Very much	Focus on all 3 objectives	About 5 years after measure/project started

Furthermore, it is helpful if applicants provide a brief potential impact chain outlining how their project's individual outputs may contribute to reducing GHG emissions. Figure 4 shows a prototypical pathway, applicants would have to fill out. This serves the dual purpose of prompting applicants to explicitly consider the climate impact of their project and ensuring the credibility of their expectations.

Figure 4 Illustration to provide information on a potential impact chain concerning GHG-emission reduction potential



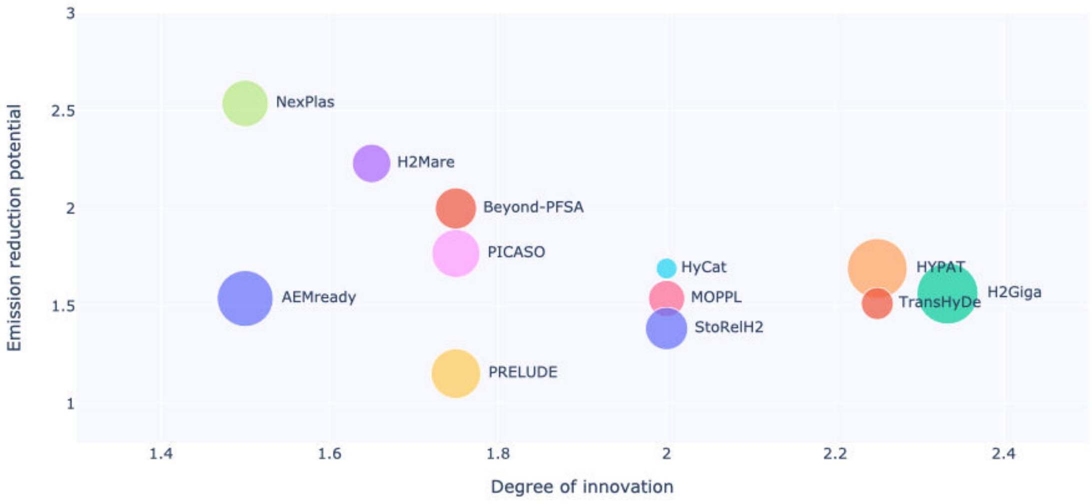
Source: IfW/Technopolis

4.3 Illustrative Results for an exemplary R&I Programme

In order to be able to interpret the collected data at a glance, the above mentioned four-level scale can be used to indicate the degree of innovation and potential GHG impact of the funded R&I projects, in our case under the German KSG. In that regard, our indicator-system can contribute to assessing implicitly the potentials of current research on future emissions and the achievements of sectoral climate targets. A value of 1 represents a very low emission reduction and innovation potential and a value of 4 a very high emission reduction and innovation potential.

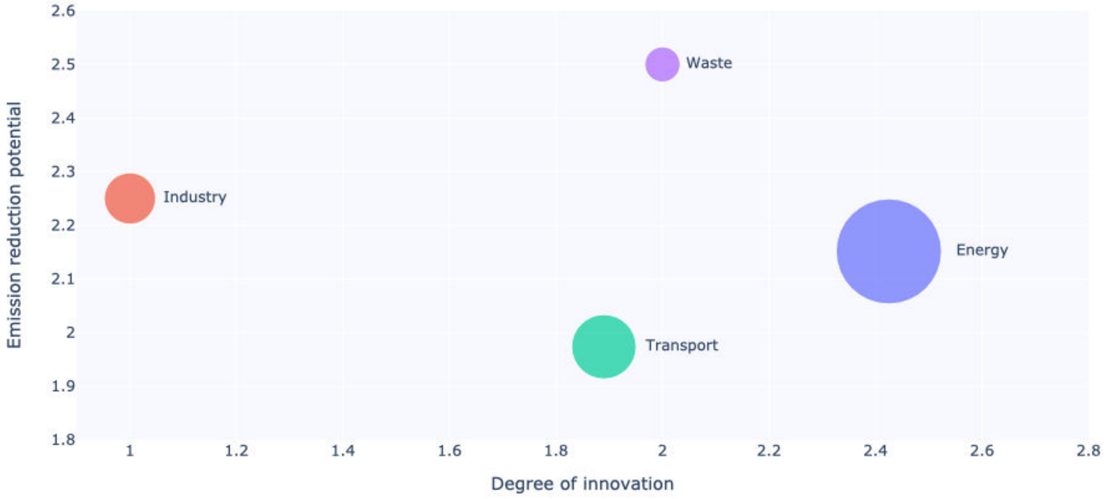
Figures 5 and 6 illustrate the results for our collected data related to a number of selected hydrogen projects funded by the German Federal Government. The data is systematically collected through a comprehensive analysis of the German Federal Government's website which provides an overview of all projects (Bundesministerium für Bildung und Forschung, 2024). The validation of the indicators is conducted independently based on the impressions obtained from this review. In Figure 5, the estimated qualitative potential for GHG emission reductions for individual projects is depicted in relation to the overall degree of innovation. This allows for a quick assessment of the qualitative strengths of emission reduction potentials and the average degree of innovation of the projects. The degree of innovation is calculated based on the mean of the indicators: innovation leap, applicability, application status, and intangible infrastructure. While each output is rated according to the scale explained above (1-4), the figure shows the mean of all individual outputs in each project. This means that the values shown can deviate from the scale used and are decimal numbers between 1 and 4. Additionally, the size of the circles represents the funding amount allocated to each project. Projects with greater funding should ideally be associated with a larger effect on emission reduction than projects with lower funding.

Figure 5 Project Overview: Emission reduction potential relative to the degree of innovativeness by hydrogen projects



Source: Own illustration based on self-validated data of selected current hydrogen projects.

Figure 6 Project Overview: Emission reduction potential relative to the degree of innovativeness by sectors



Source: Own illustration based on self-validated data of selected current hydrogen projects.

Unlike in the computation of the overall degree of innovation, where all innovation indicators get the same weight, we assign weights to the individual indicators when calculating the overall emission reduction potential to reflect their relevance. Thus, we use double weighting for the direct emission reduction potential as well as for the time horizon and assign the weight of 1.5 to the indirect emission reduction potential. A final algorithm on how the indicators can be weighted will be set after the expert workshop. The system itself allows flexibility in the grading of the various impacts on the final results.

Figure 6 presents the same concept but depicts the effects not at the project level, but at the sector level, to which the outputs of all projects contribute. This illustrates in which sectors significant emission reductions can be expected. Overall, although this is a quantitative representation, the values for the individual sectors and projects can only be interpreted qualitatively and with reference to other sectors/projects.

5 Summary and Conclusions

In this paper we have discussed the role of governmental R&I support towards a climate neutral economy. As argued in section 2, governmental R&I support is generally part of an optimal policy mix and there are good arguments for governments to support R&I measures related to technologies and innovations needed for a climate neutral economy. Yet, we have also stressed, that R&I support is not always the best approach. Given that governments have decided to fund specific R&I measures these should be assessed ex-ante regarding their potential impact. Section 3 has developed a general framework for such an impact assessment and discussed its potential but also limitations. In particular, we have stressed that an ex-ante quantification of impacts is generally not possible for a whole portfolio of R&I measures. This is why we in section 4 propose an indicator system for a qualitative impact assessment focussing on the innovation and greenhouse gas mitigation potential of R&I measures. We believe that such an approach can generally help funding institutions to make better and more transparent decisions. Yet, we are aware that it needs to be adjusted to the specific needs and institutional settings, which requires a validation process resulting in tailored data gathering e.g., through questionnaires and tailored automated evaluation tools. In this sense, this paper provides the theoretical background and general set-up of a qualitative ex-ante impact assessment of R&I measures but only makes a first step towards implementation in funding institutions.

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