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A descriptive framework to evaluate instrument packages for the low-carbon transition

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ABSTRACT

We develop a descriptive framework to facilitate policy instrument evaluation in relation to the low-carbon transition. The framework consists of a stock-taking and mapping analysis based on five questions. Four questions allow the policy maker to take stock of the existing set of instruments and provide a description of the key attributes and incentive of individual instruments. These attributes are subsequently mapped to identifiers of market failures related to the transition. A fifth question considers the coherence of the mix or package of policy instruments that the instruments constitute. The result is an overview of the incentives for firms and households to contribute to the transition towards a decarbonised economy. This can then be used to evaluate whether the set of policy instruments can be improved. We apply our framework to the residential and commercial (buildings) sector in an ambitious country, Austria.

1. Introduction

Limiting global warming to well below 2 °C “and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels” has become the de facto target for global climate policy (COP26, 2021). For instance, in 2021 the European Union adopted the European Climate Law, which sets a strengthened target of at least 55% emissions reductions for the EU by 2030 compared to 1990 and commits it to climate neutrality by 2050. Such ambitious targets require countries to introduce ambitious transition policies. One example is Austria where the 2020 government declaration set the target of climate neutrality by 2040.

Such dramatic emission reductions ambitions ask for mass-deployment of low-, zero- and negative emission technologies in all sectors of the economy. For instance, leading international firms whose business models are based on the use of carbon-intensive technologies need to transform themselves into clean firms (Fankhauser et al., 2013). Eco-innovation will play a crucial role in this transition to a decarbonised economy. Indeed, invention, innovation and diffusion of low-carbon technologies (including zero- and negative emissions technologies) are crucial for the global community to achieve net-zero greenhouse gas (GHG) emissions (IPCC, 2022).

Market failures make it unlikely that, without government intervention, emission reductions and eco-innovations will be supplied by the market at the speed and level that match the ambitions (Jaffe et al., 2005; Stern et al., 2022). Not only are current GHG emissions under- or even unpriced (OECD, 2021), but the incentives to invest in Research and Development (R&D) for eco-innovations or to adopt eco-innovations are also unlikely to be at their socially optimal level. Such market failures typically require targeted government interventions. Indeed, an economy-wide emission reduction target – which is the main element of the transition towards net zero – requires identification and characterization of proper Sensitive Intervention Points or SIP’s, i.e. ‘kicks’ to the current state of socioeconomic, technological and political systems, or ‘shifts’ in the underlying system dynamics (Farmer et al., 2019).

Finding appropriate ‘kicks’, however, is far from obvious in practice. Countries usually already exploit an amalgam of instruments that provide incentives to address market failures. However, they do not provide the right or strong enough ‘kicks’ to stimulate the net zero ambition apparently. Indeed, the design of existing instruments usually also reflects solutions to transaction costs related to their implementation, lobbying by affected stakeholders and political compromise.

Attention to the role of existing instruments and instrument package

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design has thus far been rather limited, in particular in the economic literature (OECD, 2007). Economists tend to focus on a partial analysis of attaining the net zero ambition at least cost by addressing the emission market failure through proper instrument choice, e.g. by a carbon tax.[1] A more comprehensive approach that accounts for multiple market failures at the same time gets much less attention. The complexity of system-wide change, however, typically requires a set of instruments. First, in practice comprehensive pricing of emissions is usually implemented through more than one single instrument. Second, externalities in the innovation domain require instruments in addition to environmental policy instruments (OECD, 2010; Kemp and Pontoglio, 2011; Acemoglu et al., 2012; Stern et al., 2022).[2] And third, political constraints may lead to the use of multiple instruments even in the presence of only one policy objective (Bennear and Stavins, 2007).

Also in the recent literature on innovation and policy studies, attention to the role of instruments to address market failures is limited (e.g. Rogge and Reichardt, 2016; Rogge et al., 2017; Kern et al., 2019; Köhler et al., 2019; Capano and Howlett, 2020; Dijk and Kivimaa, 2020). In this literature, the focus is on the design and evaluation of policy mixes to redirect and accelerate technological change, i.e. on policy strategy and processes with their characteristics such as consistency of the strategy and coherence of the process. Only sometimes, the role of instruments and their design issues are included in this type of evaluation (e.g. Rogge and Reichardt, 2016). What usually remains unclear is how individual instruments and instrument packages are precisely linked to the market failures they should address and which the 'kicks' they should provide to stimulate the zero carbon transition.

The goal of our paper is to develop a descriptive framework that helps policy makers in their evaluation of existing and newly proposed policy instruments, with a focus on addressing the market failures of unpriced emissions and knowledge spillovers. As some policy instruments are typically already in place in the status quo, our framework asks, first of all, to describe the kicks or incentives provided by individual instruments by four key design attributes: focus, scope, strictness and time profile. Subsequently the framework asks for a description of the coherence of the existing instrument mix or package. For such an exercise it is important to explicitly map the attributes of the different instruments to the market failures they should address. Accordingly, the answers to these questions provide a clear description of the existing incentives for firms and households to contribute to the transition towards a decarbonised economy.

Our framework thus reflects the idea that useful policy advice on instrument design should be properly targeted towards the shortcomings of the system that produce the unsatisfactory results in the status quo. These shortcomings and the existing and newly proposed instruments, however, are country-specific and require context-specific assessments. Our descriptive framework thus requires stock-taking and mapping of the attributes of currently implemented policy instruments. The design of an individual instrument is determined by typical articles of law that can be found in current laws required to implement policy instruments in practice. Such articles establish precisely the aim or target of the instrument ('focus'), who will be addressed by the instrument ('scope'), how strict the regulation will be ('strictness'), and to what extent changes are provided over time ('time profile'). Thus, stock-taking of these instrument attributes describes the incentives that individual instruments provide to firms and households towards the policy objective in practice.

The combined incentives of a package of policy instruments (instrument mix) may not be equal to the sum of the incentives of the individual instruments. Therefore, it is also important to describe the coherence of the instruments that constitute an instrument package. In our framework the attributes of the individual instruments are systematically mapped to the market failures they are supposed to address – in case of the transition to net-zero these are the over-provision of GHG emissions and under-provision of key transition technologies. The application of our descriptive framework enables policy makers to more precisely identify potential SIP's. The results of the stock-taking and mapping exercises can be directly confronted with the policy objective (in our case a zero-carbon economy in 2050) to *evaluate* to what extent the existing instrument package addresses the market failures properly.

We illustrate the application of our framework including the stock-taking and mapping exercises using the Austrian residential and commercial sector as a case study. To describe the relevant context, we start with a description of the market failures to which our case study is focused. We use sectoral GHG emissions as indicators for the environmental market failure and revealed technological advantage (RTA) as an indicator for current eco-innovation performance. We subsequently take stock of the existing instrument package that is currently in place for the sector's transition towards zero carbon and describe the attributes of the individual instruments in this package as well as its coherence. Finally, we confront the results of our descriptions with the zero carbon objective for an evaluation of the instrument package.[3]

In the next section, we first discuss the idea that environmental and technology policy instruments are key to inducing technological change towards a decarbonised economy. We also explain how policy instruments may correct for the set of market failures relevant for the current transition to a decarbonised economy and discuss their interactions. Section 3 introduces our descriptive framework. Next, we turn in section 4 to the Austrian residential and commercial sector. We start with a description of the status quo with respect to the market failures that are the focus of our analysis. Next, we present an overview of the relevant policy instruments. We apply our descriptive framework in section 5 by taking stock of the existing instruments and mapping them to the relevant market failures, in particular emissions and the relative performance of eco-innovation. Section 6 shows how our framework can be used to evaluate the existing instrument package in light of the zero-carbon objective for this non-exposed sector. Section 7 concludes.

2. Transitions, eco-innovation and market failures

Our framework provides guidance in the design (a set of) policy instruments aimed at reducing GHG emissions and inducing eco-innovation. To understand why properly designed policy changes would contribute to further development and implementation of technologies that direct the economy towards fewer carbon emissions, it is essential to understand how policy instruments (or their absence) affect technological change.

2.1. The low-carbon transition as a process of inducing technological change

Schumpeter (1942) distinguishes three phases in the process of technological change. The first two phases are invention and innovation, where an invention is the first idea for a new technology, product or

[1] Usually economists believe instrument packages address different policy goals, for instance by separating efficiency and distributional goals. The idea that instrument packages also matter for attaining even a single policy goal is less commonly recognized (see, for exceptions, Vollebergh et al., 1997 and Hepburn, 2006).

[2] Note that proper adaptations and innovations in infrastructure are also key to a net zero GHG transition, in particular in the energy markets and the basic material industries (e.g. Anderson et al., 2022). These issues are also closely linked to natural monopoly considerations and competition policy, but fall outside the scope of this paper.

[3] In practice, the stock-taking and the application of the framework will be done by think tanks and consultancies, who will then write a report that can be used by policy makers.

process, and innovation is the development of inventions into new technologies, products or processes that can be sold on the market.

An important driver behind the efforts of inventors and innovators is to earn back their initial investment, e.g. by earning rents from their patented inventions. Indeed, when a patent gets granted to an invention, its owner obtains a temporary monopoly on the technology. As shown by Acemoglu (2002), such a monopoly will earn higher returns when the market for a technology is likely to be larger, i.e. when more products can potentially be sold, and when the relative price for the good that uses the technology is higher, i.e. higher profit margin per unit of product. These effects are called the market size and (relative) price effect, respectively. If the market size for eco-innovations in a particular sector (e.g. automobile industry) is smaller than that for 'dirty' technologies, then there is a risk of lock-in in a dirty technology (e.g. the internal combustion engine).

Consequently, technological change will also be directed towards sectors where the market size effect and price effect are (expected to be) largest. This implies that relatively young and small sectors attract less innovation than large, monopolistic sectors. An example are new clean technologies for climate change mitigation in the electricity sector such as wind and solar power (Johnstone et al., 2010). The market for such new technologies often has a smaller scale than the one for existing (dirty) technologies. Moreover, there is path dependency in the direction of technological change. Firms that have innovated in the old technologies in the past will find it profitable to continue to do so, rather than innovate in entirely new technologies (Acemoglu et al., 2012; Aghion et al., 2016).

The third phase in the process of technological change is diffusion, which is the process of adoption by multiple actors of the new innovations that have been proven at commercial scale. This relates to the market size effect mentioned above: the higher the adoption rate of a new (clean) technology (e.g. the electric vehicle), the larger the potential market size for new inventions and innovations for this technology (e.g. improved batteries for electric vehicles).

2.2. Market failures and motivation for policy instruments

As argued above, eco-innovations will be developed only when innovators deem it profitable to do so. However, the return on investment for *eco*-innovations is typically lower at the firm level than at the level of society, as such investments suffer from two types of market failures (Jaffe et al., 2005; Popp et al., 2010). The first type is the environmental market failure related to the production of emissions such as greenhouse gases that cause climate change. The second type of market failure is related to technological change.

If producers (or consumers) cause environmental damage through carbon emissions that is not reflected in their private decisions, they choose a production (or consumption) level that provides the greatest benefit to themselves but not to society. This negative externality causes emission levels to be higher than what is socially optimal and is a market failure.[4] In the absence of policies that reduce the level of emissions to the socially optimal level, dirty technologies prosper as their emissions are under-priced and therefore the market sizes for these technologies are larger than their socially optimal levels. This, in turn, provides larger incentives for dirty innovations than for eco-innovations and hampers a transition to a decarbonised society (lock-in).

The second type of market failure is related to the process of technological change. First, new inventions typically generate *positive knowledge spillovers* from the inventor to society (Arrow, 1962). Due to its public good characteristic – if one firm invests in new knowledge, others are also likely to benefit from the new knowledge without paying for it – typically too little invention would occur from existing market incentives only.[5] Second, positive externalities exist related to *learning by using or doing* in the production or consumption of a new technology, which is typically related to the diffusion phase of a new technology. For example, it has been shown long ago that the production of a new type of airplane becomes cheaper as more units have been produced (Wright, 1936) and this effect has been demonstrated to be relevant often since (e.g. Popp, 2019). Third, *imperfect diffusion of knowledge about new technologies* may exist among actors in the market. Various studies show that the probability of adopting a new technology is positively affected by the proximity of agents that have already adopted the new technology (see Allan et al., 2013). Finally, new technologies may also suffer from *network externalities*. With network technologies, consumption benefits depend on the number of users of the same network (Katz and Shapiro, 1985; Gandal, 2002). They play a role for instance for the diffusion of plug-in electric and fuel cell electric vehicles: the benefit of owning such a vehicle increases in the number of other uses because the total number of users affects the incentives for providers to supply a network of charging stations (see e.g. Greaker and Midttømme, 2016).

2.3. Instruments to address externalities and their interactions

To incentivize the low-carbon transition properly, policies should be implemented to address these market failures (Popp et al., 2010; Stern et al., 2022). In doing so, they should take into account the smaller current market size for eco-innovations as compared to dirty innovations. Indeed, a kick to the current state of socioeconomic and technological systems, through policy intervention, should change the incentives for firms and households and induce a shift in investment away from CO_2-emitting technologies towards zero- and even negative-emission technologies.

Emission reductions can be induced through various environmental policy instruments that address the environmental externality, such as emission standards or pricing of emissions. A tax on emissions, for instance, requires a payment by the emitter for every unit of emissions, while standards or caps specify an amount of emissions (e.g. per kilometre driven) to which emitters should adapt. Such an (emission) tax rate or cap contributes to reductions of emissions to the extent that producers and consumers react to these instruments. They can cut their emissions using the cheapest available abatement technologies or through behavioural options.

Importantly, environmental policy instruments also affect the process of technological change (see Fig. 1). This is true for all types of instruments. For instance, command-and-control instruments, such as technology mandates or emission standards, encourage the adoption of eco-innovations or even make them compulsory. This increases the incentives for invention and innovation through the market size effect if a new eco-innovation becomes the technology that forms the basis of a new standard (Dekker et al., 2012; Vollebergh and Van der Werf, 2014). Also price instruments, such as an emission tax or cap and trade, provide an incentive to adopt eco-innovations (which increases the market size effect), increase the relative price of dirty technologies (which supports adoption of clean technologies) and reduce the profit margin for dirty technologies, thereby making investments in eco-invention and eco-innovation relatively more profitable (e.g. Calel, 2020). Environmental taxes and auctioned tradeable permits provide strong additional incentives for R&D because polluters still have to pay for the remaining emissions, which is not the case for standards and grandfathered permits (Requate and Unold, 2003).[6]

Technology policy instruments affect the process of technological

[4] Ideally, the optimum would be found exactly at the point where the benefit of further damage reduction no longer offsets the further loss of (net) private benefits. Here the emission level is 'optimal'.

[5] Note that patent protection compensates for at least part of this spillover.

[6] Note that in case of a tax or auctioned permits a polluter has to pay for all emissions whereas a firm that receives grandfathered permits only has to pay for the difference between the amounts of allocated and required permits.

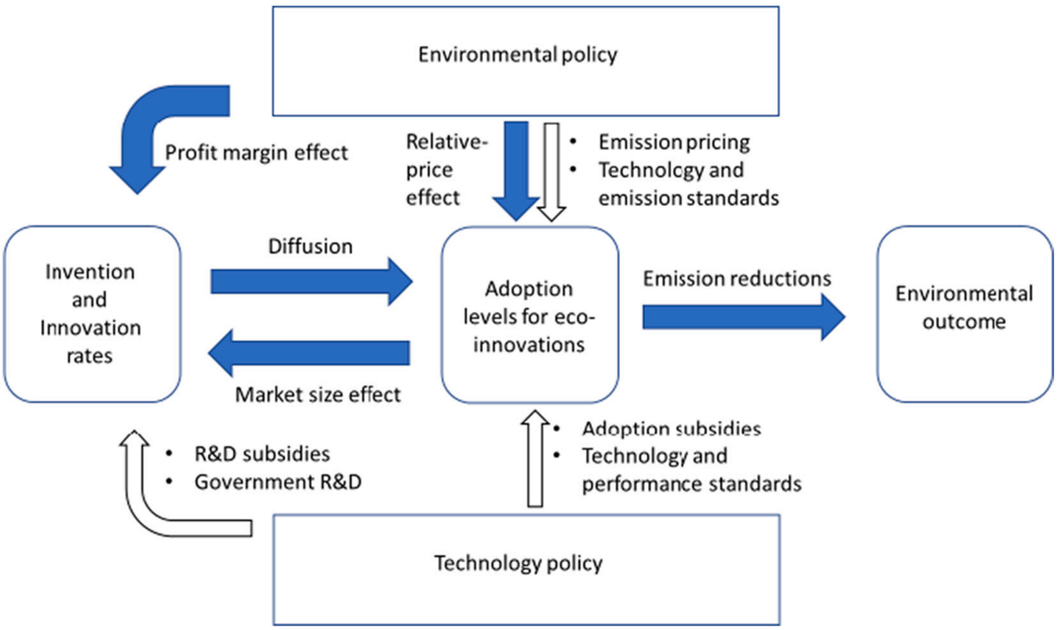

Fig. 1. The interaction between environmental policy instruments, technology policy instruments, and the process of technological change. *Note: Dark arrows indicate processes; light arrows indicate policy instruments.*

change itself by changing the incentives for invention, innovation and diffusion. Moreover, the different technology policy instruments also interact. For instance, subsidies that mitigate market failures related to the diffusion or adoption of a new eco-innovation, such as an adoption subsidy for battery-electric vehicles, change the relative price of clean and dirty technologies such that the adoption rate of clean technologies increases, which in turn increases the market size for inventors (e.g. of improved batteries), thereby reducing lock-in.

Technology policy instruments can either be generic or targeted. Generic instruments, such as patent laws and wage subsidies for R&D, typically focus at invention and innovation and support environmental policy objectives if the resulting innovations are indeed eco-innovations. Targeted technology policy instruments can be directed at the R&D phase (such as specific R&D subsidies) or at the diffusion phase (such as subsidies or tax expenditures for renewable energy technology adoption, or tradable renewable energy certificates combined with a renewable energy portfolio standard). If aimed specifically at eco-innovations, these instruments can also support the objectives of environmental policy.[7]

Policy makers can also use standards as complements to these technology policy instruments (Vollebergh and Van der Werf, 2014). For network technologies, compatibility of devices is an important issue. When multiple specifications for plugs and sockets for plug-in electric vehicles are available, a consumer runs the risk of not being able to charge her car at a given charging station. This reduces the likelihood of adopting the technology. Government intervention in the standardization process for compatibility and interface standards may then be necessary to limit the number of available specifications, perhaps even to one, in order to prevent a potentially superior technology (vis-à-vis existing technologies) from failing (Katz and Shapiro, 1985; David, 1987).

Design of instrument packages is also related to the spatial dimension of the externalities, i.e. to what extent border crossing of both environmental and technology spillovers matters. On the one hand, climate change is notably insensitive to where GHGs are emitted, which complicates unilateral measures and is likely to give rise to carbon leakage (Hoel, 1991). On the other hand, countries could benefit from technology spillovers in various ways. For example, firms are likely to invest in new knowledge on eco-technology if a country imposes more stringent measures. Next, other countries might benefit from those investments when they impose similar restrictions later on (Dekker et al., 2012).

We conclude that, without government intervention, a transition to a decarbonised society would suffer from both environmental externalities (which implies a market price for emissions to be too low or even zero) and technology spillovers (positive externalities from the generation of new knowledge, learning by doing, network externalities, and the diffusion of technology knowledge). As eco-innovations suffer from multiple market failures (an environmental externality and at least one of the technology spillovers), multiple instruments are always required to correct for these externalities.

3. A descriptive framework for instrument package evaluation

3.1. Evaluating instrument packages for the low-carbon transition

The idea to use market failures as a benchmark for policy makers to evaluate their existing policy instrument packages is far from new. Still, economic analysis of market failures directs attention of policy makers to where precisely ‘kicks’ are required to govern system change towards the low carbon transition, in particular kicks provided by the government in the form of policy interventions. Design of instruments is far from obvious in practice. First-best instruments are usually impossible to implement due to transaction costs, multiple externalities or overlapping impacts, industry lobbying and political compromise (Keohane et al., 1998; Hahn, 1995). Also, for newly designed packages or instrument (package) reform it matters whether and how environmental and technology policy instruments are already being used to address these market failures (Zodrow, 1985; OECD, 2007, 2010). So the question remains how insights from theory can be exploited by policy makers to improve upon their existing instrument packages that simultaneously address multiple market failures.

[7] Note that environmental gains from eco-innovations could be (partially) offset through behavioural responses such as the rebound effect (see e.g. Gillingham et al., 2016) and the green paradox (see e.g. Van der Werf and Di Maria, 2012).

As noted in the Introduction, within the innovation and policy studies literature the complexity of the existing system plays a much more prominent role than in the economics literature. However, this literature usually does not address the choice of instruments but rather the design and evaluation of policy mixes to redirect and accelerate technological change in terms of policy strategy and processes. What role instruments precisely have to play in transitions and why, often remains in the dark in this approach (Kemp and Pontoglio, 2011). Only recently the importance of instrument evaluation has attracted more attention. For example, Rogge and Reichardt (2016) explicitly allow for this aspect within their policy mix framework. Interestingly they also consider instrument design issues as relevant but their list of design features has no clear link with the market failures that instrument(s) ideally should address.[8]

Our framework aims to fill in this gap and provides a systematic approach that helps policy makers to evaluate more explicitly the link between instrument(s) design, the market failures they aim to address, and the net zero transition they aim at. Accordingly the shortcomings of the system that produces the unsatisfactory results in the status quo are the starting point for our framework. Moreover, our framework requires to make existing efforts that policy makers employ to address these market failures explicit. Accordingly, a clear stock-taking of the existing instruments and a description of their key design attributes are needed first. Second, this stock-taking exercise should exploit key instrument characteristics that explicitly facilitate comparability across instruments (to address a particular externality). Third, given an appropriate descriptive stock-taking exercise of instrument design features, one needs to map the instruments to the market failures they aim to address. How do the existing instruments – individually and as a package – relate to the market failures responsible for the current oversupply of emissions, undersupply of knowledge provision or insufficient adoption of eco-innovations? Accordingly, one would be able to assess whether a specific instrument reform proposal whether this is likely to improve the path towards net zero.

3.2. Instrument design attributes as a building block for our descriptive framework

A key challenge for our framework is to find instrument design features or attributes that not only make instruments comparable but also fit for the mapping of instrument attributes to market failures. Comparability of policy instruments, however, is notoriously difficult, because instruments tend to differ across many dimensions (see also OECD, 2007; Brunel and Levinson, 2016). To illustrate, a tax on carbon emissions can be, for instance, specific and direct (i.e. defined in $ per unit emitted substance), but also ad valorem and indirect (i.e. as a percentage of the price of a m^3 gas). Standards can be designed as a limit per unit of input, output emissions (Vollebergh and van der Werf, 2014). Such differences in design attributes matter a lot for the incentives provided by specific instruments and their packages but also makes comparisons of instruments difficult.

Comparability of instruments can be based on a description that follows as closely as possible their characteristics as defined by legislation, regulation and case law. Articles that define the aim or target of the instrument, who has to pay or will be liable, and how strict the regulation will be, define the instrument's incentive, together with arrangements on the exact time profile of implementation. We believe that these four key design attributes – *focus*, *scope*, *strictness* and *time profile* respectively – not only allow for a systematic comparison of instruments, but also suffice for a descriptive exercise that aims to identify the role of each instrument in addressing particular market failures. Finally, a description of the *coherence* of the package of instruments is necessary to understand the incentives that come from the combination of individual instruments. The remainder of this section introduces the instrument design attributes in more detail. Note that these attributes are relevant for both environmental and technology policy instruments.

The *focus* or 'operational goal' of an instrument is the first key instrument design attribute. It reflects the extent to which a specific instrument is targeted towards the relevant externality it aims to address. In the case of the policy goal of net-zero GHG emissions the externalities involved are the GHG emissions from all emissions sources that matter for the transition in, say, a country at a given date t and the technology spillovers described in Section 2.2.

The focus of a particular a tax, however, is usually more limited. Its focus is reflected by the choice of its object, usually defined as the tax base. This tax base could, for instance, define particular GHG emissions measured in kilograms or tons and their sources. But from the perspective of pricing externalities, tax bases could also be relevant if they indirectly target GHG emissions. An example of a relevant indirect tax instrument is a tax on energy products which is closely linked to GHG-emissions embodied in the product. Such a tax can even be considered a direct tax in case a fixed physical relationship exists between emissions and energy tax base. In the example of a tax per m^3 of natural gas, carbon emissions are also taxed directly because of the fixed emission factor between burning a m^3 gas and CO_2 emissions.

Similarly, the focus of a clean technology subsidy relates to the good or product for which the subsidy is provided, e.g. the technologies that qualify for a subsidy on eco-innovation. Such subsidies address positive externalities from new knowledge or address the learning externality of a new technology through a focussed subsidy. Its operational goal is typically increased adoption of the technology, which may address one or more technology market failures: learning by using or doing, imperfect diffusion of knowledge about the technology, and/or a network externality.

The second attribute is the *scope* of the selected instrument, in particular who is addressed precisely by the instrument. Legislation that describes an existing instrument typically refers to the agents that are addressed by it. For instance, a tax law clearly defines who is the tax payer while a law that introduces a subsidy explicitly states who is eligible for what.

To illustrate, the scope of a first-best environmental pricing policy instrument aimed at reducing GHG emissions would address all GHGs emitted by all actors (in all sectors) in an economy. In practice the scope of an actual pricing instrument depends on how its regulatory base is linked to the agents that pay the emissions price. Usually this will be the owner of the activity that causes the emissions. A clear example here is the EU Emission Trading Scheme for GHGs (EU ETS). The scope of this instrument covers only part of the EU economy – all large emitters (installations above 20 MW in EU) and intra-EU aviation – and not all GHGs emitted. The regulatory base and scope of an instrument can also be narrowed by exemptions (e.g. a carbon tax that exempts coal for electricity production).

The third design attribute of an instrument is its *strictness*.[9] Depending on the type of instrument, strictness is defined by the articles in legislation and regulations that describe its (marginal) incentive in the case of a price-based instrument or the implied restrictiveness of a quantity-based instrument. In the case of a tax, strictness is simply reflected in the choice of the level of its tax rate. The same holds for a subsidy, where it would be represented by its marginal rate. In general, the level of a tax rate or a subsidy is likely to determine to a large extent

[8] Their six features are stringency, level of support, predictability, flexibility, differentiation and depth (Rogge and Reichardt, 2016, p.1624–5). Our attributes overlap up to some point with their features but are first and foremost aimed at a description, rather than an evaluation, of instruments.

[9] Note that we do not refer to the stringency of a typical instrument. Stringency measures typically involve assessments of specific instruments in terms of several of the attributes we propose here for descriptive purposes (Brunel and Levinson, 2016; Rozendaal and Vollebergh, 2021).

the incentives for firms and households to reduce emissions or adopt a technology for a given scope. For a quantity instrument, the level of a given standard or cap reflects its strictness.

Note that strictness here is purely descriptive and does not require any interpretation in terms of stringency or assessment in terms of opportunity costs. It should also be noted that further qualifications require more detailed analysis, usually by combining our four descriptive attributes. Indeed, strictness may translate into stringency depending on these other characteristics. A tax may be imposed *de jure* while exempting most tax payers from the tax base. Also, strictness as defined by EU ETS law does not simply translate into stringency, although the emission permit price is a good indicator for stringency as it represents the scarcity in this market determined by the (opportunity) cost at the date of representation.

The fourth attribute relates to the *time profile* that is involved for a given instrument. For instance, the tax rate of a specific tax instrument (strictness) could be indexed or follow a pre-specified trajectory. Subsidies can be given to specific clean technologies but could decrease over time. Quantity instruments could become stricter over time. For any instrument, its date of coming into force (phasing-in) and end-date (phasing-out) are relevant. Note that an instrument's scope could also change over time.

Our final attribute, *coherence*, is not related to individual instruments but to an instrument package that different instruments constitute together and that should – ideally – be linked properly to the market failures they jointly address. Note that one instrument can cover multiple sectors (e.g. an emissions trading scheme), while the same emissions within a sector can also be covered by multiple instruments (e.g. an emissions trading scheme and an energy tax). Coherence refers to the joint implementation of single instruments to address particular market failures.

A description of the coherence of an instrument package first requires the mapping of (the attributes of) the individual instruments to the market failures they are supposed to address. Next their interactions can be described from which can be concluded whether the individual instruments complement each other or overlap. Each instrument within a package may address different (parts of the) externalities thereby *complementing* other instruments that also address (parts of the) externalities. For example, the EU ETS and fuel taxes have the same focus (GHG emissions) but have different scopes as the fuel tax covers the transport sector (which is not part of the focus of the EU ETS). Also, an eco-innovation with characteristics of a network technology will require environmental policies for competing polluting technologies and an adoption subsidy. In addition, non-environmental standards (such as compatibility and interface standards) are important for network technologies.

However, direct or indirect *overlap* of instruments might reduce their combined impact. A well-known example related to the overlap of local and internationally enforced policy instruments is the waterbed effect resulting from the interaction between the (pre-2018) EU ETS and domestic policies like a subsidy for the adoption of renewable energy technologies (Böhringer et al., 2009).[10] Although the two instruments address different market failures (negative externalities from GHG emissions and positive externalities from technology adoption, respectively), their combined impact reduces demand for electricity from fossil fuels, which in turn is likely to lower the (expected) price in the cap and trade system without reducing additional emissions. Combining instruments might then call for a tighter cap (increased strictness) in the cap-and-trade system. Furthermore, adjusting or abolishing existing instruments may improve the effectiveness of a new instrument or make it redundant.

3.3. A descriptive framework for the design of policy instruments

We have argued that four design attributes are key for characterizing existing incentives and provide a useful starting point for advising policy makers on new instruments or instrument (package) reform for a transition towards a net-zero economy. In addition we have argued that the coherence of a combination of policy instruments that address a particular market failure should be considered. This subsection formulates the five questions of our descriptive framework: four to describe the design attributes of individual instruments and one question to describe the coherence of a package of instruments. The result is an overview of the existing incentives for firms and households that – in combination with existing market incentives – are responsible for their current to contributions to the transition towards a decarbonised economy.

1. What is the *focus* of the instrument?

   That is, what is the operational goal of the instrument? The question serves to assess whether a particular environmental or technology policy instrument is appropriately targeted towards its objective, in this case decarbonisation or the reduction of all relevant GHG emissions.

2 What is the *scope* of the instrument?

   That is, who (e.g., which firms and households) is precisely addressed by the instrument? Here we distinguish between (a) the *environmental scope* and (b) the *technological scope*. For the environmental scope, the question is which polluters are covered by the instrument in terms of its regulatory base? For the technological scope, the question is whose technological spillovers related to the development and adoption of eco-innovations are addressed by the instrument?

3 What is the *strictness* of the instrument?

   This question addresses which level of strictness is involved for a particular instrument, e.g. what is the level of the tax rate or subsidy or how much emission reduction does a cap or standard require relative to the status quo?

4 What are the *time-related* characteristics of the instrument design?

   Answers to this question should reveal typical time-related attributes of an instrument such as the phasing in or out of a particular instrument, the time path of quantity restrictions or the indexing (or not) of rates.

5 Is the instrument package *coherent* with respect to the market failures it aims to address?

   This question asks whether the individual instruments making up an existing overall instrument package constitute a portfolio of *complementary* instruments without ineffective or inefficient *overlap* in addressing the externalities.

   Answers to the first four questions take stock of instrument attributes as defined by legislation, regulation and case law. Answering the fifth question, however, requires additional descriptive analysis. In order to determine to what extent individual instruments and their combination (instrument package) address the relevant market failures, the instrument attributes should be linked ('mapped') to the current performance of the economy, in particular indicators of the relevant market failures. For this purpose, it is important to link the environmental policy instruments to the environmental market failures (e.g. GHG emissions) and technology policy instruments to the innovation and adoption market failures of a country. Subsequently the coherence of the instrument package can be described.

Mapping instrument design features to market failures is not straightforward, however. In the case of the zero carbon transition, this requires a clear picture of the use of fossil fuels and other inputs

[10] Another example in the context of EU ETS is the crowding out effect of an additional carbon tax within EU ETS (Brink et al., 2016). Currently, the interaction between local policies and the EU ETS is much more complicated due to the implementation of new rules that govern the Market Stability Reserve (see e.g. Perino, 2018).

responsible for GHG emissions across the whole economy. Moreover, each instrument should be linked to the relevant emission base, which in the case of GHGs consists of a number of relevant emissions, such as CO_2, N_2O and NH_4. The attributes we distinguish help to align this mapping exercise. For price instruments, for instance, a country's (extended) energy balance can be used to relate at least the major part of GHG emissions to specific sectors responsible for the current GHG emissions. The computation of effective carbon tax rates of a set of (tax) instruments by the OECD is an example here (OECD, 2021).

Mapping instrument design features to technology market failures is much less straightforward. Ideally, one would like to know the size of the positive knowledge spillovers from inventions and, for each current and each known but not yet adopted eco-innovation, the size of the spillovers stemming from learning by using and doing, imperfect diffusion of knowledge about new technologies, and network externalities. With such information in place, the regulator could check the existing technology policy package and target specific sectors or technologies with instrument reform or even new instruments. In practice, the policy maker will not be able to precisely identify these spillovers and have to rely on indicators for each spillover. In this paper, we provide an example for such an exercise using so-called indices of revealed technological advantage (RTA) based on patent application data as an indicator for eco-innovation strength.[11]

4. An application to Austria: Emissions, innovations and instruments

We apply our descriptive framework for instrument choice to a case study of the residential and commercial sector (homes and other buildings) in Austria. The country has set itself the target of climate neutrality by 2040, currently the most ambitious target in the EU (Austrian Government, 2020). At the same time, Austria is one of the few EU countries whose total GHG emissions have increased rather than decreased since 1990 (European Environment Agency, 2020). Further action is therefore necessary, also considering the European Commission's proposal to raise Austria's emission reduction target for sectors outside the European emission trading system from 36% compared to 2005 to 48% (European Commission, 2021). Moreover, the residential and commercial sector is considered one of the key sectors in terms of emission reductions for a low-carbon transition by policy makers in Austria (BMNT, 2019a).

As argued above, it is essential to take stock of the peculiarities of the Austrian context before selecting which key Sensitive Intervention Points of the system might be relevant for Austria in general and the residential and commercial sector in particular. We first describe the two relevant market failures: we identify emission-sensitive activities in section 4.1 and provide some insight into sector-specific eco-innovations in Austria to get a feeling for potential failures in the technology market in section 4.2. In section 4.3 we briefly describe the relevant instruments. We apply our descriptive framework in section 5.

4.1. Greenhouse gas emissions and fossil fuel use in Austria's buildings sector

The residential and commercial sector is Austria's second largest outside the EU ETS in terms of GHG emissions and therefore plays a major role in the current national policy debate.[12] The sector emitted 16.1% of the country's greenhouse gases outside the ETS in 2017 (Anderl et al., 2019). Although emissions from the sector declined by about 33% in Austria since 2005, the trend has been upwards again since 2014. According to Austria's National Energy and Climate Plan submitted to the European Commission in 2019, national policy makers see potential for reducing emissions in the sector by a further 37% until 2030 to help achieve the country's current emission reduction target for the sectors outside the EU ETS (BMNT, 2019a). The recent declaration of the Austrian Government (2020) contains a range of measures to reduce emissions in the sector, primarily by increasing the thermal renovation rate, phasing out fossil-fueled heating systems and making zero-emission buildings the standard in building codes.

The main sources of final energy use in the residential and commercial sector in Austria are, according to Sporer (2019), electricity (30%), biomass (19%), natural gas (18%), district heating (16%), mineral oil (13%) and geothermal/solar/ambient heat (4%). Note that energy from electricity and district heating does not cause emissions in the residential sector, but rather in the energy sector and industry, respectively. Consumption of electricity, district heating, biomass and geothermal/ solar/ambient heat has increased since 2005, while consumption of natural gas and mineral oil has declined.

Besides fossil-fuelled space heating systems, low-quality thermal insulation of buildings is a key driver of (fossil) energy use in the residential and commercial sector. Currently, the thermal standard of roughly 40% of residential buildings is considered insufficient. Therefore, in addition to exchanging heating systems for renewables, at least a doubling of the thermal renovation rate is recommended in order to decarbonise the Austrian building stock by 2040 (Amann et al., 2020).

4.2. Eco-innovation performance of Austrian emission sectors

To get a feeling for the role of knowledge externalities we focus on Austria's innovation specialisation in the building sector.[13] We describe how existing knowledge on technologies compares to all other countries and thus measures the country's relative technological specialisation in specific fields. Sectoral rates of patenting of eco-innovations identify the availability of local innovations for emission reduction and thus provide a first indication which technology fields may be affected by market failures.[14] A useful indicator in this respect is an index of revealed technological advantage (RTA). This index captures one country's innovation specialisation in a particular technology compared to all other countries and can therefore be used to measure a country's relative technological specialisation (see Appendix for details).

If the RTA analysis indicates that a country is at a relative technological advantage in a particular eco-technology compared to the rest of the world ($RTA > 1$), policy instruments introduced in the past are likely to have stimulated patenting of eco-innovation in this technology field. This suggests that the knowledge spillover in this field might not be large and patents play their role in protecting the newly discovered innovations. It also indicates that the eco-innovations for that particular eco-technology group are already available in Austria and adoption of these eco-innovations could be relatively easy if appropriate instruments are in place to take away the spillovers in the adoption phase. On the other hand, if the RTA indicates that a country is at a comparative disadvantage in a particular eco-technology field ($RTA < 1$), past policy instruments have insufficiently generated patents for eco-innovations in this field, and further policy instruments to stimulate it may be required.

To construct the RTA index, we use data on patent applications by climate change mitigation technologies in different emission sectors

[11] Another example is the study by Anderson et al. (2022) in this Special Issue on the technology uptake in the Dutch manufacturing sector.

[12] The sector classification for reporting GHG emissions under the UNFCCC is defined in IPCC (2006).

[13] For brevity we exclude a detailed discussion of market failures in the adoption phase.

[14] Emission sectors within a country differ in their current eco-innovation intensity because countries tend to specialize in certain areas, particularly in response to past policies (or their absence).

from the OECD environment statistics database (see Table A1 in the Appendix for the list of technologies).[15] We present time-averaged RTA indices over the period from 2010 to 2016, the latest year for which data are available at the time of writing. Using averages helps smooth out the jumpiness of data on patent applications (e.g. two in one year, zero in the next two).

Fig. 2 shows RTA indices for Austria, Germany and the Netherlands for the residential and commercial buildings sector. Austria registers an average RTA of 0.98 between 2010 and 2016, indicating a marginal technological disadvantage compared to the rest of the world. However, as Fig. 2 shows, there is considerable heterogeneity across technological sub-fields within the sector. For example, Austria has a technological advantage (RTA of 1.2) in technologies relating to the integration of renewable energy sources in buildings, including photovoltaic, solar thermal energy or wind power systems and heat pumps. On the other hand, the country's average RTA in energy efficiency technologies for applications inside buildings is just below 1 at 0.96; and the RTA for elements that improve the thermal performance of buildings (insulation materials and specialized windows, doors, floors and roofs) and for so-called enabling technologies are considerably below 1 (at 0.69 and 0.58, respectively). The latter field includes applications of fuel cells and smart grid technologies in buildings.

Among the further sub-fields of energy efficiency technologies for applications inside buildings, shown in Fig. 3, Austria's specialisation in technologies for energy-efficient heating, ventilation or air conditioning systems is particularly relevant to decarbonising the buildings stock. This field includes central heating or hot-water supply systems using heat pumps, district heating and waste heat, heat recovery systems and passive house technology. Other areas of technological advantage are energy-efficient elevators, escalators and moving walkways; lighting technologies; and efficient end-user side electric power management and consumption (demand response systems, smart metering and switched-mode power supplies, e.g. energy-saving modes). Areas of technological disadvantage are home appliances and information and communication technologies (ICTs) aiming at the reduction of their own energy use, such as energy-efficient computing technologies and techniques for reducing network energy consumption.

As mentioned in section 4.1, the greatest potential for emission reductions in the residential and commercial sector lies in the reduced use of fossil fuel-based heating systems as well as in the improved thermal insulation of buildings. Overall, the evidence presented in this section reveals that Austria is at a substantial disadvantage in technologies related to the latter. In fact, the RTA in the category architectural or constructional elements improving the thermal performance of buildings (see Fig. 2) takes the value zero in all years from 2011 to 2016, following a relatively high value of 4.8 in 2010.

Regarding the second key driver of emission reductions in the residential and commercial sector, replacing fossil-fuelled heating systems, Figs. 2 and 3 indicate that Austria enjoys an advantage in technologies relating to the integration of renewable energy sources in buildings as well as in heating, ventilation and air conditioning technologies. The RTA values for both categories are rather stable over the years between 2010 and 2016. This finding suggests that domestic technologies for zero-emissions energy and heating systems for buildings are already available in Austria.

It should be noted that patent data representing a country's own innovation efforts are only an imperfect measure of the technological knowledge available in that country – and hence also as to whether a knowledge market failure exists or not – since new knowledge can also be imported. Hence, the RTA based on patent data may not tell the full story, but as patent data are one of the most widely used and available innovation indicators, we believe it provides useful initial evidence. When combined with our descriptive framework of relevant technology policy instruments, the policy maker has useful information at hand for reforming the existing technology instrument package.

4.3. *Existing policy instruments in the Austrian residential and commercial sector*

This section provides a short overview of the main instruments that contribute to the reduction of GHG emissions and the development or diffusion of eco-innovations in the Austrian residential and commercial sector. Our focus is on tax policy and government expenditure as well as regulation.[16]

4.3.1. *Direct and indirect GHG pricing*

The Austrian residential and commercial sector is not part of the EU ETS. Its emissions are not taxed directly under Austrian law, but energy use is taxed through a variety of energy taxes, while the EU ETS has an indirect effect on electricity prices (see also OECD, 2021). Table 1 presents the existing energy tax rates as of May 2022. All electricity use, which is the most common energy product used within this sector in Austria, is taxed at 0.015 Euro per kWh. The electricity tax incentivises consumers to reduce their electricity consumption, but does not discriminate with respect to the emission profile of its generation. In other words, the same tax rate applies to electricity produced from renewables and fossil fuels. Other energy products for heating are taxed as well, notably natural gas, heating oil and coal, although the share of coal and coke in energy consumption in Austria is negligible.

In October 2022, a new national emission trading system was introduced in Austria, covering emissions from the residential and commercial buildings sector and the transport sector (National Law on Emission Certificate Trading 2022, BGBl. I Nr. 10/2022). In the residential and commercial sector, upstream distributors of fossil-based heating fuels (i.e. the vendors of natural gas, heating oil and coal) must buy emission certificates corresponding to the emissions attributed to them. The system begins with a fixed price for emission certificates, where the initial price is € 30 per tonne of CO_2 rising to € 55 in 2025.

4.3.2. *Standards*

Perhaps the most important policy instruments applied in the residential and commercial sector are building codes (Sporer, 2019). Part of these building codes aim at energy savings and thermal insulation and are emission reduction standards. Building codes (and other direct regulations) affect emissions either for the residential and commercial sector (if they directly affect emissions from buildings) or for the energy sector (if they affect electricity consumption).

In Austria, building codes are the responsibility of the provinces (Bundesländer). However, province-level thermal insulation standards, which define minimum standards for the level of insulation of building components, have been surpassed by the national OIB (Österreichisches Institut für Bautechnik) guideline 6 since 2007. OIB guideline 6 defines requirements for the thermal quality of buildings and implements into national law the relevant EU directives. Province-level building codes have been reformulated as energy performance standards since 2007,

[15] The data refer to the number of patents applied for by a country's inventors, independent of where patent protection is sought (i.e. all jurisdictions worldwide). The patents are presented by country of inventor, priority date and patent family size, which refers to the number of patent applications protecting the same priority filing worldwide. In this paper, a patent family size of three or greater is chosen, covering only those inventions for which patent protection is sought in at least three jurisdictions worldwide, to capture higher-quality patents.

[16] For instance we do not discuss the program "klimaaktiv" which is a climate action initiative of the Federal Ministry. This instrument provides consulting and networking services, training programs and quality assurance for and in cooperation with companies, municipalities, households and public institutions like universities.

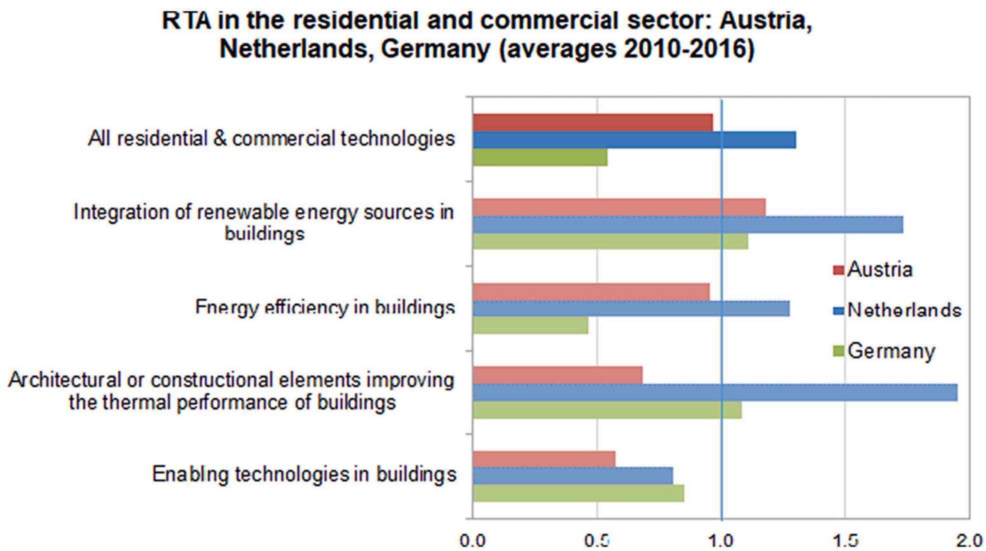

Fig. 2. RTA indices in climate change mitigation technologies related to the residential and commercial sector, averages 2010–2016.Note: Index values above 1 indicate a revealed technological advantage. Lighter shades indicate technology sub-fields.

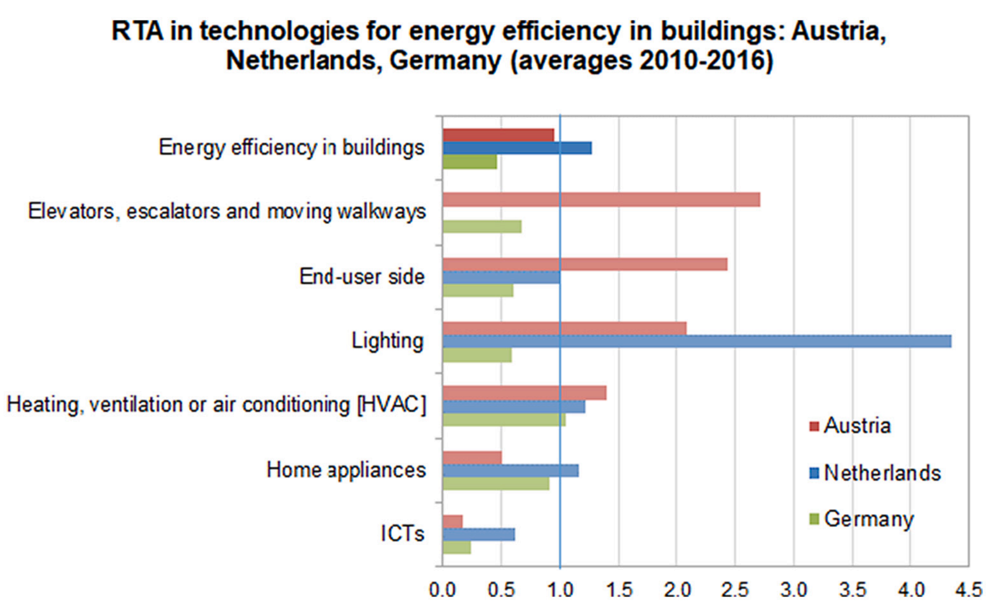

Fig. 3. RTA indices in climate change mitigation technologies related to the residential and commercial sector, energy efficiency sub-field only, averages 2010–2016. Note: Index values above 1 indicate a revealed technological advantage. Lighter shades indicate technology sub-fields.

Table 1
Energy taxes relevant for the residential and commercial sector in Austria. Sources: Sporer (2019), Kettner-Marx and Kletzan-Slamanig (2018).

Energy carrier	Tax rate	Rate per GJ	Rate per tonne of CO_2-eq.
Electricity	€ 0.015 per kWh	€ 4.17	€ 99.24
Natural gas	€ 0.066 per m^3	€ 1.66	€ 30.74
Heating oil	€ 0.098 per litre	€ 3.14	€ 40.30
Coal and coke	€ 0.05 per kg	€ 1.70	€ 18.09

which offer more flexibility to architects and reduce the risk of lock-in (IEA and UNDP, 2013). These performance standards define maximum values for energy demand of an entire building for *new buildings* and buildings that are subject to *major renovation*. Note that building codes implicitly support the adoption of new technologies (and even innovation) and can therefore be considered as technology policy instruments as well.

4.3.3. Generic technology policy instruments

Austria offers various incentives for R&D, for example the "Forschungsprämie" or R&D premium, a tax credit towards corporation tax (25% in Austria). It currently amounts to 14% of Austrian companies' annual R&D expenditures (OECD, 2019). The Forschungsprämie applies to all R&D and does not target any specific technologies.

Non-price instruments also play a role in technology policy. To support the diffusion of Austrian technology abroad, the Austrian Federal Economic Chamber and the Federal Ministry for Climate Action run two export promotion initiatives. Firstly, the Export Initiative Environmental Technologies organizes networking missions abroad for company representatives, with a focus on small and medium-sized companies. Secondly, TECXPORT provides an online platform for networking with potential clients and subsidizes travel to a technology promotion event abroad. Of the nine program areas, five could be regarded as climate-related (environment, energy, mobility, transport & infrastructure and smart cities).

4.3.4. *Specific technology policy instruments for the residential and commercial sector*

The Climate and Energy Fund is a subsidy instrument of the federal government, which funds a broad range of projects on renewable energy systems, energy efficiency and sustainable transport technologies as well as awareness-raising and knowledge transfer programs. Among its aims is to promote the development and diffusion of Austrian environmental and energy technology. Funding is available for projects at various stages of technological development, from basic R&D to support for demonstration projects, technology adoption and funding for green start-ups. Concerning buildings, the programs funded since the Fund's establishment in 2007 have included research and investment subsidies for solar thermal and photovoltaic energy systems as well as associated energy storage and network infrastructure for private households, municipalities and companies. In addition, high-standard building renovations, new building technologies like thermal component activation and planning concepts such as "smart cities" have received funding.

The Housing Support Scheme (Wohnbauförderung) is a province-level policy that subsidizes the *construction* of new residential buildings as well as the *renovation* of existing ones. In the early 2000s, it co-funded about 75% of housing permitted for construction. The Scheme combines the subsidy with a standard as the subsidy is conditional on (among other things) minimum energy performance or thermal insulation standards in all provinces.

The Domestic Environmental Support (Umweltförderung im Inland) is a national-level programme which aims at increasing energy efficiency and reducing emissions in the residential and commercial sector. The programme provides *investment* subsidies primarily to companies for improving energy efficiency and replacing fossil-fuelled heating systems with renewable ones (including biomass). An additional instrument for private households, municipalities and companies is the Renovation Campaign, introduced in 2009, which includes for the former group the 'renovation cheque' for thermal renovations as well as a bonus for renewable replacements of fossil heating systems. Both Domestic Environmental Support and Renovation Campaign support the diffusion of eco-innovations.

The Green Electricity Subsidy aims at increasing the share of electricity from renewable sources. It comprises feed-in tariffs compensating for the production of renewable electricity, investment subsidies for the installation of green electricity systems and plants (except for large hydro-power plants), as well as subsidies for combined heat and power plants that provide public district heating (and ensure energy savings and emission reductions as compared to separate heat and electricity production). The subsidy has an environmental objective and effectively supports the diffusion of existing technologies.

5. An application of the framework: A description of instrument attributes

In this subsection we answer each of the five questions of our descriptive framework. For the sake of brevity, we do so in a rather parsimonious way.

5.1. *What is the focus of the instrument(s)?*

Austria has set itself the target of climate neutrality by 2040 (Austrian Government, 2020). The operational goal for the residential and commercial sector is then GHG emission reductions via behavioural changes and the adoption of technologies that reduce emissions (i.e. a switch towards renewable energy or electricity, or improved thermal insulation). Note that GHG emissions in the residential and commercial sector can be reduced along two lines: reduction of fossil fuel use for heating of water and space, and improvement of the thermal performance of the current and new buildings stock. Furthermore, indirect emissions by the sector can be reduced via reduced electricity consumption.

The energy tax on natural gas, heating oil and coal in Austria (see Table 1) is an excise tax with the volume of the energy carrier (cubic metre for gas, litre for heating oil, tons for coal) as its tax base. Since volume of the fossil fuel energy carriers is directly related to tons of GHG emissions, the focus of the energy tax on gas, oil and coal can also be considered as a direct tax on GHG emissions. The new national emission trading system is targeted towards GHG emissions from the residential and commercial buildings sector and the transport sector. The tax on electricity, however, is an excise on electricity consumption and contributes to reducing the sector's indirect emissions.

The building codes (province-level and OIB guideline 6) are targeted more towards energy efficiency and less directly towards carbon emissions. The codes target overall energy use, not just carbon-related energy carriers, and therefore only indirectly contribute to the operational goal of carbon emission reductions. However, they do provide further incentives to reduce energy demand for space heating (insulation standards) and other uses.

Austria's general R&D tax credit (Forschungsprämie) is aimed at internalising the knowledge spillover that comes with new knowledge (on top of the general patent protection laws). There is no specific tax credit for eco-innovations. The Climate and Energy Fund, the Housing Support Scheme, Domestic Environmental Support / Renovation Campaign, and the Green Electricity Subsidy are (partly) targeted towards the adoption of insulation technologies and renewable energy systems, in particular for the existing building stock.

5.2. *What is the scope of the instrument?*

That is, who (e.g., which firms and households) is precisely addressed by the instrument? Regarding the environmental scope of the main energy taxes applied in the residential and commercial sector, generally all consumers of electricity, natural gas and heating oil (firms and households) must pay the tax on these energy carriers as part of their energy bills to the retail companies. By contrast, the national emissions trading system addresses the vendors of fossil fuels (e.g. natural gas, heating oil) as these are the ones who have to buy emission certificates. Consequently, all natural gas and heating oil consumption in the building sector falls within the scope of this instrument.

The national (OIB guideline 6) and provincial building codes cover all buildings, both new and existing, for which they specify thermal requirements if major renovations are undertaken. Both instruments address the person or entity who bears legal and financial responsibility for the building project. This could be a building owner or project developer.

The R&D tax credit (Forschungsprämie) applies to all firms that invest in R&D. This might also be relevant for innovators in technologies relevant for the building sector. The Climate and Energy Fund is a very broad instrument and thereby addresses households, firms and municipalities. The Housing Support Scheme provides a subsidy to municipalities, charitable construction associations, individuals or companies. The latter can only be granted a subsidy if the building becomes legal property of an individual once it is built (Sporer, 2019). The Domestic Environmental Support / Renovation Campaign and Green Electricity Subsidy provide investment subsidies to private households, companies and municipalities who invest in energy efficiency or replace fossil fuel-based heating systems by systems based on renewables.

5.3. *What is the strictness of the instrument?*

To get an idea of the strictness of the tax instruments in the

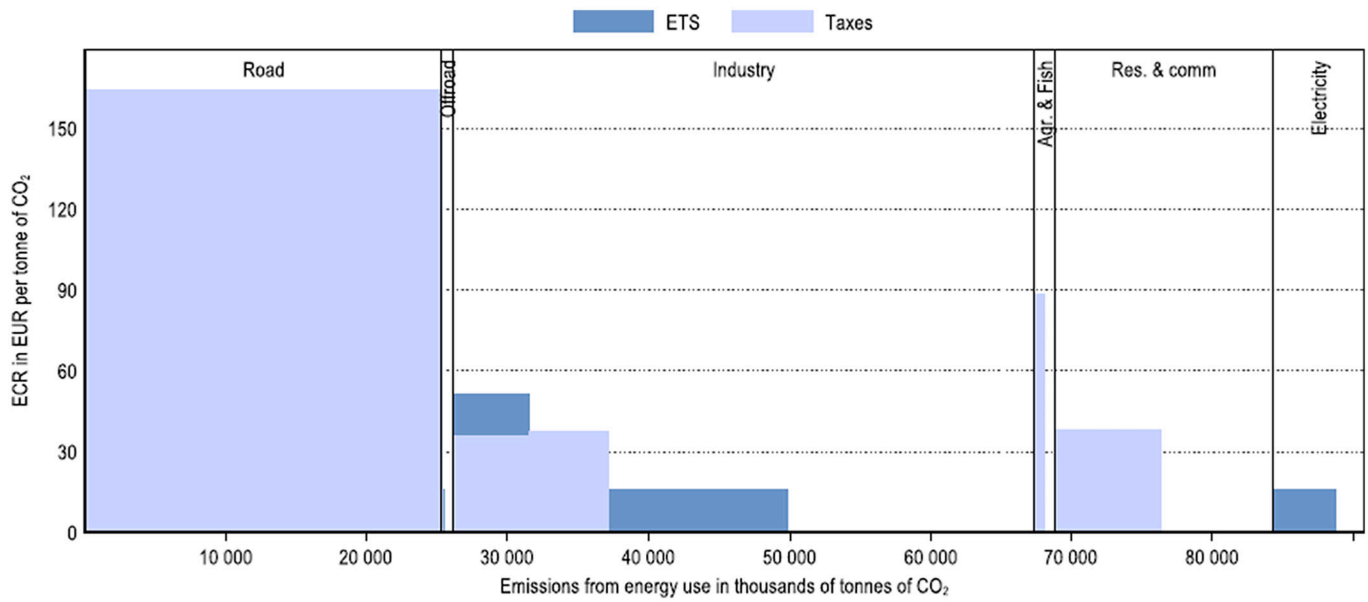

Fig. 4. Average effective carbon rates in Austria by emission sector, 2018. Source: OECD (2021).

residential and commercial sector Fig. 4 presents the effective carbon tax rates for GHG emissions from energy use in Austria (OECD, 2021). That is, it presents the EU ETS price in 2018 and energy taxes expressed in their underlying carbon tax base using emission factors. These rates reflect the strictness of the taxes and the market valuation of the strictness of the EU ETS system.[17] The figure shows that the €38 per tonne of CO_2 effective tax rate in the Austrian residential and commercial sector is much lower than those for road transport and parts of the agriculture sector and slightly lower than the effective tax rates for parts of industry. The figure does not yet include the new national emission trading system implemented since October 2022. The upstream distributers of fossil-based heating fuels for the residential and commercial sector have to buy emission certificates at a rate of € 30 per tonne of CO_2 in 2022.

The national building code OIB guideline 6 primarily implements into national law the requirements of EU directives on the energy performance of buildings (directives 2010/31/EU and (EU) 2018/844). Provinces, however, can issue their own, more stringent ones. The current OIB guideline 6 of April 2019 defines thermal requirements both for new buildings, which must classify as nearly-zero energy buildings starting from 2021, and for buildings undergoing major renovation.

The Austrian generic R&D subsidy Forschungsprämie is a tax credit of 14% of R&D expenditures, which can be claimed towards corporation tax. With the current corporation tax rate of 25% this implies that for any euro spent on R&D a firm can subtract 3,5 cent from their taxable profits. IEA (2020) data indicate that Austria provides generous public funding by European comparison in terms of total amounts spent although their corporation tax rate is average.

The Climate and Energy Fund has disbursed 1.4 billion Euro in subsidies on 144,000 projects since 2007, which triggered close to 5 billion Euro in total investments (Climate and Energy Fund, 2020). Subsidy rates vary quite widely according to individual funding programme and technology field.

Total funding available under the Housing Support Scheme amounted to 2.07 billion Euro in 2020. This funding covers 15–20% of total investment costs on average. With all housing-related state expenditures making up <0.5% of GDP, Austria ranks among the bottom third in EU comparison (IIBW, 2021). For the Domestic Environmental Support scheme and the Renovation Campaign combined, a total of approximately 100 million Euro in subsidies was granted in 2018, which triggered close to 1 billion Euro in environmentally relevant investments (BMNT, 2019b). Subsidy rates for renovations funded by the two schemes range from 7 to 11% for private houses to 15–30% for commercial buildings, depending e.g. on whether the building is renovated comprehensively or only in parts.

Regarding the Green Electricity Subsidy, almost 1 billion Euro were disbursed in 2020 for the feed-in tariff – although this is financed by final consumers themselves via a levy on electricity bills – and several hundred million Euro in investment subsidies (E-Control, 2021). As of 2021, the subsidies covered between 4% of the total investment cost for combined heat and power plants and 14% of the total investment cost for small hydro-power plants.

5.4. *What are the time-related characteristics of the instrument design?*

The energy tax rates do not follow a pre-specified time path and are not indexed to inflation. Nominal rates have not changed since the early 2000s and as a consequence real rates have eroded in value. The new emission certificates trading scheme for the buildings and transport sectors currently has a fixed price of €30 per tonne of CO_2 rising to € 55 in 2025. From 1 January 2026 onwards, the so-called "market phase" starts, in which the certificates will be freely traded. However, the design of the market phase, including the emission reduction path it should meet, is as yet unspecified. It will be determined only by 2025, following an evaluation of the fixed-price phase and its effectiveness in view of Austria's national and EU-level climate targets. Depending on the arrangements in place at EU level at this time, the market phase will either consist of a national system or an integration into or other interaction with an EU-wide emission certificate trading system for transport and buildings.

The national and provincial building codes do not follow a pre-specified time path but the national OIB guideline 6 is updated every four years to implement the latest EU directives into national law Also the R&D and adoption subsidies and schemes do not follow a pre-specified path. Their total budgets are announced annually and the funding is available until all the budget is spent. In recent years, the

[17] Note that the effective carbon tax rates implicitly assume that the taxes are solely aimed at reducing GHG emissions, while they may have multiple objectives including generating tax income and correcting for other market failures.

funds have been repeatedly topped up at times of high demand.

5.5. Is the instrument package coherent with respect to the market failures it aims to address?

To obtain an overview of the coherence of a package of policy instruments, we first map the instruments to the market failures they aim to address. Fig. 4 is an example of a mapping exercise for the emission price instruments for the year 2018 and helps to evaluate its coherence in terms of their overall contribution to addressing the environmental market failure in detail. Using the extended energy balance for Austria, the horizontal axis shows all Austrian GHG emissions from energy use as produced by the different emissions sectors. By looking carefully at the (fossil) energy sources consumed in these sectors as well as the focus, scope and strictness of the different instruments, one can map instruments explicitly to the GHG market failure as in Fig. 4 (OECD, 2021). Note that the figure does not cover the energy tax on electricity and its indirect relation with GHG emissions. The national emissions trading scheme, in its 2022–2025 design, addresses GHG emissions from fossil fuels used in the buildings sector directly and could therefore also be mapped easily on top of the effective rate as presented in Fig. 4 (note that biomass is exempted from either price instrument).

Building codes (both national and provincial) aim at saving energy and address the market failure of GHG emissions as long as current heating systems are fossil fuel based. Hence they address the same GHG emissions as the energy tax and emission trading scheme, in particular if more energy-efficient technologies lead to emission reductions. Such impacts also depend on the specification of the energy / thermal requirements, including those for major renovations. In terms of coherence the price instruments sometimes overlap but also seem to be complementary from an overall perspective. The energy taxes on natural gas and oil are all targeted at the implicit carbon emissions in the different fuels consumed in the building sector. The same holds for the new emission trading system which therefore overlaps even though different agents are addressed. The exemption of biomass is based on the assumption of net zero contribution to GHG-emissions.[18] Overall the energy taxes (bar the electricity tax) apply to all remaining 48% of all GHG emissions produced by the residential and commercial sector (the width of the light blue bar under 'Res. & comm').

The overall strictness of the different price instruments can therefore simply be derived from an aggregation of the instruments, i.e. the rate of the new national emissions trading scheme comes *on top* of the relevant energy taxes. When added to the existing effective carbon tax rates in Fig. 4, the total effective carbon tax rate increases from €38 per tCO_2 to €68 in 2022 and €93 in 2025 (assuming that the focus, scope and strictness of the tax on natural gas and heating oil has not changed since 2018). Finally, this overlap will continue until 2026. What happens after 2026 is yet unclear as the design of the market phase of the trading scheme is not yet determined.

Similarly, we consider the coherence of the instruments that address the technology failures first by looking more carefully at their linkage with the technology market failure as explored by the RTA analysis in section 4.2. From this analysis we learned that patenting of eco-innovations in the residential and commercial sector in Austria is strong in technologies for integration of renewables in buildings, whereas it lags behind in technologies useful for improvements in thermal insulation of buildings such as architectural or constructional elements for thermal performance and enabling technologies. Within the overall category of energy efficiency, where Austria performs on average, still several categories stand out in a positive way, i.e. energy-efficient elevators, escalators and moving walkways, lighting technologies, and heating, ventilation and air conditioning technologies.

Accordingly it is interesting to see how the different technology policy instruments are related to these innovative patterns in Austria. From a generic perspective the Forschungsprämie addresses the positive externalities from the generation of new knowledge but has no link to market failures that are specific for eco-innovations such as hurdles related to lock-in characteristics of existing dirty technologies. The Climate and Energy Fund though does provide such (financial) support for projects at various stages of technological development. As far as the funding is related to developing new knowledge on eco-innovations in the past it is likely to have contributed to the reduction of these spillovers.

For adoption externalities the other instruments are important. The building codes at the province-level, for instance, also mandate the use of advanced technologies and thus contribute to their diffusion. The technologies in which Austria has a high RTA include technologies for integration of renewable energy sources in buildings (see Figs. 2 and 3). As a case in point, the city (and province) of Vienna planned to mandate the installation of PV systems in new buildings as of early 2021, but variation exists across provinces in terms of ambition level.

The Housing Support Scheme (Wohnbauförderung), Domestic Environmental Support (Umweltförderung im Inland) and Renovation Campaign address GHG emissions by providing financial support for improvements of the energy performance of buildings. Since the subsidies are typically conditional on (among other things) minimum energy performance or thermal insulation standards, they also support the diffusion of known eco-innovations in which Austria is strong. The same analysis applies to the Green Electricity subsidy which aims at increasing the share of electricity from renewable sources and supports public district heating. These subsidies facilitate further efforts to exploit eco-innovations like those related to the integration of renewable energy sources in buildings as well as Austria's specialisation in technologies for energy-efficient heating, ventilation or air conditioning systems.

From an environmental perspective, the building codes, the Housing Support Scheme and the Domestic Environmental Support / Renovation Campaign overlap with the energy taxes and the emissions trading system as the former group contributes to energy savings and hence, indirectly, to emission reductions. From the perspective of technology diffusion spillovers, all instruments in the former group overlap with each other and with the Green Energy Subsidy.[19]

6. An evaluation of the existing instrument package for decarbonisation in the residential and commercial sector

Having described focus, scope, strictness and time-related characteristics of the individual instruments and the coherence of the instrument package, we can now use our findings to evaluate the instrument package in relation to the policy objective of the Austrian government to reach carbon neutrality by 2040.[20] Here we assume that this objective also applies to the residential and commercial buildings sector.

The descriptions of the energy taxes and the national emissions trading scheme and their interaction show that not all emissions from the sector are covered by a price instrument: emissions from biomass are untaxed following EU regulations. If biomass use is truly circular, and

[18] This biomass consists of about 33% wood pellets, and the remainder comes from wood logs and wood chips (Landwirtschaftskammer Niederösterreich, 2020). Whether emissions from biomass combustion should be taxed depends on many factors, including the sustainability of the biomass used. According to current EU rules, biomass does not imply net additions to the flow of carbon emissions due to carbon capture.

[19] A detailed analysis of the legal texts for the Housing Support Scheme, Domestic Environmental Support Scheme / Renovation Campaign and the Green Electricity subsidy would be needed to be able to describe how the strictness of these instruments interact (e.g. whether firms or households can apply for multiple subsidies for the same underlying investment).

[20] Note that this section does not aim to provide a complete and exhaustive analysis but aims to illustrate how our framework would work in practice.

emissions from biomass combustion are fully covered by forest carbon sequestration, then this policy choice is justified. If only part of emissions from biomass are covered, then these emissions need to be priced, for example through the energy tax. It should be noted that biomass combustion generates emissions of pollutants other than GHGs (e.g. local air pollutants) and that biomass use needs to be priced from this perspective as well. Emissions from gas, heating oil and coal, however, were already covered by the respective energy taxes. The new national emission trading system also covers GHG emissions from the residential and commercial buildings sector, which illustrates that the focus of the two instruments overlap.

Austria's current tax rates for natural gas and heating oil are € 30.74 and € 40.30 per tonne of CO_2 eq. respectively (see Table 1). The introduction of the national emission trading system adds another € 30 in 2022, rising up to € 55 by 2025. So with the additional price of the emission trading system, the overall Austrian rates for the residential and commercial sector seem to be in line with the rates that are generally considered to be necessary for a transition to decarbonisation in 2050 (estimated in 2017 to be at least US$40–80, or €36–72, by 2020, and US$ 50–100, or € 45–90 by 2030; Carbon Pricing Leadership Coalition, 2017).

Austria's objective, however, is carbon neutrality by 2040 rather than 2050. So current rates may not be sufficiently high. Also, energy tax rates are not indexed to inflation (nominal rates have not changed since the early 2000s) so real rates decline over time. To what extent the current rates properly account for other environmental damages such as impacts related to air quality is also unclear. From this broader perspective, we conclude that the observed tax rates are too low.

Another issue is the potential interaction between the two instruments during the market phase of the national trading system (which starts in 2026). What will happen precisely depends on the exact design of the trading instrument. If designed as a national cap and trade system for gas use in buildings, then a future increase in energy tax rates might not have an impact on remaining emissions because it would also decrease the certificate price in the trading system (waterbed effect).[21]

The current energy tax rate structure does not provide appropriate incentives for the use of the less emission-intensive energy carriers. The tax rate per tonne of CO_2 of the tax on natural gas is about a third lower than the rate for heating oil (see Table 1).[22] Moreover, the tax rate per GJ and per tonne of CO_2 is highest for electricity. Such a rate structure does not encourage substitution from gas and heating oil to electricity-based technologies. Furthermore, the tax on electricity does not discriminate between generation sources. If marginal costs for electricity from renewable sources are lower than that from fossil sources, then the tax distorts relative prices. Introducing differentiated electricity tax rates or input-based taxation of electricity production according to the fuel source (fossil or renewable) could improve focus and bring its strictness more in line with the transition ambition.

Austria also has a broad instrument package aimed at innovation and adoption of eco-technologies. Austria's R&D tax credit which currently applies to all companies' R&D expenditures regardless of field. As noted above, the overall public funding for energy technology R&D is relatively generous as compared to the EU as a whole, and a relatively large share of it is spent on energy efficiency in buildings, thereby contributing to reduced (fossil) energy demand.[23] To improve its focus towards climate neutrality in the residential and commercial sector, a specific (e.g. higher) tax credit for R&D supporting the decarbonisation of the building stock could be introduced. The additional stimulus to innovation provided by this instrument is particularly relevant for technologies related to elements improving the thermal performance of buildings, given Austria's comparatively weak performance in the RTA analysis in this field. The double rate of the investment allowance for ecological investments, introduced during the Covid crisis in 2020–2021, could serve as an example.

Furthermore, current building codes ensure that new buildings and construction elements used in renovation meet minimum requirements. Although these codes apply to the same regulatory base as the tax and trading system, they also have a specific role to play in shifting technological change away from the dirty lock-in. This shift is also supported by the Housing Support Scheme and Domestic Environmental Support / Renovation Campaign. Both instruments provide additional incentives to adopt eco-innovations in new buildings or for renovations.

Such incentives also change the prospect for innovators of eco-innovations (see also Noailly and Batrakova, 2010). If innovations expect policy makers to increase the strictness of building codes and diffusion support they are more likely to innovate. In Austria, the national OIB guideline 6 is revised every four years. However, national experts consider the OIB's implementation of the EU directives as not strict enough and the current rate of renovation as too low to achieve climate neutrality in the sector by 2040. This would require more than doubling the current renovation rate by 2025 (Amann et al., 2020). To this end, the Austrian government declaration (2020) includes a thermal renovation requirement coupled with means-tested financial support for poorer households, but this measure has so far not been implemented.

Whatever their impact on innovation, the federal and province-level building codes certainly support the diffusion of eco-innovations like the adoption subsidies. Austria has a technological advantage (RTA of 1.2) in technologies relating to the integration of renewable energy sources in buildings, including photovoltaic, solar thermal energy or wind power systems and heat pumps. The country also has a technological advantage in energy-efficient heating, ventilation or air conditioning systems, which include central heating or hot-water supply systems using heat pumps, district heating and waste heat, heat recovery systems and passive house technology. These high RTA scores suggest that the market failure of knowledge spillover from new knowledge has largely been abated already, but that the existing building codes and support schemes might not sufficiently support diffusion.

In section 4.2 we also observed that Austria has a revealed technological *dis*advantage for several relevant technology fields, notably enabling technologies in buildings (RTA equal to 0.58), and architectural or constructional elements improving the thermal performance of buildings (RTA 0.69). Hence additional policy support, such as specific R&D subsidies or research grants via the Climate and Energy Fund, can contribute to new eco-innovations in these technology fields, which in turn contribute to the reduction of emissions from the residential and commercial sector.

Building codes and subsidy schemes for the diffusion of particular technologies should be updated on a regular basis to avoid incentive compatibility problems (Ruijs and Vollebergh, 2013). A key feature of

[21] Similar impacts were found for the EU ETS design before the introduction of the cancellation mechanism (see Brink et al., 2016).

[22] Carbon emission from these fossil fuels have a fixed 1:1 relationship with their (energy) tax base, with natural gas typically being the lowest-emission fuel per GJ. The rate for coal is not at all in line with its pollutive power per GJ, but this fuel has a negligible share in energy consumption by buildings.

[23] While on average over the period from 2010 to 2018, 48 million Euro were spent across the EU-28, Austria spent 123 million Euro. Germany, which is ten times larger in terms of population, spent 830 million Euro, and the Netherlands, with almost twice Austria's population, spent 150 million Euro. Of Austria's total, about 12% were allocated to energy efficiency in buildings, while the corresponding figures for the Netherlands and Germany were 5% and 3% respectively (IEA, 2020).

subsidies that use a (dynamic) technology list is that this makes the regulation flexible over time, allowing policy makers to adapt the program to newly developed eco-innovations. Such a list also reduces information asymmetry between supply of and demand for new technologies which is important to reduce the likelihood of free riding.

Overall, the evaluation of policy instruments for Austria's residential and commercial buildings sector shows that there are several Sensitive Intervention Points for the Austrian government to provide kicks the current state of socioeconomic, technological and political systems. We find that neither the current price instruments (energy taxes and national emissions trading system) nor the current building codes are sufficiently strict to meet the 2040 carbon neutrality target. Furthermore, the impact of the emissions trading system on emissions could be weakened in the market phase (from 2026 onwards) if the new design of this system introduces a waterbed effect. We also identify several technology fields where Austria's RTA is low and the knowledge spillover market failure could be abated through targeted green R&D subsidies (e.g. via the Climate and Energy Fund).

7. Conclusion

In this paper, we present a framework that helps policy makers to explicitly evaluate the link between the design of instruments, the market failures they aim to address, and the policy objective of carbon neutrality. The framework is solidly rooted in the environmental economics literature and the literature on the economics of technological change. We have argued that a comprehensive policy package for carbon neutrality requires instruments that address underpricing of environmental externalities and underproduction of eco-innovations. Moreover, both instruments aimed at pricing energy use or emissions and non-price instruments, such as building codes, support the adoption of eco-innovations via a relative-price effect and the invention and innovation of eco-technologies via a market size effect. Therefore, also price instruments (including standards) can be considered as technology adoption instruments: they support learning by doing and using in the production and installation phases of new technologies and support the diffusion of knowledge about these technologies.

We have also argued that a description of the status quo is required to identify Sensitive Intervention Points for policy interventions. Descriptions of the existing environmental and technological market failures and the existing package of environmental and technology policy instruments form the basis of policy advice that is targeted towards the shortcomings of the current system. Stock-taking of key instrument attributes – focus, scope, strictness and the instrument's time profile – together with a mapping of the existing instruments to their respective market failures allows for a precise description of the interaction of the instruments and thereby of the overall incentives for a transition towards a carbon-neutral economy of the instrument package. The resulting overview can subsequently be compared against the policy objective to evaluate the performance of the instrument package and identify Sensitive Intervention Points.

The application of our framework to the Austrian residential and commercial buildings sector illustrates this claim. We find that neither the current price instruments (energy taxes and national emissions trading system) nor the current building codes are sufficiently strict to meet the 2040 carbon neutrality target. Furthermore, we find that the impact of the emissions trading system on emissions could be weakened in the market phase (from 2026 onwards) if the new design of this system introduces a waterbed effect. We also identify several technology fields where the patenting of eco-innovations in Austria is low when compared to international peers and the knowledge spillover market failure could be abated through targeted green R&D subsidies (e.g. via the Climate and Energy Fund). These conclusion build on the description of the status quo in terms of GHG emissions, eco-innovation performance and the attributes and interaction of the existing set of instruments.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. The index of revealed technological advantage (RTA)

The RTA index is computed using data on the number of patent applications in climate change mitigation technologies related to different emission sectors. The RTA index for country i and technology field d can be written mathematically as follows[24]:

$$\mathrm{RTA}_{d,i} = \frac{P_{d,i} / \sum_i P_{d,i}}{\sum_d P_{d,i} \Big/ \sum_{d,i} P_{d,i}}$$

where P refers to the number of patent applications as a measure of innovation activity. The RTA expresses country i's share of all countries' patent applications in technology field d relative to its share of all countries' patent applications in all technology fields.

For our indicator of eco-innovation performance, we select technology field d in the numerator to be an environmental technology field, specifically a climate change mitigation technology in a particular emission sector. The index then takes the value 0 when the country holds no patent in that given climate change mitigation technology field; the value 1 when the country's share of patent applications in the given climate change

[24] The RTA is identical in structure to the more commonly known index of revealed comparative advantage (RCA) used to measure relative specialisation in international trade. See OECD (2013) for further description of the RTA.

mitigation technology field is equal to its share of patent applications in all fields (no specialisation); and a value greater 1 when its share in the given climate change mitigation technology field is greater than its share in all technology fields (positive specialisation or revealed technological advantage).

Patent applications are standardized documents classified by technology field according to the International Patent Classification of the World Intellectual Property Organization. Specialized classifications of environmental technologies have been developed, such as the OECD ENV-TECH classification (OECD, 2016), which records pollution abatement technologies and climate change mitigation technologies related to different emission sectors (see Table A1 below). Patent applications are published and are thus readily available and comparable across countries. They are often used as a proxy for innovation in the empirical literature (Popp, 2002; Popp et al., 2010), although not all innovations are patented and not all patents represent innovations (i.e. commercially successful inventions).

Table A1
OECD ENV-TECH climate change mitigation technologies by emission sectors.

Transportation:
Road transport (conventional, hybrid or electric vehicles)
Rail transport
Air transport
Maritime or waterways transport
Enabling technologies in transport (electric vehicle charging, application of fuel cell and hydrogen technology to transportation)
Buildings:
Integration of renewable energy sources in buildings
Energy efficiency in buildings (Lighting, heating, home appliances, elevators, ICT)
Architectural or constructional elements improving the thermal performance of buildings
Enabling technologies in buildings
Production or processing of goods:
Metal processing
Chemical industry
Oil refining and petrochemical industry
Processing of minerals
Agriculture, livestock and agroalimentary industries
Final industrial or consumer products
Sector-wide applications
Enabling technologies with a potential contribution to greenhouse gas emissions mitigation
Energy generation, transmission or distribution:
Renewable energy generation (wind, solar, hydro etc.)
Energy generation from fuels of non-fossil origin (e.g. biofuels)
Combustion technologies with mitigation potential
Efficiency in electrical power generation, transmission or distribution
Enabling technologies in the energy sector (batteries, hydrogen technology, fuel cells, smart grids in the energy sector)
Wastewater treatment or waste management:
Wastewater treatment
Solid waste management (waste collection, processing or separation, and reuse, recycling or recovery technologies)
Enabling technologies or technologies with a potential or indirect contribution to greenhouse gas emissions mitigation
Capture, storage, sequestration or disposal of greenhouse gases:
CO_2 capture and storage
Capture or disposal of greenhouse gases other than CO_2 (N_2O, CH_4, PFC, HFC, SF6).

*Source: OECD (2016), 'Patent search strategies for the identification of selected environment-related technologies (ENV-TECH)',https://www.oecd.org/environment/consumption-innovation/ENV-tech%20search%20strategies,%20version%20for%20OECDstat%20(2016).pdf, accessed 21 July 2021; and OECD (2020), 'Patents in environment-related technologies: Technology development by inventor country, OECD Environment Statistics (database),*https://doi.org/10.1787/data-00760-en*(accessed on 10 June 2020).*

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