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Effects of environmental and carbon taxation – a literature review[1]

Angela Köppl, Margit Schratzenstaller

Abstract

In view of the challenges posed by climate change and the increase in climate targets by 2030 in the EU, as well as Austria's goal of achieving climate neutrality by 2040, the question of effective climate policy instruments is gaining in importance. The pricing of CO_2, for instance in the form of a carbon tax, and the question of its effects are therefore attracting increasing attention in the academic as well as economic and environmental policy debate. The paper provides a detailed overview of the theoretical and empirical literature on the effects of carbon taxes. The focus is on the most important impact dimensions of carbon taxes: environmental effectiveness, effects on important macroeconomic variables (especially growth and employment), effects on innovation and competitiveness, distributional effects, and public acceptance.

Keywords: carbon tax, environmental taxation, double dividend hypothesis, distributional effects, climate policy, price-based instruments

JEL-Codes: H23, Q54, Q58

[1] This paper is based on the literature review provided in European Commission, Taxation in support of green transition: an overview and assessment of existing tax practices to reduce greenhouse gas emissions, final report, Brussels: European Commission, 2020. The final report was written by Ecorys and WIFO and received funding from the European Commission. We are grateful to Stefan Schleicher for important contributions and suggestions. Moreover, the paper benefited greatly from thorough reviews by Mikael Skou Andersen and Stefan Weishaar and from fruitful discussions with Thomas Kruger, Marta Kulesza and Andreas Pauer (ECORYS) as well as colleagues from the European Commission and particular from DG TAXUD. We are indebted to Susanne and Andrea Sutrich for careful research assistance. All remaining errors are our own.

Introduction

This paper provides a comprehensive review of the relevant theoretical and empirical literature addressing the effects of environmental taxes regarding several criteria commonly used in the literature: effectiveness, cost efficiency, impacts on competitiveness and innovation, distributional implications, and political acceptance and administration of the environmental tax schemes.

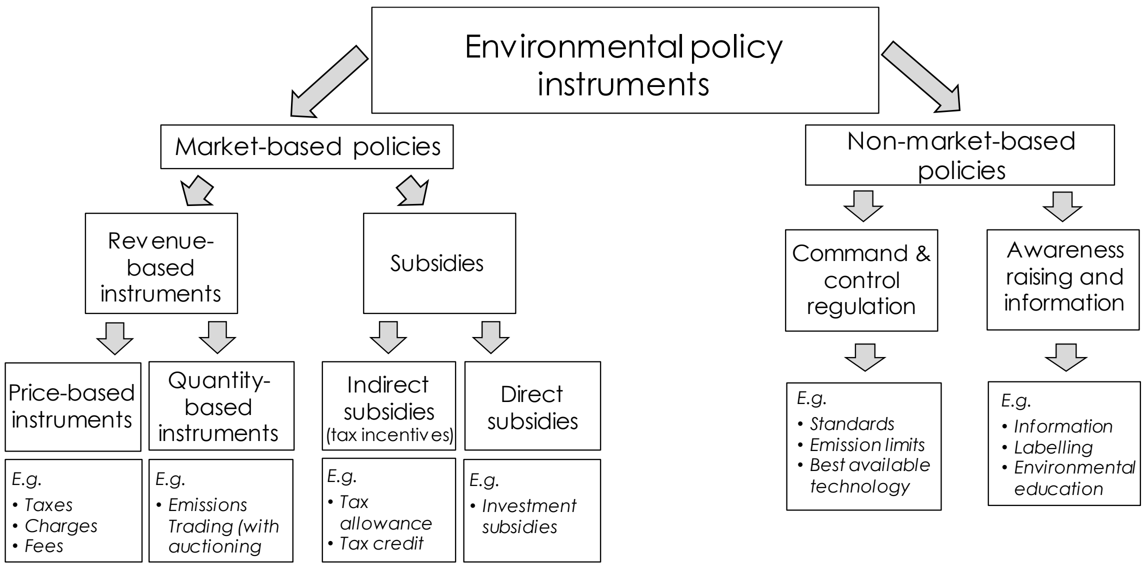
1. Overview over environmental policy instruments

Environmental taxes are one instrument in a toolbox of available environmental policy instruments. Figure 1 gives a schematic overview over the range of environmental policy instruments.

Two basic categories can be distinguished: Market based (e.g., fiscal) instruments on the one hand and non-market-based instruments on the other hand. The latter group includes regulatory instruments which will not be considered further in the following.

Fiscal instruments, in turn, can be differentiated into incentives that make environmentally undesirable behaviour more expensive (taxes, emissions trading[2]) or that promote environmentally desirable behaviour (environmentally beneficial tax incentives, subsidies, grants). The paper focuses on taxes among price-based instruments.

Figure 1: **Overview of environmental policy instruments**



Source: Own.

[2] Emissions trading is in the case of grandfathering allowances not a fiscal instrument per se.

In the following we focus on fiscal instruments and provide an overview over the current state of the theoretical and empirical literature on the topic of environmental taxes as the most important pricing instruments[3].

2. The rationale for environmental taxes – theoretical framework

The literature review on the theoretical aspects of environmental taxes refers to both newer contributions focusing on carbon taxes and to contributions that reflect the increasing importance of taxes in environmental economics starting already several decades ago. It summarises the literature on environmental taxes in terms of effectiveness, efficiency, impacts on distribution as well as innovation and competitiveness and elaborates on some specificities of environmental taxes in the context of climate change. These aspects are complemented by a review on instrument choice.

2.1 The basic idea of pricing instruments and environmental tax reforms

Economists and environmental economists have been promoting environmental taxes already for several decades now as key instrument of environmental policy (Baumol and Oates 1971, Pearce and Turner 1990, Pearce 1991, Goulder 1995, Köppl et al. 1996, Speck et al. 2006). The field is the subject of broad and intensive research, both on theoretical issues as well as from an empirical perspective. Accordingly, there is a vast body of literature available on environmental taxes in general and, more recently, with a specific focus on carbon taxes (e.g. Kosonen and Nicodème 2009; Milne and Andersen 2014; Goulder et al. 2018). Thus, the design and the effects of environmental taxes are one of the best researched areas in environmental and climate economics, which stands in contrast to their actual relevance in existing tax systems so far.

Environmental taxes aiming at pricing individual environmentally harmful activities are emphasised as an effective and efficient instrument in environmental economics (e.g. Baumol and Oates 1988, Tietenberg 2009) to internalise negative impacts stemming from individual consumption behaviour and production activities. This goal is to be achieved by putting a price on negative externalities with the tax rate being set at the marginal social damage caused. The basic idea to use taxes to cope with negative externalities that are not included in market prices dates back to Pigou (1920), who, however, does not specifically or exclusively focus on the environment. Based on his seminal work so-called Pigouvian taxes have gained a place as key market-based instrument in the form of environmental taxes in general and of carbon taxes in the context of climate change in particular.

Environmental taxes are repeatedly integrated in the broader context of an environmental tax reform[4], i.e., the shift of the tax burden from labour to resource and environmental

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[3] Emissions trading as an alternative pricing instruments is discussed briefly.

[4] The common view of environmental tax reform (ETR) is the use of the revenue from environmental taxes to reduce distortionary taxes, e.g. taxes on labour. The European Environmental Agency (EEA 2005) e.g. defines an ETR as "… the term used for changes in the national tax system where the burden of taxes shifts from economic functions, sometimes

consumption. Such tax reforms have been a top research focus in environmental economics and have been on the agenda in the economic policy debate already for several decades (Pearce 1991, Goulder 1995, Ekins and Speck 2011). They are based on the double dividend hypothesis, arguing that such a tax shift, in addition to reducing environmental pollution, also brings about positive economic effects by using the revenues from environmental taxes to cut other more distortionary taxes[5].

In contrast to quantity-based instruments that have been gaining in importance worldwide in the aftermath of the Kyoto protocol and are applied in the EU in the form of the EU emission trading system, aiming at establishing a price for carbon emissions by regulating their quantity, environmental taxes set a price for environmentally harmful activities (e.g. the emission of greenhouse gases) to influence their quantity. The similarities and differences between price- and quantity-based economic instruments are also discussed in the context of carbon pricing as well as political economy arguments that support the acceptability of carbon taxes.

2.2 How to determine the pricing of externalities

In an ideal world, the appropriate price of environmental externalities can be determined precisely, marginal damage and abatement costs are known, technologies for abatement investments are available, and the optimal abatement activity in response to the tax is chosen. In theory and in a perfect market situation taxes and allowance prices in a trading system are identical. The underlying assumption and pre-condition for the similarity of both regulatory systems are that the regulator and all market actors have equal information and uncertainty is negligible.

Figure 2 exhibits the basic elements of this understanding both for consumption and for production of a commodity that generates besides private (marginal) costs also (marginal) damage costs. The optimal private choice both for a consumer or a producer is characterised by equating marginal benefits and marginal costs. However, the existence of social damage costs requires a tax that allocates the external costs to private actors, where the tax rate reflects the social damage costs. This shift from a private optimum to a social optimum can be induced by a Pigouvian tax.

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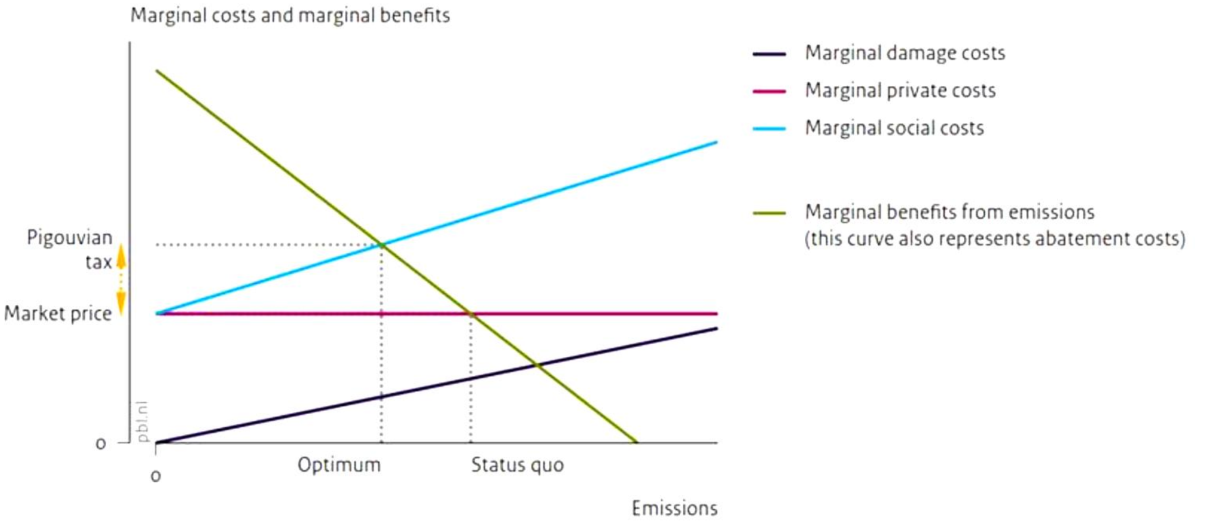
called 'goods', such as labour (personal income tax), capital (corporate income tax) and consumption (VAT and other indirect taxes), to activities that lead to environmental pressures and natural resource use, sometimes called 'bads'."

[5] See, e.g., Bovenberg and de Mooij (1994, 1997), Parry (1995), Goulder (1995, 2000, 2013) and Fullerton and Metcalf (1997) on such an interaction of environmental taxes with the overall tax system.

Figure 2: **The basic theory of environmental pricing**



Source: Vollebergh (2012).

In the context of carbon emissions this tax rate on the market price would then be the optimal carbon price. In the case of a stock pollutant[6], as GHG emissions, however, and due to the complexities of the climate system, as well as the time separation of abatement costs and climate damage or benefits from emission mitigation, there is a broad range of estimates for the optimal carbon price, originating from differing model assumptions. Furthermore, as follows from Weitzman (2009, 2014) and his arguments on the climate tail risks (Wagner and Weitzman 2018) – i.e. the low probability of catastrophic climate change –, the determination of the optimal carbon prices is restricted by the underlying uncertainties. A similar argumentation can be found in Marron and Toder (2014) who stress that the estimated social costs of carbon[7] depend on controversial model assumptions. This argument does not dwarf the usefulness of carbon taxes and carbon prices but sheds more light on risks and uncertainties connected to climate change that are often not shown in standard modelling exercises. Pindyck (2013a, 2013b) argues that because of high uncertainty and risk regarding the damage function of climate change, technological change and thus on the social cost of climate change[8], these aspects taken together limit standard cost-benefit analysis. These constraints to standard cost-

[6] GHG emissions remain in the atmosphere for a long time and the yearly flows of GHG emissions add to GHG concentration in the atmosphere.

[7] For the transport sector, the European Commission takes a broad perspective on external costs of transport and relies on the concept of avoidance costs for climate costs. In the assessment not only climate costs are considered but also other external costs such as noise, congestion, accident costs, etc. (European Commission 2019).

[8] The social cost of carbon (SCC) corresponds to the monetarised marginal cost of carbon emissions and is used for the assessment of climate policy. An overview over different modelling approaches and estimates on the SCC can be found in Wang et al. (2019) and Tol (2018).

benefit analysis are, however, often not reflected in conventional economic models. This leads to a broad range of estimates on the social cost of carbon, which are differentiated further by the chosen rate of pure time preference and the discount rate of consumption[9] (e.g. Stern 2007, Mankiw 2009). Pindyck (2013b, 2019[10]) concludes that even if the true social costs of carbon are not known, a tax based on a rough estimate would signal that the costs of climate change need to be internalised in the prices. With increasing knowledge on the social costs of climate change the tax could be adjusted accordingly. Marron and Toder (2014) put forward as an alternative approach a carbon tax rate aligned to a political emission target. The resulting tax rate would not necessarily reflect the true social cost of carbon but would still ensure a cost-effective achievement of the policy target. Rezai and van der Ploeg (2019a) discuss in a simple framework how assumptions on the development of various drivers of climate policy, like the discount rate, technological progress, geophysical reactions as well as international climate policy impact outcomes. One of their conclusions is that the price for carbon is crucially driven by ethical considerations, that is on assumptions on the size and the development of the discount rate over time. Specifically, they illustrate how a hyperbolic discount rate impacts the carbon price.[11]

2.3 Effectiveness of environmental tax (dis)incentives

In principle, the introduction of environmental taxes or the implementation of an environmental tax reform should focus on the steering effect or environmental effectiveness of the instrument. The main motive is to set prices for negative external effects via fiscal interventions which increase the price of environmentally damaging inputs or activities. The tax base can be specified according to various criteria, depending on the type of externality to be regulated. This should change production and consumption activities towards more sustainable or environmentally friendly structures.

An environmental tax can be used to increase the price of a certain input or activity (e.g. a levy on fertilizers, pesticides or aircraft noise). If environmental pollution is caused by all economic sectors, a cross-sectoral, uniform environmental tax should be chosen, such as a tax on fossil fuels according to their specific climate impact in order to influence the current consumption by setting a price for external effects. Alternatively, instead of a tax on fossil fuels, i.e. an input tax, one could apply an emission tax, i.e. an output tax directly related to the pollution

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[9] Since climate change is a long-term issue the size of the discount rate is a decisive factor on cost estimates of climate change. The differentiation between the rate of pure time preference and the discount rate on consumption refers on the one hand to the value the current generation ascribes to welfare and wellbeing of future generations. On the other hand, the discount rate for consumption transfers the value of a unit of future consumption into the value of a unit of consumption today.

[10] In a recent paper Pindyck (2019) presents the estimation of an average social cost of carbon based on an expert survey. The expert opinions on average deliver higher costs of carbon than can typically be found in economic analyses. The higher SCC from the survey analysis are driven by experts' beliefs regarding a potential extreme damage with large GDP losses.

[11] For a thorough discussion on the appropriate carbon price, see also Rezai and van der Ploeg (2019b).

caused. In practice, inputs are often more easily accessible and are used as basis for calculating or estimating emissions. This is also the case in the context of climate change.

Taxing carbon emissions directly is not straightforward. Instead, in practice emission factors of the use of fossil fuels and their respective carbon content are used. However, such an indirect approach does not account for process emissions e.g. from steel or cement industries. Also, putting a tax on non-carbon greenhouse gas emissions might be associated with high administrative costs compared to taxing fossil fuel-based emissions.[12] When deciding on the tax base, policy makers will thus be confronted with a trade-off between the scope of the GHG emissions covered on the one hand, and administrative costs on the other hand.[13]

Taxes can also be used to influence investment and purchase of durable consumer goods, since these decisions subsequently determine emissions over the whole service life of the capital stock and of products. Fiscal interventions to influence the investment phase are set, e.g. a purchase tax for the transport sector, often with a specific environmental differentiation in tax rates.

Environmental taxes are characterised by a variety of design options with respect to tax base, tax rate and exemptions, and in the broader context of environmental tax reforms also regarding the redistribution of tax revenues. The price elasticity of demand or the tax incidence of environmental taxes influence the effectiveness of the tax. The extent to which the tax burden can be passed over e.g. to consumers when the production sector is taxed determines the distributional effects.

Summarising, the basic economic rationale underlying the effectiveness hypotheses is twofold: (1) there is a need for taxing certain side effects from economic activities, as the harm they are imposing on society (i.e. their negative external effects) is otherwise not considered in market transactions; and (2) the tax that attaches a price to these external effects alters individual choices and thus reduces environmentally harmful effects. Pricing negative externalities has been one of the central pillars in environmental economics for long.

2.4 The double dividend hypothesis

The so-called double dividend hypothesis brings together the economic and the environmental dimensions of environmental taxes. The double dividend hypothesis claims that a double dividend may be expected if revenues arising from environmental taxation are used to decrease taxes on labour (Pearce 1991, Goulder 1995, 2000, 2013, Bovenberg and Goulder 1997), thus reducing existing distortions caused by labour taxation. Accordingly, increased or more effective use of environmental taxes might lead to both environmental and economic improvement, by shifting the tax burden away from more distortive taxes (OECD 2010). A revenue-

[12] There exist clear emission factors for each fossil fuel that can be readily translated into CO_2 intensity (emissions per energy unit) which can be the basis for a respective carbon tax. Such a carbon tax translates into a specific price increase per fossil energy consumed. Non-CO_2 emissions vary greatly among sectors (e.g. livestock, fertilizer production) and regions. Data requirements and estimates on emission intensities thus could be more challenging than for CO_2 emissions.

[13] On a discussion on administrative costs of green taxes see e.g. Smulders and Vollebergh (1999).

neutral environmental tax reform can generate positive employment effects (second dividend) in addition to achieving a specific environmental goal (first dividend). Obviously, the redistribution of tax revenues is central to the realisation of this effect.

The strong double dividend hypothesis postulates that using environmental tax revenues to decrease distorting taxes leads to an overall welfare increase, while according to the weak double dividend hypothesis revenue recycling via a reduction of distorting taxes is more efficient than granting lump-sum transfers (Goulder 1995). An intermediate double dividend is the claim that whether an internalising environmental tax that replaces a distortionary tax will increase welfare depends on the specific properties of the distortionary tax (McCoy 1997, Andersen 2009).[14]

The findings in the theoretical literature on the double dividend hypothesis are ambiguous, however. A critical assessment has been put forward by Bovenberg and de Mooij (1994) who show in a simple general equilibrium model that pre-existing distortionary taxation can even be aggravated by environmental taxes. Fullerton and Metcalf (1997) state that a double dividend cannot be expected in all cases. They basically argue that it depends on the specific economic environment in which a restructuring of the tax system takes place. One of the authors' main conclusions is that the focus on the revenue-raising effect of environmental taxes is misplaced by showing that different policies might have the same environmental and economic effects but differ in their revenue-raising effect. They analyse three policy options that result in identical environmental benefits and economic outcomes: (1) one policy raises revenue from the environmental component to be used for a reduction of income taxes; (2) a command-and-control policy that shows identical economic effects compared to the former option; and (3) a subsidy financed by an increase in income taxes. The crucial point is that it is the specific design of policies that determines the economic outcome. Barrios et al. (2013) argue that the main weakness of environmental taxes consists in their decreasing revenues due to their shrinking tax base if they are successful in containing the environmentally harmful activities they are taxing. In his review article, Freire-González (2018) summarises the theoretical aspects discussed above and provides an empirical meta-analysis on the validity of the double dividend hypothesis (see section 3.4.2). Although the theoretical literature on the double dividend hypothesis is extensive, there is no consensus concerning its validity, albeit the first dividend is not contested. Two aspects drive the specific results: (1) the complexity of the model and the economic structure that forms the starting point for the analysis; and (2) the assumptions that enter the model.

2.5 Cost efficiency of the tax measures

The main advantage of taxes and other market-based instruments compared with command-and-control instruments (standards, quotas, product bans) is their efficiency (Kosonen and Nicodème 2009). The efficiency of internalising environmental taxes vis-à-vis regulatory measures is explained with the flexibility polluters are provided with in how to respond when

[14] Jaeger (2012) discusses the evolution of the literature on the DD literature and points at remaining ambiguities in the debate stemming from specific conditions in the economy. See also Parry (1995) on the tax interdependency effect.

adjusting their operations. The cost efficiency of taxes and other price instruments may be reduced, however, when fiscal interactions, i.e. the effects of environmental taxation in factor markets (labour, in particular), are accounted for. The "tax interaction effect" as argued by Parry (1995) Parry and Oates (1998) describes a negative welfare effect resulting from the interaction of the newly introduced environmental tax with the already existing (distortionary) tax system. The environmental tax is reflected in higher consumer prices, which in turn means a reduction in real wages and leads to a decline in the supply of labour, unless revenues are recycled back into a lowering of other taxes. Parry (1995) suggests offsetting environmental tax burdens by lowering income taxes and/or the social security contributions of employers and thus to mitigate the tax interaction effect.

Generally, taxes are favoured by economic theory as they are expected to encourage broad-based action to reduce environmental damage at least cost. Pricing instruments are seen as cost efficient in a static and a dynamic perspective: it is left to firms and individuals to find the least cost solutions and to search for new solutions that may reduce emissions further (Aldy and Stavins 2011). This of course implies that the regulator sets the optimal price and that economic actors know the social costs of carbon and have perfect information on abatement costs, which is not always the case in practice.

The empirical evidence on existing taxes shows, however, a large differentiation in effective tax rates when looking at the cost efficiency of carbon taxes (OECD 2018, 2019). In addition, doubts regarding the effectiveness of the tax, market barriers and stock-flow-interactions pose as behavioural constraints affecting the efficiency of taxes. GHG emissions are the result of the interaction between stocks and flows, e.g. the quality of the building stock and the related need for energy flows (Köppl and Schleicher 2018). Different barriers may arise as environmental taxes are typically levied on energy flows that do not directly influence infrastructure decisions. A tax on transport fuels may lead to the avoidance of redundant trips or may influence the model choice when purchasing a new car. However, fuel taxation has no direct influence on decisions on transport infrastructure investment (rail versus roads), which ultimately determines mobility options (e.g. Köppl et al. 2019). A well-known market failure related to the stock-flow interaction in housing is e.g. the tenant-owner problem. Typically, the tenant must bear the costs arising from an environmental tax on energy for housing but cannot decide on the energy efficiency of the building stock which determines the need for energy flows. Most of the standard literature and analyses on carbon taxes do not address these market failures explicitly.

2.6 Impacts on Competitiveness and innovation

From the perspective of economic sustainability, their incentive-enhancing effects towards green innovation are another benefit of environmental taxes. They provide incentives for further efficiency gains, green investment and innovation (OECD 2010). Van den Bergh (2013) highlights the importance "to get the prices right" in the context of environmental innovation. Acemoglu et al. (2012, 2013, 2014) and Popp et al. (2010) conclude that environmental taxes coupled with state subsidies can effectively redirect innovation towards environmental-friendly technologies and energy efficient innovation. Borissov et al. (2019) argue that clean production tends to be skill intensive, carbon pricing may have a positive effect on human capital accumulation and therefore on economic growth: A carbon tax influences technology choice and thus provides incentives for human capital accumulation. Lilliestam et al. (2020) refer to the theoretical argument of a dynamic effect of taxes on innovation. In theory environmental taxes incentivise continuous innovation of low-emission technologies in order to avoid paying the taxes. They point out, however, that besides costs, other relevant mechanisms influence the technological transition process.Since the beginning of the 1990s, and significantly influenced by Porter (1991) and Porter and van der Linde (1995), the hypothesis that environmental regulation can have a positive influence on growth and competitiveness has gained in importance. The proponents of this so-called Porter hypothesis assume that environmental policy can play an active role in improving and securing the competitive position of companies or entire industries. At the heart of the argument is the idea that environmental policy and regulation creates competitive advantages in a dynamic perspective because firms develop new innovative technologies and products as a result of environmental regulation that is efficient and flexible, e.g. by means of economic instruments.

In practice, however, concerns about competitiveness losses often lead to the introduction of exemptions from environmental taxes: a number of countries grant rebates on energy taxes for exposed industries or exempt these industries from environmental taxes if e.g. they are already regulated by emissions trading. This strategy is applied, for example, by Sweden, Norway and Denmark (Andersen 2004) and Switzerland (Diekmann and Bruderer Enzler 2019). Obviously, such exemptions reduce the environmental effectiveness of carbon taxes, while increasing the administrative burden. At the same time, accounting for competitiveness concerns of the industry in the design of environmental taxes supports their public acceptance.

Regarding the impact of carbon taxes on the competitiveness of companies affected by the tax, the argument is that in a highly globalised world, differences in the stringency of environmental policy could influence location decisions and shift polluting production capacities to countries or regions with less environmental regulations. This discussion is led under the heading "carbon leakage" (Zhang 2012, Barker et al. 2007) and the "pollution haven hypothesis" (e.g. Koźluki and Timiliotis 2016, Ambec et al. 2013, Rubashkina et al. 2015), when it comes to carbon pricing. Marron and Toder (2014) also point at potential competitive disadvantages caused by a national carbon tax and refer to the option of border tax adjustment, which, however, would be very complex when applied to intermediate and final products. The fear of relocation of emissions was one of the reasons why the EU emissions trading scheme stipulated free allocation of emission rights for production sectors that face international competition and in certain cases may not have emission avoiding alternatives (e.g. Aldy and Stavins 2011, Dechezleprêtre and Sato 2017, Aldy and Pizer 2015). However, policies aiming at avoiding losses in competitiveness are suboptimal from an environmental perspective as Klenert et al. (2017) point out. Their argument is that mitigation policies would allow low-emission industries to gain competitive advantages vis-à-vis more emission-intensive industries. Porter and van der Linde (1995) argue that innovation is induced and stimulated by environmental regulation. In this understanding, the function of politics as a prerequisite or support for the emergence of competitive advantages is brought to the fore. The first mover advantage argument is also emphasised by the EU as an essential advantage of medium-term energy and climate policy objectives.

Regarding innovation effects according to the Porter hypothesis, the theoretical literature[15] generally points to a positive effect of environmental regulation on environmental innovations, but this does not offset the regulatory costs.

2.7 Distributional implications and public acceptability

Baranzini et al. (2017) address several issues related to the political economy of carbon pricing: the distributional consequences, lobbying, co-benefits, international policy coordination, motivational crowding in/out, and long-term commitment. While an in-depth discussion of all these political economy issues would exceed the scope of this study, distributional implications and public acceptability, as important political economy aspects associated with the implementation of carbon taxes, shall be briefly addressed in this section. The bulk of existing research on distributional effects of carbon taxes and the impact of various recycling options consists of empirical studies. This is also reflected in Section 3.6 on the review of empirical studies of distributional effects.

Distributional implications and acceptability are predominantly discussed from a household perspective in the literature, with only a minor share in analyses addressing distributional effects for the production sector. Typically, a pass-through of carbon taxes to consumers is assumed. Similar to other consumption taxes, carbon taxes would be regressive as lower income households spend a larger share of their income or a higher share of their consumption expenditure on energy intensive products (e.g. Marron and Toder 2014). Similarly, Combet et al. (2010) show in a partial equilibrium setting that low-income households are affected in two ways by carbon pricing: an income effect that shows in a lower purchasing power of their disposable income, and the basic need character of emission-intensive goods, resulting in a higher welfare loss for lower-income households compared to high-income households. This reasoning, however, assumes that the entire tax impact is passed on to consumers and no structural changes in the energy system will result from carbon pricing.

Distributional impacts not only apply to the household sector but may also affect production sectors differently. One relevant determinant of the distributional impacts in the production sector is the size of the price elasticity of demand, which determines the extent to which firms can pass on the tax to consumers and which may differ across sectors (Wang et al. 2016). Sectors with a high price elasticity, i.e. large demand reactions to price changes, would have to absorb the carbon tax from the direct use of fossil fuels as well as potential price increases from intermediates. Confronted with a price-sensitive demand this could lead to profit losses in price elastic sectors. Sectors with an inelastic demand could shift the tax burden to downstream sectors and consumers. The sectoral impact of a tax may therefore vary considerably.

Sectors with high fossil fuel consumption and exposure to international competition are likely to be affected by a higher tax burden, at least in the short term. In the long run innovation and the switch to less emitting production technologies may alleviate this effect. (Temporary)

[15] Enevoldsen et al. (2009) try to empirically assess the effects on the competitiveness of industries.

preferential tax treatment, lower tax rates or tax exemptions could reduce sectoral distributional effects. An undesired effect of such policies, however, is that they may reduce the environmental effectiveness of environmental taxes. The substitution of emission-intensive technologies and products by less emission-intensive ones does not only play a role for production sectors, but is also an option for the household sector. Sectors and households that can switch to low emission technologies more easily will be less affected than others.

Concerning the household sector, the focus on distributional implications and acceptability of tax measures to reduce greenhouse gas emissions has gained attention recently, against the background of massive protests by citizens in several countries (e.g. France[16] or Iran) as a reaction to the introduction or the increase of taxes aiming at the reduction of greenhouse gas emissions. A rather broad consensus has emerged in the literature that motor fuel taxes are less regressive than other environmental taxes. This result is due to the fact that the share of household transport expenditure rises with income, whereas the share for household energy consumption for housing decreases with income. If there is a subsistence level of carbon intensive goods to satisfy basic needs of consumers, a carbon tax will have a regressive effect (Klenert and Mattauch 2016), meaning that the tax takes a larger percentage of income from low-income households compared to high-income households. In addition, distributional impacts of carbon taxes are also determined by socio-economic household characteristics like location, household type, demographics etc.

Similar to distributional aspects, political acceptance has drawn growing attention in research and in the political debate on emission-reducing tax measures. Baranzini and Carattini (2014) analyse ancillary benefits as one of the determining factors for public acceptance of carbon taxes. Case studies show that political and social acceptance crucially depends on the tax design (Klenert et al. 2018).

Both aspects, distributional impacts, and public acceptability, have increasingly drawn attention towards the use of tax revenues.[17] Wang et al. (2016) distinguish between ex-ante and ex-post measures to mitigate adverse distributional effects. Ex-ante measure reflect preferential tax rates or tax exemptions for most vulnerable groups. This, e.g., could ensure the subsistence level of emission intensive consumption or apply to sectors exposed to foreign competitors. Ex-post measures refer to revenue redistribution either through lowering other distortionary taxes (see also the double dividend hypothesis) or through an increase in transfer payments. In OECD (2002) compensation measures are referred to as basically ex-post, not affecting the tax rate or tax base of environmentally related taxes. Carattini et al. (2018) stress the role of communication strategies as an instrument to secure public acceptability, to reduce information asymmetry and to address the main concerns, like high personal costs, regressivity of the tax, negative impact on the wider economy and the lack of an incentive effect. Klenert at al. (2017)

[16] In France these protests occurred in the context of a wider tax reform, which had other re-distributional effects, that put a disadvantage at lower income groups.

[17] In a broader context additional policy measures also play an important role for acceptability. In the case of e.g. fuel taxes the available choices for mobility as public transport, secure bicycle lanes or rural planning that reduces mobility needs may support public acceptability.

conclude that political trust together with the concrete tax design are decisive factors for acceptability of carbon taxes from a political science perspective.

If one summarises the discussed aspects of a carbon tax, three aspects are of particular relevance for the tax design: (1) a system perspective; (2) the specific tax design; and (3) strengthening public acceptance. The system perspective is of relevance in order to account for the stock-flow-interactions and possible persisting barriers as argued above. In addition, the existence of potential synergies and trade-offs vis-à-vis other important policy objectives suggests pursuing a system perspective.

2.8 Taxes versus emissions trading

Economists agree on the recommendation to use pricing mechanisms as the core element of an effective environmental policy. However, this consensus is embedded in a broader debate on instruments in environmental policy, which reflects the controversy over price (taxes)or quantity (emissions trading) regulation. A tax sets the price of emissions, while uncertainty remains on the resulting aggregate emissions level. Cap and trade systems define an aggregate emissions level, leaving the resulting price uncertain. In theory, in a world with perfect information both instruments, taxes and quantities, achieve the same result. In the real world, where uncertainty and asymmetric information prevail, the two instruments may deliver outcomes that are different from the theoretical optimal solution.

Whether taxes or quantity restrictions are the preferable instrument, is addressed in the seminal paper by Weitzman (1974), who shows that no clear conclusion can be drawn about which of the two approaches is to be preferred. He argues that only in the case of identical information on marginal costs and marginal damages would it be feasible to set the correct quantity or price signal. In a world with uncertainty and asymmetric information both instruments face efficiency losses. Weitzman's theoretical model shows that the preferred policy instrument depends on the steepness of the marginal abatement and marginal benefit (damage) functions. In his model a price instrument is preferred by a regulator when the marginal benefit function from reducing emissions is flat relative to the marginal cost of abatement. The opposite holds if the marginal benefit function is steeper.

Goulder and Schein (2013), Haites (2018) and Stavins (2019) provide a review of the differences and similarities of carbon taxes and trade systems. Carbon taxes are associated with lower administrative costs. Absence of price volatility is another advantage of taxes compared to trade systems. Floor or ceiling prices are tax elements introduced into trading systems to prevent price volatility. Floor or ceiling prices thus are exogenous price elements for trading systems and transform a pure cap and trade system into a so-called hybrid system with the aim to dampen price volatility. Metcalf (2009) in contrast discusses hybrid systems by introducing quantity elements in a tax system, i.e. to introduce a (automatic) change in the tax rate if a certain benchmark target regarding emission quantity is not reached. He argues that such an approach would have two advantages over a cap and trade hybrid system: It avoids the need for a new administrative structure to oversee this major new program as well as the creation of financial assets.

A price floor in an emissions trading system, defining a minimum price for allowances, is another form of hybrid system. It provides more certainty for firms that invest in abatement technologies and turns out to be especially important when abatement costs turn out to be lower than expected before implementation of the scheme. A price floor acts as an insurance for firms investing in low carbon technologies and abatement measures, guaranteeing a minimum return on investment and increasing planning security (Kettner et al. 2011). A price floor could be implemented easily (as design element of the auctioning or as part of the existing tax system) and without compromising the advantages of a cap-and-trade scheme. The introduction of a price floor could, however, lead to an increase in transaction costs and might increase the administrative costs of the trading scheme. The Market Stability Reserve[18] in the EU ETS is another example of an instrument designed to increase the resilience of an emissions trading system to shocks by automatically adjusting the supply of allowances to be auctioned, according to pre-set rules.

One conclusion from the theoretical literature could be that policy choices depend on weighing different policy goals and that the concrete design of the policy instrument may play a more important role than general characteristics of the two instruments (taxes or emissions trading) applied in a pure manner.

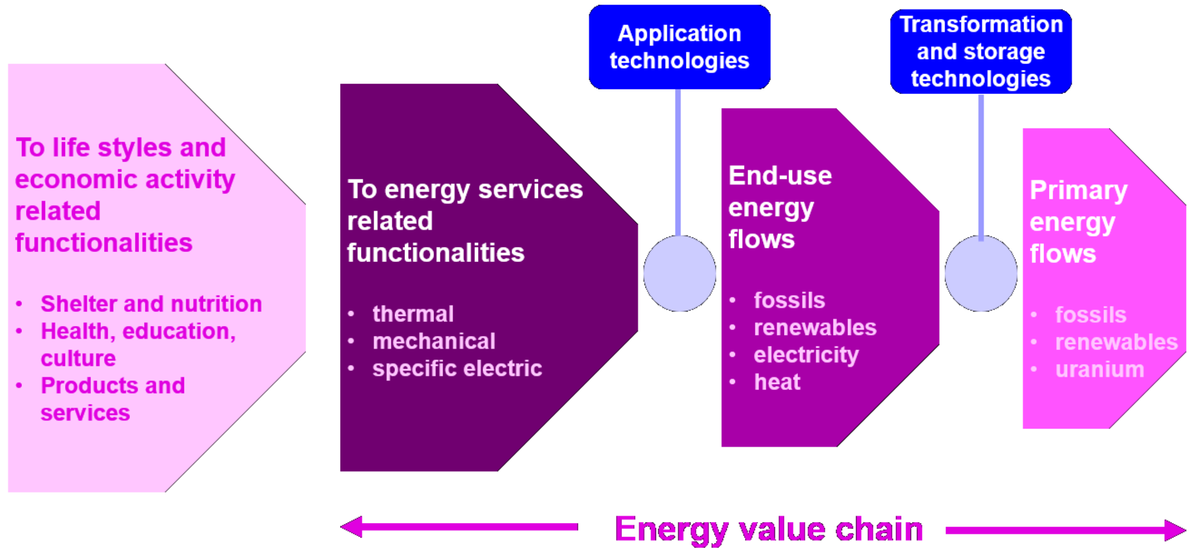
2.9 Additional aspects of carbon pricing

Attempts to green the tax system by shifting the tax base reflect an ongoing evolution of the underpinning theoretical concepts. The starting point was Pigou's seminal insight of the potential discrepancy between private and social costs of economic activities. The next step was the embedding of this discovery into the neoclassical paradigm, as exhibited e.g. in Figure 2 above. It took some time, however, to acknowledge the limits of this reasoning: damage costs are difficult to monetise, all cost components are dependent on the time horizon considered and are not always independent of other decisions made. An important step was the emerging alternative, instead of taxing negative externalities to limit them within a cap-and-trade mechanism. The EU Emissions Trading System is the most far-reaching implementation of this approach so far, however, so far with limited success (Marcu et al. 2020).

Recently, the concept of using taxes for targeted energy and climate policies has experienced new momentum by widening the scope of the system addressed (Creutzig et al. 2018, Köppl and Schleicher 2018). Essential for this approach is an expansion of the full value chain, e.g. in the case of energy from supply of primary energy to the final thermal, mechanical and specific electric functionalities of energy services demanded, which in turn reflect life styles and the profile of economic activities along the entire energy value chain and pointing at the important role of application, transformation and storage technologies as depicted in Figure 3.

[18] https://ec.europa.eu/clima/policies/ets/reform_en

Figure 3: **Deepened structural concepts of resource use**



Source: Köppl and Schleicher (2018).

This approach opens several other lines of reasoning: Köppl and Schleicher (2018) discuss the interaction of stocks and flows for providing the functionalities relevant for well-being, the need for differentiating incentives for investment and the use phase, the market failures from incomplete markets because of the separation of investors and users, the opportunities for harvesting synergies from this systemic approach. A basic message of this approach, which emphasises the details of resource use on this extended value chain, is the insight that a single instrument, such as a tax-based or a trade-based mechanism, will not be sufficient for correcting inefficiencies or externalities. Stiglitz (2019) therefore emphasises the importance of an instrument mix that is compatible with such a deepened structural view of our economies by considering the circumstances in which such differential policies may be best implemented through regulation or differential pricing.

Distributional concerns are another aspect of the discussion regarding carbon taxes in a broader context and generally of paying more attention to options for recycling tax revenues. In principle, revenue recycling options include lump-sum transfers to households, cutting existing taxes for households and/or firms, public spending for low-carbon infrastructure and/or subsidies for clean technologies, and support for developing countries. Each recycling option of the tax revenues has its pros and cons, as summarised by Stern (2019) in Table 1.

Summarising, a broad agreement among environmental economists (EAERE 2019) exists that taxes are an indispensable instrument for an effective decarbonisation strategy (World Bank Group 2019). The specificities of climate change, however, require expanding the perspective on carbon taxes as the exclusive solution for climate change (Rosenbloom et al. 2020). Several aspects have been addressed already above, like market failure due to stock-flow relations, or uncertainty on the likelihood of irreversible climate change. Carbon taxes thus need to be integrated in a broader policy package (e.g. World Bank Group 2017). One important element in such a policy package would be the elimination of environmentally harmful subsidies as they reduce the price of emission intensive activities and act as adverse incentive for investment in clean energy technologies and in energy efficiency.

Table 1: **Carbon Tax Revenue Use: Pros and Cons**

All uses can be assessed relative to efficiency, equity, administrative burdens and environmental impact		
OPTION	**PROS**	**CONS**
General government budget	• Relatively simple to implement and manage. • Provide potential allocation to "best-use".	• Lack of transparency in allocation. • Potentially limits acceptability if low trust in politicians.
Revenue neutral-households	• Can be used to reduce distortions in other tax systems. • Ability to support lower-income/ vulnerable households.	• Potentially limited public awareness and understanding, unless direct "carbon transfers". • May divert revenue from better uses.
Revenue neutral-firms	• Simple and easy to manage. • Support can be offered to emission-intensive sectors and trade exposed firms. May overcome oppositions from industry.	• Less equitable than other revenue-recycling options. Might slow adjustment.
Allocation for 'green' purposes	• Demonstrates commitment to 'green' initiatives. • Additional support for investment in infrastructure/R&D programs with broad benefits.	• Limited flexibility due to need for long term allocation. • Possible mistrust of government 'schemes'.
Support for developing countries	• Demonstrate commitment to support objectives of Paris Agreement and SDGs. • Well established system for allocation and management.	• Potential public acceptability of use of revenues outside of the country.
All options should be coupled with clear communication and transparency of revenue-use. Important that uses are relevant for a broad range of constituencies. Must observe country specific regulations/laws e.g. ear-marking.		

Source: World Bank (2019).

The arguments put forward about limits for carbon taxes mean that policy makers must carefully weigh up the different pros and cons when deciding on a coordinated climate policy package that is likely to achieve the envisaged long-term climate targets.

3. Empirical evidence on the effects of GHG taxation

3.1 Methodological approaches

The number of studies analysing the effects of taxes directly or indirectly addressing carbon emissions on various outcome dimensions has been growing considerably during the last four decades. Meanwhile a large body of empirical studies has accumulated, which can be classified along various criteria.

First of all, very generally, as with most types of policy, also with regard to the effects of GHG taxation ex-ante and ex-post evaluations can be distinguished (Sachintha 2019). A "first generation" of empirical studies focusing on energy and emission taxes and starting in the beginning of the 1990s simulates the hypothetical effects of energy and/or emission taxes ex-ante prior to their implementation based on model simulations or other projection methods. A "second generation" of empirical analyses unfolding a decade later has been attempting to determine actual outcomes of energy and emission taxes ex-post, after their implementation, since the beginning of the 2000s. While the number of ex-post studies has been increasing recently, the vast majority of evaluations still consists of ex-ante analyses. As OECD (1997) states, ex-post analyses on the one hand have the advantage to yield more reliable results than ex-ante studies, as the latter generally need to rely on numerous assumptions when formulating specific simulation scenarios. On the other hand, as Andersen (2004) points out, the validity of results from ex-post analyses may differ as well, depending on the quality of data as well as the rigour and methodological approach they apply. Moreover, one important challenge ex-post studies are confronted with is to disentangle the effects of carbon taxes from other determinants (political measures as well as relevant economic developments) and thus to isolate the pure causal tax effect (Baranzini et al. 2000).

Ex-ante analyses are based on model simulations conducted with a variety of models. The results of ex-ante simulations may differ due to differing model specifications, assumptions, data and simulated scenarios. In the context of attempts to determine macroeconomic effects of environmental taxes, including their potential impact on environmentally relevant variables as emissions and energy use, Freire-González (2018) distinguishes between macro-econometric models, input-output models, and applied computable general equilibrium (CGE) models, with the latter playing the most important role. In contrast, distributional analyses aiming at capturing the potential impact of environmental taxes on personal income distribution rest on micro-econometric simulation models or micro-economic projection schemes.

Existing ex-post evaluations of environmental taxes and tax reforms, respectively, are based on a variety of methodological approaches, ranging from qualitative methods (e.g. expert interviews) and descriptive statistics over case studies and simulation exercises to a variety of statistical and econometric approaches.[19] According to Andersen (2004), ex-post approaches may be separated in a first group requiring a baseline to be able to compare actual and projected developments (revealed behaviour) and a second group attempting at quantifying the impact itself (stated behaviour). Ex-post studies may also differ with regard to their scope: some aim at determining economy-wide effects, while others focus on specific branches (e.g. industrial firms) or sectors (households versus industry or firms). The results of ex-post evaluations may differ due to varying methodological approaches, data bases, and time periods studied. In addition, the effects of taxing GHG emissions may differ between countries due to different tax designs (regarding tax rates and base as well as exemptions), but also because of different general macroeconomic conditions (e.g. openness, productivity etc.) and specific framework conditions (e.g. energy mix, consumption and production patterns, transport infrastructure, energy policy etc.) (Andersen 2004).

[19] See Andersen (2004) for a detailed discussion of various methodological approaches to conduct ex-post evaluations in the 1990s for the Nordic countries, which were the European forerunners regarding the introduction of carbon taxation.

Empirical analyses of GHG taxes may also be differentiated with respect to their geographical scope. Evaluation studies often cover a single country. Such case studies come in the form of ex-ante as well as ex-post evaluations. Besides, there are analyses for country groups, mostly EU Member States or the whole EU. These are almost always ex-ante analyses, while ex-post cross-country studies are very rare.

Finally, the theoretical effects of environmental taxes that are researched empirically differ between studies. Naturally, one central aspect studied empirically is the environmental effectiveness of environmental tax (dis)incentives, whereby their impact on GHG emissions is of particular interest. Also, further effects on the economy are evaluated, e.g. the impact of GHG taxation on GDP, output and employment. Another important question examined empirically is the distributional impact of GHG taxes. Furthermore, efficiency of environmental taxes is studied. Not the least important issue is social and political acceptability of tax measures to reduce GHG emissions. Many studies focus on one specific impact dimension associated with GHG taxation. Some studies analyse various effects jointly, particularly those examining whether GHG taxation may yield a double dividend (see section 3.4.2). Thus, all theoretical aspects addressed in the section below have been examined empirically, with one exception, namely the administrative costs of GHG taxation, which is an under-researched area in the relevant empirical literature.

3.2 Environmental effectiveness of environmental tax (dis)incentives

Environmental taxes as instrument to reduce GHG emissions is a broadly studied area of research, both theoretical and empirical. A large part of the empirical literature reflects ex-ante studies, which are complemented by an increasing number of ex-post analyses. However, the overall number of ex-post studies is still small and focuses on a rather limited number of jurisdictions or regions, as Green (2021) concludes from her meta-review of ex-post evaluations of carbon pricing. This lack of empirical ex-post evidence on the effectiveness of carbon taxes is problematic also because it restricts the diffusion of experiences and knowledge gained on the effectiveness of climate policy instruments across countries (Carraro et al. 2015), and because informed policy-making relies on sufficient empirical evidence (Green 2021).

3.2.1 Elasticity of demand as crucial determinant of effectiveness of environmental taxes

The effectiveness of environmental taxes crucially depends on the price elasticity of demand, which reflects the relative change in the quantity demanded resulting from a change in prices. Empirical evidence on the size of price elasticities is still limited. Most of the existing evaluations focus on the price elasticity of demand for fuel or for energy. The results lie within a rather broad range, which can be explained by differing sample periods, types of publication, and estimation methods[20] (Labandeira et al. 2017).

Empirical estimations of the elasticity of motor fuel consumption suggest that the demand for fuel is highly inelastic particularly in the short run, while it is larger in the longer run and indeed

[20] The authors provide a brief overview over the various estimation procedures applied in the literature to determine energy price elasticities.

leads to reduced fuel consumption (Sterner 2007). Dahl (2012) finds a price elasticity for gasoline consumption of -0.13 in the short and of -0.33 in the long run and for diesel consumption of -0.13 in the short and of -0.38 in the long run for 120 countries. Kettner-Marx and Kletzan-Slamanig (2018) estimate a price elasticity of –0.31% for gasoline and -0.16 for diesel for 22 EU Member States for the period 2004 to 2015. In their meta-study, Labandeira et al. (2017) stress that there are only few meta-studies summarising the results of existing research on fuel price elasticity and provide a brief overview over these meta-studies. The results of these studies for the short-run gasoline or car fuel price elasticity range between -0.09 and -0.76, for the long-run price elasticity between -0.31 and -1.16. In their own meta-analysis, the authors find a short-term price elasticity of -0.2 and a long-term price elasticity of -0.6 for diesel, while the average price elasticity for gasoline is about -0.2 in the short run and -0.7 in the long run. These results confirm those of earlier studies according to which the short-term price elasticity for fuel lies between -0.1 and -0.25, while the long-run price elasticity reaches about -0.7 on average (Graham and Glaister 2002, Goodwin et al. 2004). For the example of the carbon tax levied in British Columbia Rivers and Schaufele (2015) demonstrate a higher impact on fuel demand compared to equivalent market price changes, thereby confirming results derived by Liet al. (2014) for the US.

There are numerous papers estimating energy price elasticities, whereby studies for EU Member States are rather scarce and primarily exist for the front-runner carbon pricing Nordic countries (Kettner-Marx and Kletzan-Slamanig 2018). Enevoldsen et al. (2007) arrive at an energy price elasticity for the Swedish industry of -0.44 and of -0.38 for the Danish industry in the period 1991 to 2001. For Denmark, Bjorner and Jensen (2002) find an energy price elasticity for energy-intensive firms of -0.2 and of -0.7 for the remaining industry, yielding an average energy price elasticity of -0.44. The estimate provided by Enevoldsen et al. (2007) is of a similar magnitude, with an energy price elasticity of -0.38 for the Danish industry in the period 1991 to 2001. In their meta-analysis, Labandeira et al. (2017) find that on average estimations of the price elasticity of energy demand arrive at an elasticity of -0.22 in the short run and of -0.65 in the long run.

Finally, it should be noted that empirical evidence suggests that demand may react more sensitive to long-lasting carbon taxes than to short-term price fluctuations (Davis and Kilian 2011, Baranzini and Weber 2013, Li et al. 2014, Andersson 2015). Information on the permanent nature of carbon pricing mechanisms may thus strengthen their effectiveness by reducing uncertainty about future prices for investors and households (Antweiler and Gulati 2016). Allcott and Rogers (2014) show, based on experimental studies, that the impact of carbon pricing could be reinforced by providing information to households and firms about emission reducing opportunities. Also complementary mechanisms to overcome information failures and bounded rationality can support an effective reaction of private actors to carbon pricing and tax incentives promoting low-carbon decisions and behaviour (Baranzini et al. 2017). There is also empirical evidence suggesting that carbon pricing does not lead to reduced climate-friendly behaviour, but on the contrary to "motivational crowding in".[21]

[21] See Baranzini et al. (2017) for a brief overview over relevant empirical analyses.

3.2.2 Impact of carbon taxes on emissions

The environmental effectiveness of carbon taxes, as measured by their impact on carbon emissions, has been studied based on ex-ante model simulations as well as by ex-post econometric evaluations. While the former still dominate the existing body of empirical studies, the growing number of countries that have introduced some form of GHG taxation has brought along an increasing number of ex-post analyses on the environmental effectiveness of GHG taxation.

Most ex-ante simulations focus on the Nordic countries and a few other countries that introduced carbon taxation or some other form of environmental taxes or tax reforms rather early. Such ex-ante simulations either attempt at quantifying the effects of governments' actual tax reform plans, as part of an ex-ante impact assessment, or of hypothetical tax proposals that in many cases have never been implemented, at least not in the proposed design.[22] These studies generally estimate rather sizeable effects of such taxes and tax reforms, respectively, and had a dominant role, compared to ex-post evaluations, in the 1990s. Generally, ex-post evaluations yield smaller effects of carbon taxes on emissions than ex-ante simulations do (Rafaty et al. 2020). According to Speck et al. (2006), for example, the Danish Environmental Protection Agency estimated that the Danish carbon tax would reduce emissions by 24% in the period 1990 to 2011 vis-à-vis a business-as-usual scenario. Recently Ó Broin et al. (2019), utilising the residential sector's price elasticity of demand for energy estimate that had France, Germany, Italy, Spain and the UK introduced a carbon tax according to the example of Sweden in 1997, demand for fossil fuels would have been reduced at least by 10% to 20%, implying a yearly GHG decrease of a minimum of 60 Mt carbon equivalents.

Already in the 1990s, a few ex-post evaluations were carried out, mostly for the Nordic forerunner countries Norway, Sweden and Denmark, which introduced carbon taxes as early as 1991 and 1992, respectively.[23] Andersen (2004) provides a brief summary of ex-post evaluation studies unanimously demonstrating that the carbon tax indeed reduced emissions in Sweden and that the carbon tax reduction for the industry implemented in 1993 resulted in a carbon emission increase. For Denmark, redistributing its carbon tax revenues to the industry to finance energy efficiency improving measures and conditioning reduced tax rates for energy-intensive processes on agreements with firms on energy savings, early ex-post studies show relatively sizeable emission-reducing effects in the industry (Andersen 2004). In the first five years, 20% of the revenues from Denmark's carbon-energy taxation were earmarked to support energy-efficiency measures and upgrade production technologies. According to an ex-post assessment by Bjorner and Togeby (1999), the energy savings achieved by firms participating in this energy savings programme were larger by 60% on average compared to the firms that paid the tax only. Larsen and Nesbakken (1997) show a decrease of household sector emissions in Norway by 3% to 4% between 1991 and 1993, while (because of numerous exemptions) the tax was much less effective in the industrial sector, where emissions were reduced by 0.5% only.

[22] See Köppl et al. (1996) for an early example for Austria.

[23] Actually, Finland was the first (Nordic) country to introduce a CO_2 tax in 1990 already; however, probably due to the initially low level of the tax, there are no early ex-post evaluations (Andersen 2004).

The bulk of ex-post studies, however, was conducted after the beginning of the new century. During the last 20 years, an increasing body of ex-post studies has emerged estimating the impact of environmental/carbon taxation on emissions, many of them focusing on EU countries. As mentioned above, for the EU, ex-post analyses concentrate on the Nordic countries as frontrunners in carbon taxation. Brännlund et al. (2014) study the environmental performance of the Swedish industry at the firm level, finding an improvement in all industry sectors examined, which suggests a decoupling of production growth and carbon emissions mainly driven by the Swedish carbon tax. Most recently, Andersson (2019) finds that the Swedish carbon tax and a value-added tax on transport fuel reduced carbon emissions in the transport sector by almost 11%; with the carbon tax alone accounting for a reduction of 6%. Using various econometric methods, Runst and Thonipara (2020) show that the augmentation of the Swedish carbon tax in the early 2000s, implying an increase of the carbon tax rate from around 40 € to 100 € per ton of carbon emitted between 2001 and 2004, significantly reduced carbon emissions also in the residential sector: from 200 kg per capita per year compared with other countries applying a carbon tax at a rate above 20 € to 800 kg compared with no-carbon-tax countries. One central finding of this analysis is that the effectiveness of the carbon tax crucially depends on its level.[24]

For Finland, Sairinen (2012) reports that a government working group on environmental taxation found that carbon and energy taxation decreased carbon emissions between 1990 and 1998 by over 7%.

According to the ex-post analysis provided by Enevoldsen et al. (2009), the energy productivity of the Danish industry was increased by 30% during the first decade of carbon-energy taxation – two to three times as much compared to comparable European countries without carbon-energy taxation. Moreover, carbon emissions were decreased by almost 10% compared to a business-as-usual-scenario. Without carbon taxes and energy investment subsidies, industrial CO_2 emissions in Denmark would have been about 13% to 17% higher.

Bruvoll and Larsen (2004) find a rather modest decrease of CO_2 emissions induced by the carbon tax in Norway, amounting to 2.3% in the period 1990-1999. According to the authors, the rather small emission-reducing effect of the Norwegian carbon tax identified in this study is due to the generous exemptions for fossil fuel-intensive industries.

Using a common methodological framework, the synthetical control method, for the four Nordic countries Denmark, Finland, Norway and Sweden, Sachintha (2019) finds that Norway has experienced the highest per capita emission reduction through its carbon taxes, followed by Sweden.[25] The emission reducing effects of the Finnish and Danish carbon taxes, however, are less clear according to this analysis. These findings somewhat differ from that of an earlier study by Lin and Li (2011), that based on the difference-in-difference-method shows that carbon taxation in Finland had a significant negative impact on the growth of CO_2 emissions per

[24] This finding confirms the result of the earlier study by Aydin and Esen (2018) for 15 EU member states, according to which environmental taxes must exceed certain thresholds to be environmentally effective.

[25] It should be noted that the study focuses on national emissions, not on the emissions in the sectors subjected to carbon taxation.

capita, while the impact of the carbon tax in Denmark, Sweden and the Netherlands were also negative, but not significant. The authors explain this finding by generous exemptions for energy intensive industries.

According to the ex-post assessment based on modelling with E3ME conducted by Barker et al. (2009a and 2009b), carbon-energy taxes implemented within environmental tax reform in Europe reduced greenhouse gases by 4% to 6% in the Nordic countries (Denmark, Finland, Sweden) and Germany between 1995 and 2004 compared to a business-as-usual-scenario, primarily resulting from a decrease in fuel demand. The greenhouse gas reductions achieved in the Netherlands and the UK amounted to about 2%, as these countries implemented their environmental tax reforms later and at less ambitious levels. Martin et al. (2014) find that the British carbon tax had a strong negative effect on manufacturing plants' energy intensity and electricity use.

Outside the EU, the carbon tax implemented in British Columbia in 2008 has attracted some interest in empirical research on the effectiveness of carbon taxation. Murray and Rivers (2015) provide a review of empirical ex-post assessments suggesting that the carbon tax effectively reduced carbon emissions in British Columbia. The tax level had arrived at 30 C$/t CO_2 emissions and covered about three quarters of all GHG emissions in the Canadian province. According to empirical evaluations and model simulations, the carbon tax has decreased emissions in the range of 5% to 15% since its implementation. Pretis (2019) reviews several empirical ex-post evaluations of the impact of the tax across different sectors, showing that it has decreased residential and commercial natural gas demand as well as fuel demand. Rivers and Schaufele (2015) demonstrate that the carbon tax reduced fuel demand to a greater extent than equivalent market price changes. Using various econometric approaches, Pretis (2019) cannot detect a significant reduction in aggregate carbon emissions induced by the British Columbia carbon tax, besides a decrease by 5% of transportation emissions, as existing carbon taxes (and prices) are too low yet to unfold a significant impact.

For Switzerland, Ecoplan (2017) estimates, based on a time series analysis, that between 2008 and 2015 the Swiss carbon tax resulted in a carbon emission reduction of 6.9 million tons (4.4% of combustion emissions). Davis and Kilian (2016) find a significant effect of US gasoline taxes on vehicle emissions.

To date, there are only a few cross-country empirical studies on the effectiveness of carbon pricing. One challenge when attempting to assess the effectiveness of carbon taxation in a cross-country comparison is the availability of data on effective tax rates which are comparable across countries, account for tax exemptions, and cover all sectors and energy sources (Rafaty et al. 2020). Sen and Vollebergh (2016) estimate the long-run effectiveness of a uniform carbon tax on energy consumption using a new and unique dataset containing effective tax rates of OECD countries related to carbon dioxide emissions across different energy user and resource categories and including all taxes directly or indirectly addressing carbon emissions. Their approach has several advantages. First, it allows to study the impact of taxes on energy consumption directly; in contrast to many previous studies using energy prices as a proxy for energy taxes. Second, in contrast to nominal tax rates, these effective tax rates account for tax exemptions. Third, the effective tax rates are comparable across countries, which allows to analyse their impact on energy consumption in a cross-country perspective. Finally, they are also comparable across energy use and resource categories, thus capturing the carbon content of the entire energy tax base. The authors find that taxing the carbon content of energy use in OECD countries effectively reduced carbon emissions. Rafaty et al. (2020) research the impact of carbon pricing on carbon emissions across five sectors for 39 OECD countries in the period 1990 to 2016. According to their study, the introduction of carbon pricing has decreased growth in carbon emissions by 1% to 2.5% on average. In a recent study, Best et al. (2020), based on various econometric modelling approaches, analyse the effectiveness of carbon pricing in decreasing national carbon emissions from fuel combustion for 142 countries over a period of 20 years. Of these 142 countries, 43 applied a carbon price by the end of the period analysed. The authors find that on average carbon pricing decreased the annual carbon emissions growth rate by about two percentage points compared to no-carbon-pricing countries. Increasing the carbon price by one euro per ton of carbon emissions reduces the subsequent annual emissions growth rate by around 0.3 percentage points. Also recently, Aydin and Esen (2018) show that energy and transport taxes in 15 EU countries were able to significantly reduce emissions in the period from 1995 to 2013 when they were above certain thresholds.[26] Of interest is also the analysis provided by Best and Burke (2018), which studies EU member states and a sample of additional countries to show that carbon pricing changes the energy mix away from higher-emission energy sources towards lower-emission energy sources such as wind power. According to the study by Metcalf and Stock (2020b), a carbon tax of $ 40/ton carbon emission covering 30% of emissions leads to a cumulative decrease of carbon emissions between 4% and 6%.

Altogether, there is an increasing number of ex-post studies demonstrating that carbon taxes can effectively reduce carbon emissions or at least dampen their growth. The existing empirical results for individual countries differ somewhat due to differing methodological designs and approaches as well as databases used; and also the time period covered matters (Andersen 2004).[27] These factors also determine cross-country differences in the empirical results regarding the effectiveness of carbon taxes. In addition, the tax design as well as differing economic conditions (including the structure of the energy system and the availability of low carbon alternatives) influence the effectiveness of carbon taxes. Moreover, regardless of the rather broad range of estimates concerning the size of the emission-reducing effects, the existing empirical research suggests that the order of magnitude of the effects is rather modest (Green 2021) and thus insufficient to reach current medium- and long-term emission goals as stipulated in international and national agreements and plans (Rafaty et al. 2020), which may have to do with the fact that in most countries tax rates are rather moderate.

Finally, it is of interest whether carbon taxes or cap-and-trade systems are more effective to contain carbon emissions. Based on a review of recent empirical studies researching the effectiveness of carbon taxes and emission trading systems, respectively, Haites (2018) concludes

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[26] For energy taxes, including carbon taxes, the threshold level is 2.2%; at this threshold level the effect on carbon emissions changes from insignificantly positive to significantly negative.

[27] See also section 2.1.

that these do not allow to rank the two instruments with regard to their environmental effectiveness. They should rather be viewed as "… components of a portfolio of mitigation policies rather than as alternative 'first best' policies." (Haites 2018: 963) From her meta-review of ex-post quantitative evaluations of carbon pricing policies world-wide, Green (2021), however, concludes that the performance of carbon taxes is better compared to emissions trading schemes.

Box 1: **Vehicle Taxes**

In theory, under the assumption that consumers are far-sighted, the optimal instrument to decrease carbon emissions from transport is a fuel tax, as carbon emissions per litre of fuel are known (Anderson and Sallee 2016).[28] However, myopia from the side of consumers causing them to insufficiently consider future fuel savings from improved fuel efficiency may require additional tax instruments (Koch et al. 2019). Empirical evidence on the existence of myopia of consumers tending to undervalue fuel savings through low-emission cars does not yield clear-cut results. However, existing studies suggest that future fuel savings may at least be modestly undervalued.[29] Vehicle taxes complementing fuel taxes put a price on inefficient vehicles and provide incentives for more efficient ones.

A comprehensive set of vehicle taxes addressing carbon emissions rests on three pillars. Conventionally, the relevant literature identifies two pillars, namely fuel and vehicle taxes, as elements of a second-best taxation of vehicles (Bjertnaes 2017), with vehicle taxes equalling the social costs of future emissions minus the part of social costs internalised by the fuel tax (Innes 1996).

Summarising recent empirical analyses for the effects of fuel taxes as the first pillar of vehicle taxation, Koch et al. (2019)[30] point out that higher fuel prices improve vehicle fuel efficiency by inducing consumers to buy more fuel efficient as well as smaller and lighter vehicles. Frequent drivers and diesel car drivers react particularly sensitively to fuel taxes, as well as the demand for trucks and SUVs. Fuel taxes may also incentivise consumers to scrap old inefficient vehicles and to keep newer and more efficient vehicles for a prolonged time period. Their effect on fuel economy is larger in the US compared to Western Europe. At the same time, fuel price elasticity of distance travelled is larger in Europe than in the US.

[28] See Bjertnaes (2017) for the theoretical foundations of vehicle taxation.

[29] See Yan and Eskeland (2018) and Koch et al. (2019) and the literature cited therein.

[30] See Koch et al. (2019) for references.

Vehicle taxes as second pillar of vehicle taxation comprise car purchase (registration) taxes and annual vehicle circulation taxes. Grigolon et al. (2018) find that regardless of consumer myopia, vehicle taxes have an impact on the structure of sales of new vehicles in Europe. Ryan et al. (2009) study vehicle taxes in EU15 countries for the period 1995 to 2004. The authors find that total new passenger car sales are strongly influenced by annual circulation taxes. The average CO_2 emissions intensity of car fleets is determined by the price of petrol fuel as well as the circulation tax for petrol and diesel cars, the latter reducing total new car sales and reducing the overall carbon intensity of new cars. In contrast, the car purchase tax does not have an important influence on the CO_2 emissions intensity of the new passenger car fleet. The authors' results also suggest that raising the diesel vehicle circulation tax can lead to an increase in the share of the (less fuel efficient) petrol vehicles and thus an increase in carbon emissions. According to Runkel et al. (2018), an annual circulation tax may again be undervalued by myopic consumers, as it may be reformed in the future and the car holding period is uncertain, while a car purchase tax represents upfront costs payable at the time of purchase and is therefore much more salient for buyers. Similarly, Yan and Eskeland (2018) show stronger effects of a car purchase tax compared to a circulation, when the former is based on CO_2 emissions. Nonetheless, many countries apply both a purchase tax and an annual circulation tax, as the latter provides regular revenues and is thus advantageous from a budgetary perspective.

In many European countries, vehicle taxes have been reformed since the beginning of the 2000s and are now often based on vehicles' carbon emission intensity. The studies by Gallagher and Muehlegger (2011), Haultfouille et al. (2014), Alberini and Bareit (2019), Gerlagh et al. (2018), Malina (2016) and Klier and Linn (2015) suggest that carbon-based registration taxes are more effective in reducing the carbon intensity of new vehicles than carbon-based annual circulation taxes.

The taxation of company cars can be regarded as third pillar of vehicle taxation. In principle, the private use of a company car is to be taxed as benefit in kind. However, in most European countries, the actual benefit accruing to users of company cars is considerably higher than the taxable benefit in kind (Runkel et al. 2018). Therefore, company car taxation often represents an environmentally harmful tax incentive, promoting the purchase and use of larger and more expensive cars (Harding 2014, Damert and Rudolph 2018) and benefiting higher incomes over-proportionally. Introducing environmental elements into company car taxation (emission intensity, distance travelled privately, fuel efficiency) would contribute to a vehicle taxation mix aiming at the reduction of carbon emissions.

COWI (2002) point out that effective vehicle taxation requires a combination of various specific taxes. To influence carbon emission intensity of new cars, vehicle taxes are more effective than fuel taxes. The latter are more effective to curb mileage driven and to promote efficient driving behaviour.

Obviously, transport causes other externalities besides carbon emissions. These range from greenhouse gas emissions other than carbon emissions over road congestion and local air pollution to accidents. The internalisation of these externalities calls for additional instruments including pricing mechanisms (e.g. road pricing or congestion charges) and regulatory instruments (Koch et al. 2019). In this context, Bjertnaes (2017) argues for a combination of a fuel tax and heavier taxes on fuel-efficient vehicles to decrease externalities from road traffic, as otherwise drivers avoid the road use element of the fuel tax by buying fuel-efficient vehicles.

Increases in fuel taxes are often associated with distributional concerns. However, recent empirical results suggest that generally fuel taxes have only weak regressive or even progressive distributional consequences (Kosonen and Nicodème 2009). Potential negative impacts could be overcome by redistributing revenues back to households via lump-sum transfers (Bento et al. 2009, Tovar Reanos and Sommerfeld 2016).

3.3 Cost efficiency of carbon taxation

Cost efficiency can be measured in terms of abatement costs, i.e. the costs accruing to economic actors when trying to avoid one tonne of carbon emissions. The 2013 OECD report on "Effective Carbon Prices" (OECD 2013) calculates abatement costs per tonne of carbon emissions associated with different environmental policy instruments for two sectors. For the electricity sector, emission trading and tax incentives cut carbon emissions at very low cost, while abatement costs are rather high for capital subsidies and feed-in tariffs. In the transport sector, fuel taxes are most cost effective, with fuel mandates and capital subsidies being associated with substantially greater abatement costs.

3.4 Macroeconomic effects of environmental taxes

The effect of environmental taxes on the economic performance has been a debated issue right from the beginning. Often fears concerning a negative impact of environmental taxes on key macroeconomic variables, as GDP or employment were voiced in the theoretical and political debate, making governments reluctant to implement environmental taxes. The theoretical reaction to such fears was the formulation of the double dividend hypothesis, stating that recycling carbon tax revenues via reducing other, more distortive taxes (e.g. labour taxes or social security contributions) might bring about simultaneous environmental and economic benefits. We first present some empirical research on the economic impact of environmental taxes, before summarising empirical evidence regarding the double dividend hypothesis.

3.4.1 Effects of environmental taxes on macroeconomic performance

The macroeconomic impact of environmental taxes is subject of numerous empirical studies. Generally, the isolation of the economic effects of carbon taxes from those of other policy instruments is challenging, particularly in those cases where – as in the Nordic countries – carbon taxes were introduced as element of more comprehensive environmental tax reforms (Kettner-Marx and Kletzan-Slamanig 2018). Generally, the separation of the effects of carbon taxes on the economy from those of other environmentally relevant measures (e.g. public investment programmes, subsidies, standards, etc.) also implemented in the time period analysed is methodologically difficult (Rafaty et al. 2020). This is a challenge also for empirical research on the double dividend hypothesis (see next section).

For the Danish environmental tax reform implemented in 1992, the Danish Ministry of Finance identifies a positive, but rather small effect on growth, at 0.3% of GDP for the period 1990 to 1995 (IEEP 2013). Andersen et al. (2007) find that the reform increased employment by 0.5% annually between 1994 and 2012. Infras and Ecologic (2007) identify only short-term positive employment effects, with (albeit negligible) negative medium-term effects. For Finland, Andersen et al. (2007) arrive at an average annual GDP enhancing effect of 0.5% between 1994 and 2002; for Sweden they find a long-term annual increase of GDP in the same order of magnitude accompanied by a growth in employment. According to an ex-post evaluation based on the E3ME model of the environmental and economic effects of the environmental tax reforms implemented in seven EU member states (Denmark, Finland, Germany, the Netherlands, Slovenia, Sweden, and the UK) between 1990 and 2002, these reduced CO_2 emissions in all member states with the exception of Slovenia, without harming GDP growth (Barker et al. 2009a). For the same group of countries, the results of the analysis by Enevoldsen et al. (2009) neither confirm the existence of a strong double dividend nor of negative economic effects. Murray and Rivers (2015) in their review of ex-post empirical studies find no significant impact on economic growth for the carbon tax levied in British Columbia, a result which is confirmed by Bernard et al. (2018) and Metcalf (2019).

According to a study by Martin et al. (2014), carbon pricing in the United Kingdom did not negatively affect manufacturing employment and revenue. For France, Dussaux (2020), using data for 8,000 firms representative for the French manufacturing sector for the period 2001 to 2016, shows that increasing energy prices and carbon taxation decreased energy use and carbon emissions without reducing net employment at the industry level. Several studies find differing sector-specific effects: According to Carbone et al. (2020), the carbon tax induced a shift of employment from carbon-intense to less carbon-intense sectors. Differing industry-specific effects are also found by Azevedo et al. (2018).

For a panel of European countries over the time period 1985 to 2017, Metcalf (2019) identifies no or slightly positive effects of carbon taxes on GDP. In their ex-post evaluation of carbon taxes in 15 EU countries Metcalf and Stock (2020a) conclude: "[…] we find no robust evidence of a negative effect of the tax on employment or GDP growth. For the European experience, at least, we find no support for the view that carbon taxes are job or growth killers." No effect of the British Columbia carbon tax on aggregate employment can be detected by Azevedo et al. (2018). As the concrete design of carbon taxation in these countries varies (e.g. with regard to revenue use, exemptions for certain sectors, level and long-term trajectory of tax rates, etc.), it is difficult to identify the factors behind the overall positive or at least neutral effects on macroeconomic performance without further in-depth analysis. However, the results of the studies included in Andersen and Ekins (eds.) (2009) suggest that full revenue recycling via reducing social security contributions and the income tax is the or at least one key factor.

Another economic aspect is pointed out by Haites (2018), who compares existing carbon taxes and cap-and-trade-systems. He finds that while for the existing carbon taxes rates generally are specified only for a period of three to five years, so that a longer-term rate trajectory is missing, existing emission trading systems often specify annual reduction targets for a longer period in the future, thus providing a more stable and certain medium-term framework for tax subjects with regard to abatement investment. However, quantity-based pricing systems bear the risk of price volatility that can result in uncertainty on abatement investment. Carbon taxes based on a longer-term tax rate trajectory credibly implemented by the government may be advantageous compared to cap-and-trade-systems, as they provide planning security to businesses. This conclusion is corroborated by the study by Rafaty et al. (2020) who find that the effectiveness of carbon prices is the higher the less volatile they are and when they are on a credible upward trajectory, which points at the importance of a cost path that allows longer-term planning by tax subjects.

3.4.2 The double dividend hypothesis

The findings in the theoretical literature on the double dividend hypothesis are ambiguous, as an extensive survey provided by Freire-González (2018) shows: they range from the limited number of studies over the heterogeneity of empirical approaches, differing assumptions, data and scenarios to structural factors, as the existing tax structure and design of taxes, socio-economic conditions etc. (see section 2.4). The same is true for empirical research attempting at identifying double dividends of environmental tax reforms. Almost immediately after the double dividend hypothesis had been put forward by Pearce (1991) and Goulder (1995), economists set out to examine it with modelling studies. Early surveys provided by the IPCC (1995, 2001, 2007) deliver ambiguous results of ex-ante research of the double dividend hypothesis.

Ex-ante studies often use General Computable Equilibrium (CGE) models. An early example are the simulations by Felder and van Nieuwkoop (1996) which demonstrate that implementing a carbon tax and using the proceeds to reduce labour taxes in Switzerland would result in a significant simultaneous decrease of carbon emissions and an increase in employment and GDP. A recent study by Groothuis (2016) for 27 EU Member States (EU27 without Croatia) simulates a tax shift from labour taxes towards taxes on natural resources and consumption using the macro-econometric E3ME model. A gradual shift within the period 2016 to 2020 would raise employment by 3% and GDP by 2%; water and energy use as well as carbon emissions would decline by more than 5%.

The ex-post analysis by Yamazaki (2017) suggests that the carbon tax recycling schemes applied in British Columbia had a positive impact on employment, thus supporting – similarly to the analysis by Murray and Rivers (2015) – the double dividend hypothesis.

In a recent review of 40 studies delivering altogether 69 different simulations of environmental tax reforms done with CGE models from 1993 to 2016, Freire-González (2018), using a statistical and a meta-regression analysis, finds that almost all environmental tax reforms simulated (about three fourth of which use carbon taxes, while one fourth apply energy taxes) are environmentally effective. However, a double dividend in terms of a simultaneous improvement of environmental and economic conditions is demonstrated by only 55% of the simulations (i.e. 38 simulations) included in the review. The review suggests that key to achieving a double dividend is the recycling instrument used in simulations. Accordingly, revenue recycling via reducing social security contributions is most effective (9 out of 10 -simulations show a double dividend). Also, recycling via reducing taxes on labour income, capital taxes and other taxes mostly creates a double dividend, while lump-sum transfers generate a double dividend in only 10% of simulations. These empirical results corroborate Goulder's (1995) distinction between a strong, intermediate and a weak double dividend hypothesis (see section 2.4).

Maxim et al. (2019) conduct a meta-regression analysis of simulation studies exploring the hypothesis of an employment double dividend, differentiating between European and non-European countries. A central finding of this meta-analysis is that both tax and recycling policies are important determinants of an employment double dividend, and that the optimal policy mix differs for European and non-European countries, requiring region-specific policy design.

Somewhat related to the double dividend hypothesis by (implicitly) building upon it is the "taxing for growth" debate that has been initiated by the OECD and gained momentum in the aftermath of the 2008 financial and economic crisis. This debate is based on empirical research demonstrating that a revenue-neutral tax shift away from labour towards other revenue sources may help to stimulate growth and to increase employment and investment (Arnold 2008, Arnold et al. 2011). It is generally considered that some types of tax bases are less detrimental to growth, in particular consumption taxes, recurrent housing taxes and environmental taxes. Possible employment gains by substituting distorting taxes on labour through revenues from environmental taxes have been labelled as "third dividend" in the literature (Freire-González 2018). However, some recent economic literature points to heterogeneity of responses, non-linear effects and differences in amplitude between the short-term and long-term effects. In their empirical analysis Baiardi et al. (2019) show that these results are only valid for the specific sample of countries and time period but are not robust to a different estimation set up. Analysing also short run effects they cannot find a growth-enhancing effect of a shift in the tax structure. These results, inter alia, underline the fact that the detailed design of a tax is at least as important as the type of tax and the tax base, respectively.

3.5 Impact on competitiveness and innovation

Potential impacts of carbon taxation on competitiveness and innovation are further economic aspects of interest. For carbon pricing in general, Ellis et al. (2019) conclude that ex-ante and ex-post analyses lead to contradicting results. Most model-based ex-ante simulations demonstrate that unilateral carbon pricing negatively impact competitiveness (Carbone and Rivers 2017). In contrast, most ex-post studies fail to identify statistically significant effects on various dimensions of competitiveness. Empirical ex-post evidence on the impact of carbon taxes on competitiveness is scarce. Salmons and Miltner (2009) cannot find evidence for a general loss of competitiveness for seven EU countries (Finland, Denmark, Sweden, Germany, the Netherlands, the UK and Slovenia) in the period 1990 to 2002 resulting from introducing environmental tax reforms. A review of the few existing empirical ex-post analyses provided by Arlinghaus (2015) finds that carbon taxes impair competitiveness to a small extent only, if at all.

The empirical evidence on the existence of carbon leakage is ambiguous, also because it is hard to be detected empirically. Again, ex-ante and ex-post studies on carbon leakage rates differ: the extent of carbon leakage expected in ex-ante model simulations is considerably higher compared to ex-post evaluation studies (Felbermayr and Peterson 2020).[31] Moreover, there is only little empirical evidence specifically on carbon leakage related to carbon taxes. Various model simulations show that unilateral carbon pricing may cause international carbon leakage (e.g. Böhringer et al. 2012, Fowlie et al. 2016, Fischer and Fox 2012)[32]. Some recent econometric analyses support these results. For example, Aichele and Felbermayr (2015) conclude that the Kyoto Protocol was indeed responsible for carbon leakage. For the US, Casey et al. (2020) show that state-level carbon pricing reduces employment, output and profits in the regulated state and increases them in nearby states. According to the meta-analysis by Branger and Quirion (2014) which covers 25 studies carbon leakage estimates range from 5% to 25% without policy; border carbon adjustment reduces leakage by 6 percentage points.

For the EU ETS, the few studies conducted up to now were not able to find empirical support for the theoretical expectation that it would cause carbon leakage. Naegele and Zaklan (2017), for example, do not find evidence for carbon leakage in European manufacturing induced by the EU ETS, thus corroborating the results of several earlier empirical ex-post analyses. Also, the brief overview by Joltreau and Sommerfeld (2019) over recent studies shows that up to now there is no convincing evidence for the existence of carbon leakage caused by the EU ETS. However, this finding could be explained by the low or zero emission costs the EU ETS imposed on firms during the first decade of its operation. As Lowe (2019) and Joltreau and Sommerfeld (2019) point out, more stringent emission-reducing policies in the EU, as planned for example within the European Green Deal, may well lead to carbon leakage in the future. The results of the ex-post assessment of environmental tax reforms in seven EU member states (Denmark, Finland, Germany, the Netherlands, Slovenia, Sweden, and the UK) performed by Barker et al. (2009a, 2009b) suggest that these tax reforms neither impaired the competitiveness of the respective countries vis-à-vis other member states, nor did they lead to carbon leakage.

The innovation effects of green policies in general have been researched by numerous empirical studies.[33] There is also some empirical evidence for positive innovation effects of carbon pricing schemes (see, e.g., Martin et al. 2013 and Calel and Dechezleprêtre 2016 for the EU ETS). Popp (2006), using patent data, finds that energy prices have the most important inducement effect on innovation. According to Ley et al. (2016), a 10% increase in energy prices in OECD countries leads to an increase of the number of green innovations by 3.4% and of the ratio of green to non-green innovation by 4.8%. The ex-post assessment of environmental tax reforms in seven EU member states (Denmark, Finland, Germany, the Netherlands, Sweden, and the UK) conducted by Enevoldsen et al. (2009) provides indication of innovation effects in industry. According to the evaluation of the Swedish carbon tax for the period 1990 to 1995 by Bohlin (1998), the carbon tax combined with investment support policies resulted in a shift in the district heating sector from coal to bioenergy (forestry residue), while no effect in the transport and electricity sector can be found. Bruvoll and Larsen (2004) identify a fuel switch in

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[31] Zhang (2012) discusses the reasons for differences between ex-ante and ex-post estimations of carbon leakage rates.

[32] See also the brief review of model-based ex-ante simulations in Condon and Ignaciuk (2013) and Naegele and Zaklan (2017) and the references cited therein.

[33] See Joltrau and Sommerfeld (2019) for a brief overview over empirical analyses.

heating, from fossil fuel to electricity, for the period 1990 to 1999 caused by the Norwegian carbon tax, which delivered a contribution of -1% to the (modest) overall CO_2 emission reduction of 2.3%. Aghion et al. (2016), using firm-level panel data on auto industry innovation for 80 countries over several decades, find that higher tax-inclusive fuel prices encourage auto industry innovation towards clean (e.g. electric and hybrid) patents. Hereby, it should be noted that empirical research suggests (see, e.g., Popp 2006) that to induce innovation, the carbon price should be rather high, and there should be a credible future path for a high and stable carbon price (Laing et al. 2013).

Lilliestam et al. (2020) review ex-post analyses for the EU, New Zealand, British Columbia, and the Nordic countries exploring the effectiveness of carbon pricing in promoting innovation and diffusion of the new technologies required for full decarbonisation. This review leads to the overall conclusion that so far there is no convincing empirical evidence suggesting a positive impact of carbon pricing on the necessary technological change. Hereby, however, it has to be noted that the review focuses on the innovation effects of emissions trading, while considering just a very small number of evaluations examining the effects of carbon taxes on technological change.[34] Moreover, the overall conclusion of the review is also the result of a very small number of studies explicitly studying the effect of carbon taxes on technological change and innovation.

3.6 Distributional implications

The distributional consequences of environmental/carbon taxes have been the subject of empirical studies for three decades now. Recently they have gained increased attention, against the background of massive protests by citizens in several countries (e.g. France or Iran) as a reaction to the introduction or increase of taxes aiming at the reduction of GHG emissions.

Generally, the existing empirical evidence suggests that the distributional impact of carbon taxes depends on the energy sources taxed and the indicators used to capture distributional effects (Kirchner et al. 2018). Two indicators are used in empirical research to identify the distributional effects of environmental/GHG-related taxes: while income-based indicators reflect the distribution of the tax burden across income groups, expenditure-based indicators measure the tax burden relative to expenditure.

Kirchner et al. (2018) identify three groups of empirical approaches to study the distributional effects of carbon taxes, differing with regard to the indicators they use to determine the distributional impact as well as the analysed effects. A first group comprises empirical analyses making use of household consumption surveys or micro-simulation models, while a second group is based on static input-output models with household data or micro-simulation models. Both groups of approaches usually assess the tax burden relative to income or expenditure. A third group of studies simulate macroeconomic feedbacks, e.g. CGE or macroeconomic input-

[34] For example, the review ignores the analyses by Enevoldsen et al. (2009) and Aghion et al. (2016) reviewed in this section.

output models, measuring distributional consequences in terms of changes in equivalent variation or as changes in household expenditure and income.

The following review summarises the most important results from the rather extensive body of empirical analyses that has developed since the beginning of the 1990s.[35] Hereby we first present studies examining the distributional consequences of carbon taxes. In addition, analyses researching the distributional effects of compensation measures for households are summarised.

3.6.1 Distributional effects of carbon taxation

There are numerous empirical studies, based on different methodological approaches, showing that generally, carbon taxes pose an over-proportional burden on low income households compared to higher income groups.

Callan et al. (2009) survey earlier macroeconomic and micro-simulation studies conducted in the period 1991 and 2008, concentrating on high-income countries. Despite country-specific differences, carbon taxes generally turn out to be regressive in most countries: they result in rising energy prices, which over-proportionately burdens poorer households who spend a higher share of their incomes on energy consumption. Callan et al.'s own model simulations for Ireland identify a regressive impact of carbon taxation.

Earlier studies for the US find regressive effects for taxes on transport fuel (e.g. Poterba 1991). Kosonen (2012), focusing on the Nordic countries, reviews the literature on the distributional implications of environmental taxes and concludes that these differ for different taxes. The author's survey shows that in contrast to taxes on transport fuels, taxes on heating and electricity are associated with a regressive impact, as the shares of expenditures for heating and electricity are decreasing with income, while the shares of expenditures for fuel are lower in the low-income range and then are growing with income. These findings are supported by the study by Sterner (2012) who examines the distributional effects of energy taxes on transport fuels in seven European countries (France, Germany, United Kingdom, Italy, Serbia, Spain and Sweden). A (very weak) regressive effect on an income basis can be identified for Sweden and Spain only, while for the other countries the tax burden is proportional across income groups. Based on lifetime incomes, even this very weak regressive effect disappears; and it does not occur at all in Serbia as the poorest country in the group analysed. In an extensive survey of empirical research for G20 countries McInnes (2017) also finds that generally transport fuel taxation is progressive in most countries, while taxes on heating fuels are mildly regressive and taxes on electricity are clearly regressive.

Flues and Thomas (2015) study the distributional effects of energy taxes in 21 EU countries. Their findings suggest that taxes on transport fuels on an expenditure basis generally are not regressive, which may be explained by the fact that car ownership is less widely spread in the lower expenditure deciles. Energy taxes affecting heating fuels generally tend to be mildly regressive,

[35] This review is based on Kirchner et al. (2018), who provide a more detailed presentation of methodological approaches and issues as well as additional empirical literature.

while taxing electricity has more marked regressive effects. The only EU country levying a substantial carbon tax that is included in the study is Finland. With respect to transport fuel, the Finnish carbon tax is found to be roughly proportional across income groups, while displaying an inverted U-shape impact across expenditure deciles, implying the largest burden for middle income households. In contrast, the carbon tax on heating fuels as well as on electricity has a clear regressive effect.

These findings corroborate the results of an earlier analysis by Wier et al. (2005) studying the distributional implications of carbon taxes on heating fuels and electricity in Denmark. The authors show that direct and indirect carbon tax payments (through tax-induced price increases for carbon-intensive goods and services due to the carbon tax levied on industry) imply a regressive distribution of the tax burden across households. Based on a similar approach, Kerkhof et al. (2008) show that similarly to the results for Denmark, direct and indirect carbon taxes are associated with regressive effects in the Netherlands.

A joint analysis of environmental and distributional effects of environmental taxes on transportation for Norway is conducted by Aasness and Roed Larsen (2003). The authors find that higher tax rates on air transportation and taxis, as rather pollution-intensive means of transportation, improve environmental quality and decrease inequality. The same is true for lower tax rates on rather environmentally friendly modes of transportation as buses, bikes and mopeds. Higher taxes on gasoline have beneficial environmental effects but are inequality increasing. That this last result of regressive effects of gasoline taxes contradicts the findings of most other empirical studies may have to do with specific Norwegian circumstances, with more low-income households depending on a car in the sparsely populated country.

Finally, a simulation study by Rausch et al. (2011) researching the distributional impact of a carbon tax for the US points at the importance of considering not only differing income groups in distributional analyses, but to also take into account differences between household types, regions, or race, as these influence spending patterns and thus the incidence of carbon taxes. This conclusion is supported by the findings by Cronin et al. (2017) for the US highlighting that besides vertical distribution, also horizontal distributional effects need to be accounted for. A recent meta-analysis by Ohlendorf et al. (2020) including 53 studies and 183 effects in 39 countries finds that about one third of the effects of market-based climate policies, inter alia carbon pricing, analysed in the study are progressive or proportional. One interesting finding of this meta-study is that the probability of identifying progressive effects is higher for lower income countries, and that it increases when lifetime incomes are used and when a broader range of economic aspects (e.g. indirect and demand-side effects) are considered.

3.6.2 Distributional consequences of compensation measures

An also much debated and topical issue is how to avoid or at least mitigate undesired distributional effects of carbon taxes. Empirical research illustrates that the distributional impacts of environmental taxes crucially depend on the use of tax revenues.[36] In an early study modelling ex-ante a carbon tax for Switzerland, Felder and van Nieuwkoop (1996) show that lump sum

[36] See, e.g., Pizer and Sexton (2017) and the literature cited therein.

payments to compensate for the regressive effect of the carbon tax benefit lower incomes over-proportionately, while labour tax reductions benefit higher incomes more. Besides their progressive distributional impact, lump sum distribution is the easiest and administratively least complex and burdensome option to recycle carbon tax revenues (Baranzini et al. 2000, Padilla and Roca 2004). Similarly, in their analysis of the distributional impact of carbon taxation in Ireland, Callan et al. (2009) study the distributional impact of various compensation measures and find that labour tax cuts are well suited to provide relief for middle- to high-income groups, while lower incomes can be better compensated by increasing transfers. These results are confirmed by Rausch et al. (2011) in model simulations of the implementation of a carbon tax in the US. From their CCE model simulations of the introduction of a carbon tax in France, Combet et al. (2010) conclude: "A mix recycling scheme, which devotes the tax levied on firms to payroll tax rebates, and that levied on household to the financing of redistributive transfers, is proven to provide a compromise between the two polar options: it allows to achieve both an improvement of all macroeconomic indicators, and a control of the distributive impacts of the reform." Similarly, analysing various scenarios of carbon taxes on car fuels in France, Bureau (2011) finds that recycling carbon tax revenues via lump sum payments to households to mitigate the regressive effects of the tax makes poorest households better off. The study also shows that the regressive impact of the tax is reduced by accounting for the benefits from the reduction of congestion achieved by the tax. Flues and van Dender (2017) in a simulation for 20 OECD countries show that combining an energy tax increase with income-tested compensation financed by one third of tax revenues would make energy use affordable for the poorest population groups, leaving two third of tax revenues for other uses.

To sum up, the distributional impacts of carbon taxes as well as the results of empirical research attempting at measuring them are influenced by a number of factors: "… consumption and income patterns of households, the structure of the economy, macroeconomic feedbacks (e.g. factor incomes), price transmission of industries taxed, tax design (especially tax recycling), as well as the modelling approach and indicators used, and impacts will differ in the short- and long-term." (Kirchner et al. 2018: 8). Similarly, Pizer and Sexton (2017) highlight that the incidence of energy taxes depends on the energy commodities taxed and on the physical, social and climatic conditions of the taxing jurisdictions.

Altogether, the great majority of empirical analyses for high-income countries find that without revenue recycling or compensation mechanisms a carbon tax tends to have a regressive effect, with lower-income groups typically spending a higher proportion of their income on carbon-intensive commodities (Wang et al. 2016). Hereby, a rather broad consensus has emerged in the empirical literature that fuel taxes are less regressive (or may even be progressive) than taxes on heating fuels and electricity. It should also be noted, however, that recent research calls for a more differentiated approach to and perspective on the distributional implications of carbon pricing. Cronin et al. (2017) point out that the measures used to capture distributive effects of carbon pricing play a crucial role. In particular, the authors underline that annual incomes, which are influenced by short-term fluctuations induced, e.g., by the employment and health status or family conditions, may be less suited than measures based on lifetime income or annual consumption. Moreover, they stress the necessity to also account for horizontal aspects, as focusing on the aggregate impact on household groups differing, e.g., with respect to their consumption expenditures, bears the danger of hiding differences within given household groups. The necessity of such a broader and more differentiated approach is supported by the recent meta-analysis by Ohlendorf et al. (2020). Related is the aspect of gender-differentiated distributional impacts of carbon taxes. Although the existence of such gender-differentiated effects appears plausible, as Chalifour (2010) argues, there is practically no relevant empirical research. This is true as well for intergenerational equity, another important distributional dimension (Baranzini et al. 2017).

It should also be noted that the overall distributional effects of carbon pricing are underestimated in empirical research, which generally neglects indirect effects in the form of tax-induced price increases of non-energy goods. On the other hand, distributional analysis confined to static effects may be misleading or at least may provide an incomplete picture: in the longer run, adjustment reactions by households may alleviate initial undesirable distributional effects, rendering them a transitory phenomenon (which would be supported by providing adequate alternatives to the taxed activities, for example affordable public transport). The analysis of distributional effects of carbon taxes in a dynamic perspective, however, is confronted with substantial methodological challenges. Not least, studies of the distributional impact of carbon taxation should be put into perspective by comparing them with the distributional effects of the resulting environmental improvements and of the cost of inaction.

Our literature review also allows some conclusions regarding the suitability of various compensation measures to mitigate undesired distributional effects of carbon taxation. Existing research suggests that lump sum payments are better suited to mitigate the regressive effects for lower incomes, while higher incomes benefit more from labour tax reductions. At the same time, there is a consensus that lump sum transfers are associated with an equity-efficiency trade-off whereas a decrease of labour taxes is more efficient economically (Kirchner et al. 2018). This conclusion is corroborated by the empirical research on the validity of the double dividend hypothesis summarised above showing that recycling schemes reducing labour taxes are far more likely to create a double dividend in terms of environmental and economic improvements than those compensating lower income households by lump sum transfers. As Cronin et al. (2017) highlight, also with regard to the design of compensation schemes, differences within various classes of households should be considered. Finally, it should also be mentioned here that the long-term potential of carbon taxes financing labour tax cuts within environmental tax reforms will decrease, as a successful significant reduction of GHG emissions, as envisaged in the existing international and national climate agreements and commitments, will significantly lower the potential tax base and thus the revenue raising potential of the tax (Speck 2017). This could be mitigated by maintaining energy taxes, subjecting all energy use to some level of taxation so as to contain overall demand for energy.

3.7 Political acceptance of carbon pricing schemes

Political aspects of carbon pricing have been attracting growing attention in academic research. Issues that have been researched empirically recently are the role the international climate policy framework, economic and fiscal crises, policy paradigms or country-specific economic conditions (e.g. income level, openness, emission intensity) play for countries' decisions whether to adopt carbon pricing policies.[37] Also the role of lobbying for or against carbon taxation has been studied empirically.[38]

Of particular importance in the context of this study is the issue of public acceptability of carbon taxes. As a consequence of an increasing number of failed attempts to introduce carbon-reducing measures,[39] awareness is rising among policymakers as well as within academia that the successful implementation of carbon taxes is not just a matter of setting the technical parameters, like tax rates and bases, right. As Jagers et al. (2019) point out, there are two aspects related to the political feasibility of carbon taxes. First, there is the issue of the determinants of public support for or resistance against carbon taxes. The second question is how public resistance against carbon taxes can be avoided or mitigated. Moreover, with a perspective to the US, Feldman and Hart (2018) and Shwom et al. (2010) conclude that the motivation of policymakers to introduce climate policies crucially depends on public support.

Summarising the recent literature, Jagers et al. (2019) identify numerous determinants of public attitudes towards environmental and climate policy, ranging from individual motivation over political ideology as well as institutional, political and interpersonal trust to contextual variables, as the degree of political polarisation, economic conditions and dependencies, political culture, and quality of government.[40]

Criqui et al. (2019) conduct a comparative country study (Sweden, France and Canada) to identify factors that support the introduction of carbon taxes. According to their analysis, trust in the government is a central factor (thus confirming an empirical analysis for 18 EU countries by Kollmann and Reichl (2015) and for 23 European countries by Levi (2021)), as well as the consideration of the wider perspective on the economy and energy system (e.g. availability of district heating). Awareness of potential lobbying interests and finally the use of the revenues contribute to the success of carbon taxes. The importance of national policy styles is stressed by Andersen (2019). Examining seven smaller European countries, the author finds that policy styles with neo-corporatist features make it easier to introduce carbon taxes despite larger pressures from international competition in smaller countries, as these provide coordination mechanisms allowing the introduction of complementary proactive macroeconomic policies.

In addition, Jagers et al. (2019), in a large-scale randomised survey experiment conducted in Sweden, find that perceptions of fairness are important determinants of public support for carbon taxes. Their results support similar results by Johansson-Stenman and Konow (2010) and Kallbekken et al. (2013). Also Savin et al. (2020), based on a computational linguistics analysis, show that different mindsets play an important role in shaping public views on carbon taxation and its fairness and need to be taken into account when designing and communicating carbon taxes. While people accepting a carbon tax stress the necessity to solve environmental

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[37] See Skovgaard et al. (2019) for a brief overview over recent empirical studies on the factors influencing the adoption of carbon pricing policies by polities.

[38] See Baranzini et al. (2017) and Sterner et al. (2020) for a brief overview over relevant empirical studies.

[39] See Jagers et al. (2019) and Drews and van den Bergh (2016) for examples.

[40] See Jagers et al. (2019) for references.

problems, people sceptical of a carbon tax emphasise fairness problems of the tax and the lack of low-carbon transport and renewable energies, and they exhibit less trust in politicians.

Altogether, most factors influencing public support that are identified in this research are, as Jagers et al. (2019) point out, rather stable over time and can hardly be changed by external pressure. However, the authors stress that policy attitudes are also influenced by the design of policy measures itself and by the perceived consequences. Accordingly, public support may be increased, for example, by cushioning off undesired distributional consequences through compensatory measures.

Kirchner et al. (2018) report several examples where governments decided to forego the introduction of carbon taxes due to equity considerations.[41] Thus, their distributional effects are a crucial determinant of the political feasibility of carbon taxes (Baranzini et al. 2017). Bristow et al. (2010), Brannlund and Persson (2012), Gevrek and Uyduranoglu (2015) and Baranzini and Carattini (2016) find that public acceptability of climate policy in general and carbon taxes in particular can be substantially enhanced by a design that avoids burdening low-income households. To mitigate undesired distributional consequences of carbon taxes, existing carbon taxes often are embedded in recycling measures giving back carbon tax revenues to compensate households and firms. For example, the carbon tax recycling scheme in British Columbia uses a significant share of carbon tax revenues to compensate lower incomes (Murray and Rivers 2015) as well as rural households (Beck et al. 2016). Thus, compensation measures very generally help to increase public acceptance of carbon taxation, as concluded by Jagers et al. (2019). Maestre-Andrés et al. (2019) study the role of individual preferences with regard to the design of revenue recycling schemes and their importance for the acceptability of carbon pricing schemes. Their review of empirical studies shows that generally there is a lack of trust in governments regarding the use of revenues from carbon pricing. Also, there is widespread concern that carbon taxation particularly hits lower incomes and thus is associated with regressive effects; and policy acceptability and support is improved if carbon pricing instruments are perceived as fair. Most interestingly, the bulk of empirical studies does not suggest that most people prefer to use carbon tax revenues to compensate particularly lower incomes. Rather, there is a significant share of people preferring to recycle carbon tax revenues via investment in "environmental projects". One recommendation the authors derive from these empirical results is that compensation measures for lower incomes should be combined with spending for "environmental projects", for example in renewable energy. Another one is that governments should provide sufficient information for citizens about the policy instruments used, as this also improves acceptance. This recommendation is supported by the work by Murray and Rivers (2015) and Carattini et al. (2016) which shows that the provision of evidence for the effectiveness of carbon taxes in decreasing emissions raises citizens' support for carbon taxation. That ideological preferences matter with regard to people's attitudes towards the necessity of compensatory matters is shown for Sweden by Jagers et al. (2019). The authors find that right-leaning voters' support for carbon taxes is increased by offering compensatory measures, whereas left-wing people support a carbon tax combined with an income tax cut less.

[41] See also Wang et al. (2016) for more examples.

4. Concluding remarks on environmental taxes in a wider policy context

A broader perspective of environmental taxes in the context of climate change needs to take into account the fact that the transition towards climate neutrality requires deep structural change that cannot be achieved by incremental (policy) steps. Such a deep structural change rather implies huge investment needs. In this context the focus on a broader policy mix that integrates a broad range of instruments like pricing instruments, subsidies, standards and public infrastructure investment will be needed, not to forget the greening of finance. Several studies (e.g. Grubb 2014, Mercure et al. 2014, Rafaty et al. 2020) suggest that a strategic combination of climate mitigation policies may bring about considerable synergies. Environmental taxes thus need to be integrated in a broader system perspective. Given the urgency of GHG emission reductions the transformative signal of policy instruments towards long-run decarbonisation is of utmost importance.

Several conclusions can be drawn from the review of the theoretical literature on the effects and importance of environmental taxes in general and carbon taxes in particular.

First of all, as Hepburn et al. (2020) emphasise recently, environmental taxes are one important instrument in a toolbox of available environmental policy instruments but are not sufficient for various reasons. Still, pricing negative externalities has been one of the central pillars in environmental economics for long. Hereby, "optimal" pricing in the context of climate change is faced with uncertainties related to the complexities of the climate system. The specificities of climate change require a broadening of the perspective on carbon taxes due to the importance of stock-flow relationships or market barriers such as the principal agent problem between homeowners and tenants. Crucial for carbon pricing is the concrete policy design, in particular regarding the distributional impacts, which considerably influences public acceptability and distributional aspects play an important role. Although there is broad agreement on the usefulness of carbon taxes, there is also a consensus that they have to be embedded in a broader policy mix.

The review of empirical studies further yields several conclusions regarding the various impact dimensions considered. An increasing number of ex-post studies – case studies as well as cross-country analyses – demonstrate that carbon taxes can effectively reduce carbon emissions or at least dampen their growth without harming economic growth and employment. The estimates of the emission-reducing effects derived in the existing ex-post evaluations lie within a rather broad range and often are rather modest. The level of the carbon tax rate is a crucial factor determining its effectiveness: Only a sizeable tax rate is able to effectively reduce carbon emissions. Key to achieving a double dividend consisting of environmental effectiveness and the improvement of economic welfare is the use of revenues: Revenue recycling via reducing social security contributions and reducing taxes on labour income mostly creates a double dividend, in contrast to lump-sum transfers. Moreover, carbon taxes impair firms' competitiveness to a small extent only, if at all. Up to now, there is no convincing empirical evidence that carbon pricing, e. g. via carbon taxes, can bring about the technological change required to achieve full decarbonisation of the economy and the society. There is also an empirical consensus that environmental taxes have differentiated distributional effects: Generally, fuel taxation is progressive in many countries, while taxes on heating fuels are mildly regressive and taxes on electricity are clearly regressive. Lump sum transfers are better suited to mitigate the regressive effects for lower incomes, while higher incomes benefit more from labour tax reductions. Finally, public acceptability of carbon taxes is dependent on a number of factors and can be increased by public information, avoiding negative distributional consequences and earmarking part of revenues for "environmental projects". "Package solutions" combining several climate policies in general and carbon pricing and tax incentives in particular may be more effective than stand-alone measures.

Apart from the broad theoretical and empirical consensus on the usefulness of environmental taxes, any concrete policy reform needs to consider the system boundaries as well as the specific policy context and general socio-economic conditions and policy styles in the given country. Moreover, the relevant literature suggests that international or at least EU-wide policy coordination yields additional economic and environmental benefits.[42]

[42] See, e.g., Parry (2020).

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