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SYNTHESIS ARTICLE

Designing an effective climate-policy mix: accounting for instrument synergy

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ABSTRACT
We assess evidence from theoretical-modelling, empirical and experimental studies on how interactions between instruments of climate policy affect overall emissions reduction. Such interactions take the form of negative, zero or positive synergistic effects. The considered instruments comprise performance and technical standards, carbon pricing, adoption subsidies, innovation support, and information provision. Based on the findings, we formulate climate-policy packages that avoid negative and employ positive synergies, and compare their strengths and weaknesses on other criteria. We note that the international context of climate policy has been neglected in assessments of policy mixes, and argue that transparency and harmonization of national policies may be key to a politically feasible path to meet global emission targets. This suggests limiting the complexity of climate-policy packages.

Key policy insights:
- Combining technical standards or targets, such as renewable-energy quota, or adoption subsidies with a carbon market can produce negative synergy, up to the point of adding no emissions reduction beyond the cap. For maximum emissions reduction, renewable energy policy should be combined with carbon taxation and target expensive reduction options not triggered by the tax.
- Evidence regarding synergy of information provision with pricing is mixed, indicating a tendency for complementary roles (zero synergy). Positive synergy is documented only for cases where information provision improves effectiveness of price instruments, e.g. by stimulating social imitation of low-carbon choices.
- We conclude that the most promising packages are combining innovation support and information provision with either a carbon tax and adoption subsidy, or with a carbon market. We further argue that the latter could have stronger potential to harmonize international policy, which would allow to strengthen mitigation policy over time.

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1. Introduction

Many academic writings on climate policy are concerned with the performance of single instruments targeting greenhouse gas emission reduction. In reality, however, one typically finds an extensive set of policy instruments implemented simultaneously, often on different regulatory levels. There are many potential reasons for using multiple instruments. The instruments might be complementary or even create positive synergy in

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terms of the associated goal. More specifically, they might deal with distinct market failures (Freire-González, 2018; Jaffe et al., 2005). Another important reason for combining instruments is that they can accomplish multiple objectives, such as effectiveness, efficiency and equity. In more abstract terms, a policy mix can reflect a second-best (non-optimal) response to a first-best (theoretically optimal) single instrument not being feasible – because of monitoring of pollution being imperfect, the control span of policy being limited, or the existence of political constraints. The additional instruments then compensate for the non-optimal level of the main policy instrument (Bennear & Stavins, 2007). More practically, multiple instruments might arise from political compromises between stakeholders with distinct policy preferences, or from adding instruments to compensate for the insufficiency of already available instruments (Bouma et al., 2018). Finally, in line with the Tinbergen (1952) rule, a distinct type of policy mix results from the presence of multiple objectives, such as climate change mitigation and limiting biodiversity loss (Braathen, 2007; Sterner et al., 2019).

There are also several reasons to be careful about combining instruments into a policy mix. As will be illustrated for various cases in Section 3, policies may overlap or create negative synergies. This can even lead them to offset each other in terms of emissions reduction. In such cases, a policy mix would perform no better or even worse than a single instrument. Taking into account that each policy instrument generates an additional cost for the regulator or government in terms of expenditures and human resources – including transaction costs of political and policy processes until implementation, cost of monitor and control, and sometimes serious budgetary sacrifices (such as with subsidies) – policy-makers may want to limit the number of instruments in the policy mix. Moreover, given that policy instruments often cause unintended market distortions, employing multiple instruments runs the risk of introducing potentially multiple distortions into the economy. Finally, policy mixes complicate the comparison of policy stringency among regions and countries compared to single instruments. Schmidt and Sewerin (2019) demonstrate this for renewable-energy policy mixes in nine OECD countries. Difficulty to compare policies in turn confounds policy integration between distinct governance levels within a country or within a supra-national system like the European Union (Howlett et al., 2017). As we argue in Section 4, reducing the complexity of climate policy might increase the feasibility of international policy harmonization.

In view of these contrasting arguments, this article examines the synergy of combining specific instruments in a policy mix aimed at effectively reducing greenhouse gas emissions. To this end, we consider both theoretical arguments and empirical or experimental evidence from a variety of disciplines that have devoted attention to policy mixes, notably economics, psychology, and innovation and transition studies (Bulkeley & Kern, 2006; Howlett & Rayner, 2007; Jaffe et al., 2005; Mundaca et al., 2019; Oikonomou & Jepma, 2007; Oikonomou et al., 2010; Rogge et al., 2017; Somanathan et al., 2014, Section 15.7.3). This allows us to obtain a comprehensive picture of possible combinations of climate policy instruments that can achieve non-negative or even positive interactive effects on emissions reduction. Most of the aforementioned reviews do not focus on systematically assessing synergy of particular instrument combinations as we do here, nor do they include all the instrument combinations we address. Hence our study adds to the existing literature. While we focus on climate mitigation policy in the context of emission reduction, there are also reviews or synthetic studies of policy mixes for energy-efficiency (Boonekamp, 2006; Hood, 2013; Rosenow et al., 2017; Wiese et al., 2018), renewable energy (Pitelis, 2018), accelerating technological change (Rogge & Reichardt, 2016), or broader environmental issues (Lehmann, 2012).

Following the logic of Bowles (2016, Appendix 1) for the relationship between incentives and social preferences, we distinguish between four cases of interaction between policy instruments, namely (i) no (zero) synergy, (ii) positive synergy, (iii) (moderately) negative synergy, and (iv) backfire. The first case indicates that the overall effect of a policy mix is the sum of the individual instrument effects, meaning there are no synergistic interaction effects, or the instruments are independent and complementary. This is also known as additive separability. The second case describes cases in which one instrument reinforces another, meaning a positive interaction effect is at stake. This case is sometimes referred to as super-additivity, super-modularity and crowding-in.[1] An example is information provision creating awareness which in turn strengthens an incentive effect. The third case reflects that one instrument weakens another, such as when monetary incentives crowd-out intrinsic pro-environmental preferences. Here the interaction is negative, and the outcome is variably known as substitutability, sub-additivity or crowding-out. This happens, for instance, if instruments overlap in their impact on particular decisions by agents and associated emissions, so that the effect of the policy mix is lower than the sum of the isolated effects. The instruments are then (partial) substitutes of one another. An extreme version of this is the fourth case of 'backfire', denoting that one of the instruments offsets the effect of the other, causing the policy mix to perform worse than the best-performing instrument alone. This differs from moderate negative synergy, which is still reasonably effective in that it means that the combination of instruments reduces emissions more than a single instrument alone. The boundary between these two cases is what we will call 'compensating negative synergy': here negative synergy results in overall emissions reduction equalling *B*, i.e. the level achieved by the most effective instrument alone. Figure 1 illustrates these various potential outcomes of interactions between two policy instruments.

The remainder of this article is organized as follows. Section 2 discusses the approach, consisting of identifying main categories of instruments and assessing possible interactions between these. Section 3 examines the performance of specific instrument combinations in terms of emissions reduction. Section 4 summarizes the findings and generalizes these for more than two instruments, discussing relative advantages and disadvantages of a set of potential climate policy mixes. Further, it pays attention to the international context of climate policy and its implications for policy mixes. Section 5 concludes.

2. Approach

There are many classifications of environmental and climate policy instruments aimed at altering behaviour of firms and households to achieve reductions in carbon emissions (Bulkeley & Kern, 2006; Goulder & Parry, 2008; Somanathan et al., 2014; Sterner, 2002). Here we focus on a set of instruments that has received considerable attention in the literature on policy mixes:

1. Performance and technical standards. Performance standards can take various forms, such as a quota on a sector's emissions, a renewable energy portfolio target (e.g. a certain share of renewables in electricity generation), phasing out fossil fuels (e.g. coal), or banning the use of high-emission cars in cities. Technical standards specify minimum criteria for consumer or production technologies, such as fuel-efficiency standards for cars or best available technologies for pollution abatement.

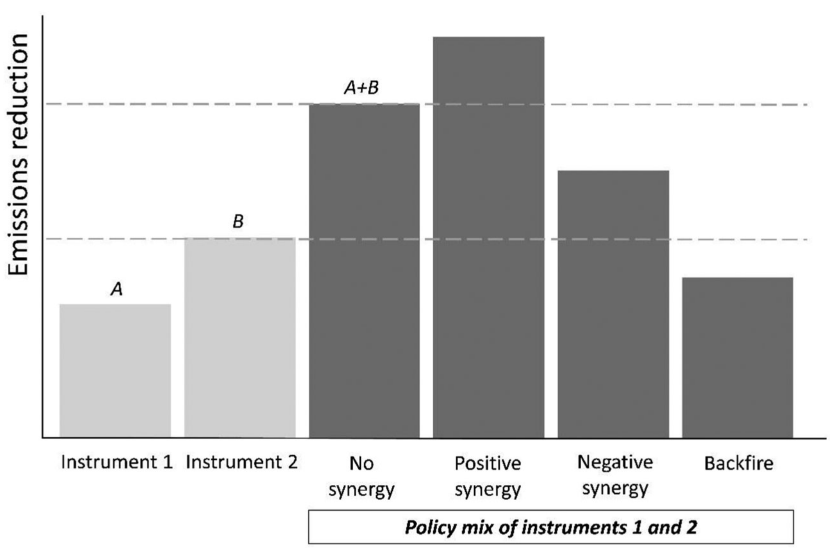

Figure 1. Potential outcomes of instrument interactions. Note: Adapted from Drews et al. (2020). The horizontal dashed line on top separates between positive and negative synergy, and the one underneath between backfire and other negative synergy.

2. Carbon pricing means incorporating the direct and indirect external costs of CO_2(-eq) emissions in the prices of fuels, resources, intermediate products, and final goods and services. This can be done through a carbon tax or emissions trading (market creation or tradable permits), which do not necessarily generate identical outcomes (Foramitti et al., 2021; Goulder & Schein, 2013).[2]
3. Adoption subsidies encourage the adoption and diffusion of energy-efficient or low-carbon products by financially rewarding the purchase of energy-efficient or low-carbon products (e.g. hybrid or electric cars).
4. Innovation support aims to increase private investment in, and success of, research and development (R&D) on energy-efficient and low-carbon technologies and products. A common way to do this is through R&D subsidies. Many other instruments fall into this broad category (Dolfsma & Dongback, 2013): e.g. green procurement, funding basic research at universities and in research centres, or legislation on intellectual property rights.
5. Information provision and nudges address lack of information – such as limited awareness of environmental challenges, solutions or associated behavioural options – and behavioural barriers – such as limited attention, self-control issues and status concerns. Instruments of the first type include providing basic information, often in a simplified form (e.g. eco-labels and energy certificates). Instruments of the second type, targeting specific behaviours, entail reminders of excessive energy use, commitment devices, and feedback about choices of others (e.g. smart electricity metres).

One can distinguish symmetric from asymmetric instruments mixes: while in the former case all sectors are subject to the instruments, in the latter case some sectors receive different treatment than others. For example, renewable electricity is subject to future targets and feed-in-tariffs, EU-ETS is limited to large industrial and energy power firms, a carbon tax is often focused on non-export sectors, and concrete technical standards apply to particular sectors – such as fuel-efficiency standards in car manufacturing.

The approach we followed to select studies for review consists of two parts. The first is a snowball method: we looked for relevant studies in existing reviews which offered a good entry point into the literature. From there we skimmed the reference lists of all identified papers until we did not find additional suitable papers. The second part involved a search in Scopus, using the following search terms:

> ("policy interaction" OR "policy synergy" OR "instrument combination" OR "instrument mix" OR "instrument interaction" OR "instrument synergy" OR "instrument combination" OR "instrument mix") AND ("climate" OR "energy" OR "emission*").

This generated a list of 273 studies of which a little over ten percent were considered relevant to our specific purpose of assessing instrument synergy in regard to emission reduction. Most of these studies are from environmental economics, while additional ones come from energy studies, environmental science, psychology and other policy areas. We excluded studies that did not focus on instrument synergy, did not provide a clear basis for their claims, or did not relate directly to climate policy and emission reduction.

3. Specific instrument combinations for emissions reduction

3.1. Carbon pricing combined with performance or technical standards

First, we consider combinations of pricing instruments, such as taxes or cap-and-trade, and direct regulation, such as quotas/targets or standards. As this topic has already been covered well in a previous IPCC report (Somanathan et al., 2014), we will keep it relatively short.

With cap-and-trade the addition of specific sector targets, technical standards (Beckenbach et al., 2018; Thurber et al., 2015) or a forced phase-out of an energy source, such as coal (Osorio et al., 2020), will certainly result in negative synergy. Theoretical studies indicate this (Christiansen & Smith, 2012, 2015; Roberts & Spence, 1976). The reason is that the target and the standard reduce emissions in sectors that then need fewer permits, leading to lower permit prices and higher emissions in other sectors subject to the cap but not the target or standard. This is known as the 'waterbed effect': emissions are not reduced but just appear in another place (Perino, 2018). It means that the carbon market price is determined not only by marginal abatement costs of emitting firms but possibly also by the other policy instrument, namely if it stimulates or obliges emissions reduction with a relatively high marginal cost (i.e. beyond the permit price in an isolated carbon market). The overall abatement cost will come out higher (OECD, 2011; Sijm, 2005). This holds equally for countries and multilevel systems. Well-intended energy policies by states or countries, respectively, can undercut the consistent approach aimed for by a national or supra-national policy such as the EU-ETS, frustrating the effectiveness and efficiency of emissions reduction. An assessment for the EU by Böhringer and Rosendahl (2011) finds more than 60% cost increase of achieving 25% CO_2 reductions when a renewable energy quota is set 10% points higher than the endogenous renewable energy deployment level under the EU-ETS, and that the permit price falls from €41 to €16 per ton of CO_2.

Table 1 clarifies how synergy resulting from adding renewable energy policy (REP) in the form of standards or targets to carbon pricing differ between a carbon tax and carbon market creation (such as emission trading). With a carbon market, the outcome is compensating negative synergy (on the boundary of backfire; see discussion of Figure 1) making the second instrument unnecessary, while with a carbon tax synergy can range from negative to zero (complementarity). For maximum effectiveness REP is thus best combined with a carbon tax rather than carbon market creation. Moreover, as explained by the difference between the two cases in the columns, such policy should avoid targeting relatively cheap options that are already triggered by the carbon tax.[3]

The previous problem pertains to California, China and the EU given that they all have climate policies combining emissions trading and sector-specific targets or standards (Duan et al., 2017; Fankhauser et al., 2010; Schatzki & Stavins, 2012). Many more studies report the same finding (e.g. del Río, 2011; Delarue & Van den Bergh, 2016; Görlach, 2014; Tu & Mo, 2017). The overall policy mix will then perform equal to emissions trading on its own.[4] Evidence for various countries is summarized in Fankhauser et al. (2010).

Finally, low-carbon technical standards on technologies for adoption may suffer from energy/carbon rebound in the user phase, causing a loss in overall effectiveness of emissions reduction. Combining standards with carbon pricing will limit such rebound by making energy and emissions during the use phase more expensive, thus discouraging more intense use and associated rebound (Font Vivanco et al., 2016; Freire-González, 2020; van den Bergh, 2011). As a result, technical standards and carbon pricing have positive synergy in terms of emissions reduction.

3.2. Carbon pricing combined with adoption subsidies

Combinations of taxes and adoption subsidies take different general forms, including feebates, deposit-refund systems and environmental tax revision. The connection is particularly relevant for carbon pricing, as both revenues from carbon taxation and permit auctioning can serve to finance a subsidy, rebate or refund. In fact, the carbon tax and its revenue recycling can then be regarded to form a policy mix.

Adoption subsidies as an additional instrument to carbon pricing can be motivated in various ways. First, they create protected niche markets for low-carbon technologies and products, which stimulate expansion of associated production capacity, in turn creating scale and learning effects. This causes the low-carbon alternatives to become more competitive with incumbent high-carbon options (Hoppmann et al., 2013). Second, adoption decisions are often subject to peer pressure and hence early adopters may have a positive external effect on late adopters. For instance, houses with solar photovoltaic panels on rooftops have been found to increase the probability of neighbours installing it as well (Bollinger & Gillingham, 2012). Third, with only carbon pricing, adoption and thus diffusion of low-carbon options

Table 1. Emissions reduction (and synergy) of combining carbon pricing and renewable energy policy.

	Combined effect (emissions reduction and synergy) with renewable energy policy	
	MAC > *p*	*MAC* < *p*
Carbon market	emissions reduction *X* implying synergy -*Y*	emissions reduction *X* implying synergy -*Y*
Carbon tax	emissions reduction *X* + *Y* implying synergy 0	emissions reduction *X* implying synergy -*Y*

Note: *X* denotes emissions reduction of carbon pricing on its own (isolated carbon market and tax are equivalent in terms of emissions reduction, i.e. tax = market price = *p*); *Y* is emissions reduction of renewable energy policy (REP) on its own. *MAC* denotes the marginal abatement costs of renewable energy investment. Of course, a part (say a, with $0<a<1$) of renewable energy investments could have a *MAC* below and the rest above *p*, in which case the negative synergy of tax and REP will be $-a \cdot Y$. Since a in general will be non-negative, some degree of negative synergy is likely here.

may be hampered by behavioural factors such as myopia, warranting tailored incentives like adoption subsidies. An alternative to overcome behavioural barriers is information provision, as discussed in Section 3.4.[5]

Despite these advantages, adoption subsidies for low-carbon options are best not implemented on their own, but complemented by carbon pricing. Support of investment in renewable energy capacity through subsidies alone makes energy use overall generally cheaper and can thus increase demand for energy, thus limiting overall emissions reduction (Murray et al., 2014). In particular, while adoption subsidies stimulate purchase of low-carbon options (e.g. low-carbon vehicles), they effectively lower energy costs per unit of use (e.g. km driven). This in turn tends to give rise to energy/carbon rebound through more intense use (more trips or longer distances travelled with the vehicle). As argued in Section 3.1, carbon pricing will limit such rebound and thus generate positive synergy. Hence, one should be careful using adoption subsidies to stimulate the purchase of products whose use causes carbon emissions, such as electric vehicles running on electricity that is not entirely carbon-free; without a carbon price in place emissions could rebound and even rise.

According to Fankhauser et al. (2010), feed-in tariffs (FITs) to support renewable energy obligations for a sector that is also subject to a cap-and-trade system will weaken the carbon price and thus decrease emissions reduction, compared to the sum of emission reduction potential for each instrument in isolation (see also Sorrell et al., 2009; and Twomey, 2012). Fais et al. (2015) analyse interdependencies between the EU-ETS and the German FITs for renewable electricity using a bottom-up energy system model. They find that permit prices decline by between 1.9 and 6.1 €/tCO2 and the burden sharing between participating countries changes, distorting the cost-effectiveness of cap and trade, with additional costs under FIT between €44 billion and €57 billion over the period 2013–2020. To this, one has to add the pure cost of the FIT which is €320 billion in the same period. So, while not adding extra emissions reduction, i.e. causing negative synergy, the FITs also contribute to significant additional costs.

Feebates (fee + rebate) or bonus-malus schemes combine a carbon tax (or a sales tax with a carbon component) on high-carbon options with an adoption subsidy for low-carbon alternatives. The simple idea behind it is that the high-carbon option is discouraged and the low-carbon one encouraged. However, like a pure adoption subsidy, a feebate suffers from the above-discussed rebound problem (Haultfœuille et al., 2014) and requires a consistent price on all carbon to limit more intense use of the low-carbon option. An advantage of feebates is that, instead of requiring a high carbon tax to shift consumer decisions to low-carbon options, which has been politically infeasible so far, one can combine a lower carbon tax with a rebate, which might be more politically acceptable. Ideally, the combination of these instruments creates the same price gap between high- and low-carbon options as achieved by the high carbon tax alone. Another advantage is that the system can be self-financing, namely the subsidy (rebate) can be paid out of the fee revenues. However, it may be impossible to satisfy the two conditions – i.e. an optimal price gap and revenue or budget neutrality – simultaneously. In addition, governments have to address the challenge that an effective carbon tax erodes the emissions base of tax revenues, requiring them to think about timely implementation of additional revenue-raising taxes.

A disadvantage of feebates, and adoption subsidies generally, is that overall consumption is encouraged compared to an equivalent carbon tax (i.e. with the same price gap between low- and high-carbon), given that low-carbon usually also involves carbon emissions (in production and use phases).[6] However, as diffusion may go faster, there is uncertainty about the net effect on emissions in the long run. Exact outcomes depend on the precise design including whether it satisfies self-financing or not. For instance, Durrmeyer (2018) finds that under a flat rate tax, the feebate scheme favours individuals in the middle-income class, while if the tax is proportional to income, the feebate redistributes some income from the richest to the poorest households. Unlike a pure carbon tax, where revenues can be used to compensate lower-income households, in the feebate approach no funds are automatically generated to pay for such compensation. Note that both instruments have a rebound effect: carbon-tax revenue recycling to poor households creates a positive income effect on consumption; and the feebate's rebate stimulates consumption of the low-carbon option.

3.3. Innovation support combined with other instruments

The traditional economic perspective on climate policy recognizes two externalities that require a policy response. The first is negative, namely environmental externalities, which are tackled through pricing of external costs. The second is positive, namely knowledge-related spill-overs of R&D driving innovation in low-carbon technology, due to incomplete appropriability of innovation benefits. These can be regulated with adequate innovation policy, including protection of intellectual property rights and subsidies for risky R&D with an uncertain or long-term payback. This policy approach finds support in both economics and innovation studies (Jaffe et al., 2005). A third challenge for climate policy is the problem of social, economic and political lock-in of undesirable (high-carbon) technologies and practices or lifestyles (Geels et al., 2017). Others refer to 'system weaknesses' and the need for 'structural build-up of innovation systems' in this respect (Jacobsson et al., 2017). All in all, this results in what has been called 'a triple-externality problem' (van den Bergh, 2013a).

Lock-in denotes that a dominant technology or practice is so much more attractive to potential future adopters that it is difficult to escape from it (Arthur, 1989; David, 1985). It is the outcome of a path-dependent process driven by increasing returns to scale on supply sides (e.g. economies of scale, learning and technological complementarity) and on demand sides (e.g. imitation or network externalities) (Seto et al., 2016). The issue of lock-in is relevant to the adoption of low-carbon options, such as renewable energy (Zeppini & van den Bergh, 2020) or electric vehicles (Cowan & Hulten, 1996).

Implementing only environmental regulation/pricing or only technological policy in the presence of all these externalities has a disadvantage. For instance, renewable energy support in isolation can reduce fossil fuel prices, in turn leading to more rapid extraction of fuel resources as a second-order effect –known as the 'green paradox' (Sinn, 2015). To avoid it, one should also make fossil fuels more expensive through environmental pricing (van der Ploeg & Withagen, 2015). However, if the only policy instrument is environmental regulation/pricing, energy technologies that are cost-effective will survive, while promising but less developed alternatives (i.e. expensive but with a steep learning curve) will not be selected. This then gives rise to early lock-in of currently cost-effective options, even though these may not be optimal in the long run. Implementing innovation policies that encourage expensive and risky R&D can avoid such lock-in, as it keeps promising technological trajectories open (Way et al., 2019). In particular, innovation support counters the short-term selection pressure against such technologies created by regulatory instruments (standards, targets) or carbon pricing. Another consideration is the riskiness of private investment and R&D in low-carbon options. A combination of environmental and technology-specific policies reduces this uncertainty, and consistently shapes the direction and speed of low-carbon innovations towards maximum emissions reduction in the long run.

This combination may still be insufficient, however, to escape from locked-in fossil-fuel based energy and transport systems. A particular 'unlocking policy' may be needed that counters increasing returns to scale on demand and supply sides of markets. One option is to set a very high carbon price, even above the optimal (Pigouvian) level. An applied model study by Mercure et al. (2014) show that a carbon price alone can achieve escape from (fossil fuel or carbon) lock-in but that a policy mix with regulatory instruments like technical standards in addition allows to do so with a lower, arguably more politically feasible, carbon price. Alternative policies and strategies to evade lock-in include setting a clear future goal (e.g. California's ZEV programme) and creating semi-protected niche markets for innovative technology (e.g. with adoption subsidies or public procurement) (van den Bergh, 2013b). One can think of more daring strategies as well, such as restricting the advertising of high-carbon products or reinforcing social norms and status associated with uptake of low-carbon products and services. These instruments complement innovation policies, so would give rise to a policy mix with potentially positive synergy. Axsen et al. (2020) elaborate this for transport emissions.

Use of innovation policy instruments will also allow other types of instruments, such as adoption subsidies or carbon taxation, to have more impact in stimulating a shift from high- to low-carbon consumption. Conversely, the impact of public R&D support can be greater at the margin if accompanied by FIT, particularly in periods of technological maturity, as shown by Lindman and Söderholm (2016) using wind-energy patents. The reason is that learning-by-doing feeds back to the innovation phase by driving lower prices and higher sales, in turn affecting innovation investments and direction. Hence, one can expect positive synergy between innovation and adoption incentives over longer time periods. In addition, positive synergy is also feasible with regard to innovation speed and direction as these not only depend on innovation policies but also on regulation or pricing (Aghion et al., 2016; Popp, 2002). This is because innovating firms take expectations about future costs and prices into account. Therefore, regulation and pricing are not only relevant for short-term emissions reduction but also for the speed and direction of innovation, and hence long-term emissions reduction.

3.4. Information provision combined with other instruments

There seems little opposition against instruments of information provision, arguably as their administrative cost is relatively low and they leave people free to act while they do not have inequitable effects. On their own, information policies do not have a strong emissions reduction effect: on the order of 5–10% of prevailing emissions, according to various meta-analyses (Andor & Fels, 2018; Delmas et al., 2013; Wynes et al., 2018). In addition, their effects tend to fade out quite quickly (Nisa et al., 2019). But information provision can complement other types of instruments, sometimes creating positive synergy with these, though it should be said that effectiveness varies strongly between different types of information provision and nudges (Abrahamse & Steg, 2013; Schubert, 2017).

Relatively few studies offer a theoretical analysis of the interaction of information provision and other instruments. The general argument for a complementary role of information and nudges with other policies is that behaviour takes different forms (e.g. one-shot vs. habitual) and is underpinned by different drivers (Stern, 2020). These can be accounted for by tailored information and nudges. Several studies suggest that a combination of regulation/pricing and information provision can be more effective than each alone (Nyborg et al., 2006; Stern, 1999; Stiglitz, 2019). A study by Gsottbauer and van den Bergh (2014) develops a model of consumption influenced by norms or status in combination with commercial advertising. It finds that to achieve socially optimal outcomes, next to an adapted Pigouvian tax on pollution to limit the negative environmental externality, one needs also a tax on advertising or public provision of information to restrict the positive externality of norms and status that magnifies consumption. Information provision to counter advertising is by itself insufficient as it does not completely cancel the magnifying effect, necessitating a tax on advertising in addition. This is consistent with findings from Glaeser and Ujhelyi (2010), who develop a model of advertising as misinformation, showing that it is welfare-improving to impose a ban or tax on advertising, and under some circumstances to provide public information about the real cost and benefits of advertising.

The interaction of information provision and regulation, notably carbon pricing, can also be considered from the angle of social networks. Konc et al. (2021) illustrate this through a model of consumption decisions driven by socially-embedded preferences, which are formed under the influence of consumption choices by peers in a social network. It shows that the effectiveness of carbon taxation is improved due to a social multiplier effect that depends on four factors: the strength of social influence; the initial preference distribution; the specific network topology; and the income distribution. It is argued that some of these factors may be influenced by specific kinds of information provision, namely: comparative feedbacks can reinforce the social context in the formation of preferences; information correcting misperceptions about climate change can shift preferences towards low-carbon options; and information aimed at highly interconnected agents in a social network can drive them to adopt low-carbon options, in turn accelerating their diffusion. Hence, such information provision can create positive synergy by increasing the social multiplier effect of a carbon tax.

Empirical evidence is varied on how information provision influences the effectiveness of the instrument with which it is combined (Trencher & van der Heijden, 2019). For example, an informational campaign that justifies to car users the introduction of a tax on transport fuels is likely to make this tax more salient, increasing the responsiveness of consumers (Li et al., 2014). In particular, information provision affects behavioural tendencies that moderate the effectiveness of instruments; by making taxes or subsidies more salient, information provision can increase or decrease consumers' responsiveness (Allcott et al., 2015; Perino et al., 2014), or by providing repetitive feedback it can increase the effectiveness of monetary incentives (Matthies et al., 2011).

In the area of energy-conservation policies, supplementing regulatory/pricing policies with information measures can compensate asymmetric information that hampers the diffusion of energy-efficient technologies (Lehmann, 2012). Improving agents' knowledge about available energy-efficient options will allow them to respond well to monetary incentives by policies like carbon pricing. For example, in the housing sector, the landlord may be required to inform the tenant about the energy efficiency of his building by way of an energy certificate. Empirical studies show such measures can reduce energy use, depending on the market, technology and the overall policy mix (Lehmann, 2012). According to Sorrell and Sijm (2003) information provision is most useful as an additional instrument for households and small or medium-sized firms as these tend to have little knowledge about relevant options, large energy-saving potential, and low energy-price elasticities.

Studies using mostly field experiments to test synergy between incentives and information provision or nudges offer mixed evidence: positive synergy (Hilton et al., 2014; List et al., 2017), negative synergy (Dolan & Metcalfe, 2015; Sudarshan, 2017), no synergy (Handgraaf et al., 2013; Mizobuchi & Takeuchi, 2013; Panzone et al., 2018; Pellerano et al., 2017; Schall et al., 2016; Tørnblad et al., 2014). For example, a study by Panzone et al. (2018) examined how a carbon tax combined with a moral nudge affects food choices in an online supermarket in the UK. When considering the instruments in isolation, both the carbon tax and, to a lesser extent, the nudge encouraged people to choose food products with a lower carbon footprint. However, the study found no positive synergy from combining the instruments. An important caveat is that only a minority of studies include a full analysis required to arrive at robust conclusions. Drews et al. (2020) propose how to improve this kind of experimental research, recognizing that not only monetary incentives may crowd-out non-economic motivations, but also nudges or information provision can crowd out the effectiveness of monetary incentives. What matters further is how information is framed and provided, such as through feedback, advertising, contextual information, descriptive social norms, etc. (Abrahamse et al., 2007).

3.5. Other interactions, including within an instrument category

Innovation or technology policy itself makes use of multiple instruments, which has received quite some attention in the literature (Borrás & Edquist, 2013; Herrmann & Savin, 2017). One classification is into mission- and diffusion-oriented design (Ergas, 1987). A combination of diffusion- and mission-oriented instruments is common as it stimulates economies of scale and technology maturity, while supporting a diversity of technologies and start-up firms, which in the longer run can transform the economy towards low-carbon. For example, Palage et al. (2019) find that public R&D support of solar photovoltaic innovation is more effective if it is accompanied by a FIT scheme.

The literature on innovation studies further proposes to use multiple instruments to benefit from technology push and demand pull. To achieve the first, one can use instruments of innovation support, such as R&D subsidies or technology transfer (Bozeman, 2000; Martin, 2012), while the second can be encouraged through pricing of environmental externalities (punishing dirty options) or adoption subsidies (rewarding clean options). Di Stefano et al. (2012) mentions various reasons for positive innovation synergy between demand and supply (policies), such as user-producer interactions and firm innovation being driven by supply- and demand-driven opportunities.

Interactions between multiple standards and targets happen frequently in multi-level regulatory systems such as the EU and USA. Using a partial-equilibrium structural model of agricultural and energy markets, Whistance et al. (2017) examine interactions between a national renewable fuel policy in the United States, namely the Renewable Fuel Standard, and a state-level renewable fuel policy, namely the Low Carbon Fuel Standard in California. Both aim at reducing greenhouse gas emissions. The study finds that there is no interaction in terms of national-level effectiveness, but that a shift occurs in renewable fuel use toward California at the cost of other regions.

A study by Brandon et al. (2019) on electricity demand reduction in the US tests crowding-out[7] between multiple information-provision instruments, regarding peak time energy consumption, and social norm comparison. In their natural experiment involving around 42,000 households, they set up three treatment groups, finding a positively synergistic effect (6.8% versus 5.9%).

There are also some insights about very specific instrument combinations. For instance, regarding adoption subsidies, an agent-based model study by Silvia and Krause (2016) examines how these influence diffusion of electric-battery vehicles. They find that combining such subsidies for vehicle purchase with investment in extending the charging network and governmental purchase of vehicles (procurement) leads to the highest number of adopted vehicles when compared to scenarios with isolated policies at higher stringency.

Another example of particular instrument mixes concerns fleet standards and policies encouraging adoption of low-emission vehicles. Jenn et al. (2016, 2019) show that state mandates (zero-emissions vehicle policy) increasing alternative-fuel vehicle sales are counteracted by federal policy requiring automakers to meet aggregate criteria for fleet-fuel efficiency, such as 'Corporate Average Fuel Economy' (CAFE) standards. The authors find that these standards are relaxed when more alternative-fuel vehicles are sold to the extent that overall emissions increase considerably.

4. Suggestions for effective policy mixes

There are many considerations when evaluating climate policy, such as effectiveness, efficiency, equity, political feasibility and harmonization of international policy. In line with the focus of this article, in this section, we examine more complete instrument mixes from the angle of synergy in terms of emissions reduction, while giving attention to these other dimensions as well.

We first summarize in Table 2 how the previous knowledge about instrument interactions, as documented in Section 3, translates into the design of complete climate policy packages. Regarding the evidence (last column), theoretical modelling can separate clearly and precisely the effects of each instrument alone and their interactions, but inevitably tends to abstract from real-world complexity. By comparison, empirical studies include many relevant factors that play a role in reality, but have more difficulty in separating the effects, and thus interactions, of multiple instruments. Laboratory experiments can compare behavioural responses of people to single and multiple instruments, but only by abstracting from economic, social and political factors that play a role in reality. Looking across results from the three techniques used to study instrument combinations will provide a stronger basis for the design of climate policy.

Next, Table 3 suggests four relatively effective instrument mixes resulting from achieving positive, and avoiding negative, synergies among instruments – informed by Table 2. The idea behind this is that one should add instruments as long as these have zero or positive synergy, but should be careful when adding instruments that introduce negative synergies, depending on the size of the latter. For example, combining renewable energy policy and carbon markets is risky because of compensating negative synergy (see discussion of Figure 1) which limits overall emissions to the market cap. For lower values of negative synergy, exact quantification and assessment of comparative abatement and policy costs is needed (i.e. implementation, monitoring and control), to decide about the exact policy mix.

Implicit in the comparison of instrument mixes is that stringencies of instruments are such that all mixes have an equal (or at least very similar) effectiveness, absent from synergy effects. This will avoid having stringency differences dominate overall effectiveness between mixes. To operationalize this, one could assess the effectiveness of each instrument on its own (e.g. through an implicit carbon price), and then sum these to assure that policy mixes have similar overall effectiveness absent accounting for synergy effects. This will subsequently allow for separating out synergy effects through comparison. Admittedly, this restriction may limit a complete comparison of instrument mixes with varying stringencies; further empirical or experimental studies would be needed to test for this. In addition, we assume – as there is little literature providing evidence – that the effects of triple and higher interactions, i.e. between more than two instruments, are small and do not overrule the effects of dual interactions. Some studies include more than two instruments but provide insufficient information about what is the exact cause of the overall synergy (e.g. Fagiani et al., 2014; Vilchez et al., 2020).

In comparing the policy mixes, next to effectiveness (associated with synergy) we consider also efficiency, and implicitly political resistance. We can do this as efficiency features of instruments – notably overall abatement costs of complying with the policy – are well known, based on extensive theoretical and empirical insights (Aldy et al., 2010).[8],[9] The scores on the two criteria are shown in the final two columns of Table 3. Policy mix *A* is the least effective due to rebound being uncontrolled by pricing, and further is the least efficient because of fixed targets or standards rather than price incentives that select for cost-effective abatement options. As argued in Section 3.1, policy mix *B* can be less efficient in emissions reduction than mix *C*, if the standards select for relatively expensive abatement options that are not triggered by the carbon tax. An advantage of policy mix *B* is that the standards allow using a lower carbon tax, which could be a wise strategy facing less political resistance than a high carbon tax in policy mix *A*. However, policy mix *B* also can suffer from negative

Table 2. Which instruments to be combined or not in a climate policy package.

Instruments	Main role	Recommendable combination (zero or positive synergy)	Caution required when combined with (negative synergy)	Uncertain combinations (research gaps)	Supporting theory and evidence
Performance & technical standards	Assures that investment decisions by firms and purchase decisions by consumers focus on low -carbon alternatives.	With carbon tax to avoid rebound (intensity of use).	With carbon markets (i.e. cap and endogenous carbon price) as this will cause intersectoral leakage, and to a lesser extent with a tax as this may also lead to negative synergy.	Interaction with adoption subsidies, innovation support and information provision needs attention.	Theoretical modelling and empirical studies (Sections 3.1 and 3.5).
Carbon pricing	System-wide consistent regulation/pricing, controlling leakage, and controlling rebound effects due to intensity-of-use and re-spending.	With innovation support for promising but still expensive technologies, to avoid early selection and lock-in of technologies that are not the best for climate solutions in the long run.	Carbon market not combined with performance and technical standards as this will reduce effectiveness. Also not combined with adoption subsidies as this reduces price and thus emission reduction in other sectors.	Interaction with adoption subsidies and information provision needs further attention.	Theoretical modelling and empirical studies (Sections 3.1, 3.2, 3.3. and 3.5).
Adoption subsidies (including feebates or feed-in tariffs)	Encouraging adoption of low-carbon options, capturing any positive externalities such as between adopting neighbours.	With carbon taxes as otherwise high-carbon options are insufficiently discouraged. Carbon tax also controls rebound through more intense use of adopted low-carbon goods. With innovation subsidies as they magnify effect of adoption subsidies.	With carbon markets as their endogenous carbon price will be negatively affected by the adoption subsidy, which reduces the effectiveness of the carbon market.	Runs the risk of subjectively focusing on a technology that does not guarantee the best performance in the long run.	Theoretical modelling and empirical studies (Section 3.2 and 3.3).
Innovation support	Keeping promising but still expensive technological trajectories open, escaping lock-in of fossil-fuel based technologies, and basic university-based research on low-carbon options.	With carbon pricing to direct innovation and adoption towards low-carbon products, services and practices. With adoption subsidies (in later stage) to increase diffusion and learning-by-doing effects.	Can be combined with most or all other instruments (no indication of negative interactions).	Runs the risk of focusing on a technology that does not guarantee the best long-run performance. Interaction with targets and technical standards needs further attention.	Theoretical modelling and empirical studies (Section 3.3).
Information provision & nudges	Reinforcing favourable social network effects, correcting behavioural biases, dealing with split incentives, etc.	With carbon pricing as specific information provision can reinforce its effectiveness.	No indication of systematic and strong negative interactions with other instruments.	Interaction with most other instruments (only partial understanding).	Theoretical modelling and experiments (Sections 3.4 and 3.5).

Table 3. Possible policy mixes with complementarity or positive synergy.

Policy mix	Instruments						Performance	
	Performance & technical standards	Carbon tax	Carbon market	Adoption subsidy	Innovation support	Information provision & nudges	*Effectiveness*	*Efficiency*
A	x			x	x	x	low	low
B	x	x		x	x	x	high	low
C			x		x	x	high	high
D		x		x	x	x	high	high

synergy between the tax and standard (see Table 1), making it less effective than *A*. Note that renewable energy targets and adoption subsidies are excluded from policy mix *C* as they interact negatively with the carbon market (Sections 3.1 and 3.2). This means the long-term effectiveness of emissions reduction may be lower than that of policy mix *D*, which combines adoption subsidies with a carbon tax.[10]

Finally, we discuss a neglected but relevant consideration in the literature on climate-policy mixes, namely the political feasibility of stringent climate policy. Since climate policy is an international challenge with the characteristics of a public good that invite free-riding by national governments, achieving stringent policies in all countries requires global upscaling, harmonization or integration of national policies (Jordan & Lenschow, 2010). This holds especially true for regulatory and pricing instruments, as these affect competitive positions (and thus exports) of countries. Motivations for this view are diverse – see, e.g. Fowlie (2009), Fischer and Fox (2012), and Al Khourdajiea and Finus (2020). For alternative, minority views see, e.g. Bernstein and Hoffmann (2019) and Jordan et al. (2018).

While international competitiveness effects of climate policies have been found to be rather weak overall (Aldy & Pizer, 2015), two comments are in order. First, national policies so far have been lax everywhere, meaning that differences in stringency among countries have not been pronounced. In a study focused on carbon pricing, Venmans et al. (2020) conclude that 'When statistically significant results have been found, the magnitude of such effects tends to be small […] These findings are in part because carbon price levels have been low.' Indeed, a recent assessment of carbon pricing found that the average price of carbon in countries where it is implemented is about 7.90€ per ton CO_2 (Finch & van den Bergh, 2020). Hence, one cannot extrapolate empirical findings about competitiveness effects to carbon price ranges (or trajectories) recommended as needed to meet the Paris targets, i.e. US$50–100 by 2030 (HLCCP, 2017; IMF, 2019) or even US $245–14300 tCO2e (Masson-Delmotte et al., 2018). Second, perceptions matter: politicians fear for competitiveness effects and business lobby to strengthen this. Note that the EU is seriously deliberating a border carbon tariff to protect its economy for competitiveness effects of its relatively stringent climate policy. Harmonization will take away politicians concerns and thus can encourage more stringent national policies.

Such a need for global policy harmonization can be seen as an argument for limiting the number of policy instruments, or striving towards a transparent and simple policy mix that can be more easily compared and integrated among countries. If, on the other hand, countries have very complex policy mixes, it might be difficult for them to judge, compare and match these (del Río, 2014; Howlett et al., 2017; Schmidt & Sewerin, 2019), in turn possibly discouraging them to implement strong regulation/pricing instruments (Weitzman, 2014). A rich policy mix, as is common worldwide, moreover can be used as an excuse for politicians to claim 'we are doing a lot already', even when the overall effectiveness of the policy mix is disappointing. These considerations suggest limiting the number of regulatory/pricing instruments, which means a trade-off with reasons for additional policy instruments, such as positive instrument synergy.[11]

If we judge how the four policy mixes in Table 3 perform on capacity for global harmonization, then option *C* comes out best, given that harmonization so far has been more successful with carbon markets than carbon taxation (options *B* and *D*). Indeed, such markets have been integrated among regions or countries in North America and Europe, while the same has not happened with carbon taxes, possibly as governments are unlikely to hand over control over taxes to a supranational body (van den Bergh et al., 2020). Finally, achieving harmonization with options *A* and *B* seems also difficult given they involve a multidimensional challenge of harmonizing many performance and technical standards next to various subsidies, while the latter would also involve the problem of supranational financing.

Considering all criteria together then, options *C* and *D* perform well on effectiveness, and *C* best on harmonization. *A* and *B* performs worst of the four options, and choosing between them is difficult in general as *A* may perform better on effectiveness (if *B* suffers seriously from negative synergy between the standard and tax) while *B* performs better on efficiency (so there is a trade-off then between effectiveness and efficiency to be made). This suggests that a ranking of options from most to least attractive is: *C, D, B, A*. However, a provision is needed, as we only consider two values for each criterion. Since it is possible that two 'high' scores on effectiveness are not exactly the same, we cannot derive a definite ranking. This would require a trade-off between the exact performance in terms of each criterion (moving beyond the general instrument categories to specific instruments), as well as weights or priorities assigned to the different criteria. If one believes, for instance, that without harmonization significantly raising the carbon price over time to meet ambitious emissions reduction goals will be very difficult if not impossible, it would make sense to weight the final criterion more heavily. This then would result in a preference for policy mix *C*. Although this is not a complete assessment, it indicates how one can integrate insights to decide about well-performing policy mixes.

5. Conclusions

It is important to seriously consider climate-policy mixes as recommended on the basis of insights about instrument interactions. The reason is that the practice of climate policy is strongly driven by political and stakeholder processes that easily result in what Bouma et al. (2018) call a 'policy mess'. As noted by Bennear and Stavins (2007), there is no evidence that implemented policy mixes are the most effective.

This study has collected insights and evidence from theoretical modelling and empirical and experimental studies to assess the negative or positive synergy of combining instruments in climate policy, aimed at achieving effective emissions reduction. This involved a more focused and concrete approach than in previous studies on climate policy mixes (listed in Section 1). We synthesized the findings on dual instrument synergies by formulating and comparing more complex policy mixes. We conclude that the most promising packages would be to combine innovation support and information provision with either a carbon tax and adoption subsidy, or with a carbon market and no adoption subsidy. We further argue that the latter could have stronger potential with respect to harmonization of international policy and thus the strengthening of mitigation policy over time.

Given its complexity, this topic merits further research. Quantification and weighting of policy-mix performance on multiple criteria, including notably equity, can help to provide more definitive advice. In addition, political feasibility of policy mixes deserves more attention in a dynamic setting of policy sequencing, transitions and coalition formation (Edmondson et al., 2019; Gerlagh et al., 2009; Herrmann & Savin, 2017; Meckling et al., 2015; Skovsgaard Aidta & Duttab, 2004). Finally, research is welcome beyond dual instrument interactions, namely on the magnitude of synergy between three or more instruments.

Notes

1. Note that cases (i) and (ii) are sometimes also referred to as instruments being complementary. To avoid confusion, we use in this paper the term 'complementary' strictly for case (i).
2. A cap-and-trade system can itself already be regarded as a mix of policy instruments, namely a quantity-based instrument (i.e. a cap to emissions, defining the sum of all emission permits) and a price-based instrument (i.e. variable price due to trade of permits). Such a hybrid policy has various advantages (Hepburn, 2006; Grülla & Taschinibc, 2011). Specific additional elements add further benefits, such as limiting volatility of the carbon price through a minimum price or price floor, and avoiding unsurmountable costs for emitters through a maximum price or 'safety valve' (Jacoby & Ellerman, 2004; Philibert, 2009).
3. A few studies claim that despite negative synergy, the combination of carbon market and renewable energy policy can be useful: e.g., if the design of the permit market is imperfect (Lecuyer & Quirion, 2013, p. 2019) or energy market are imperfect (Lehmann & Gawel, 2013). Others point at long-term innovation benefits (del Río, 2017; Fagiani et al., 2014). However, direct innovation support seems more effective for this purpose and will avoid negative synergy with carbon markets (Section 3.3).
4. This can be compensated by a market stability reserve, as in the EU-ETS (Perino et al., 2019). Reducing the cap over time is another way to reduce negative synergy; more specifically, deducting the emissions reduced by the standards from the cap neutralizes the leakage (Richstein et al., 2015). A third option is installing a carbon price floor (Flachsland et al., 2020). Perino (2018) warns, though, that this may not be a permanent solution.

5. Stoneman and David (1986) compare adoption subsidies and information provision in their role as instruments to encourage diffusion.
6. An overall comparison of feebate and carbon tax should also account for any emissions reduction or increase due to use of carbon tax revenues.
7. This is one of the few studies that includes the four required treatments: no policy, either instrument in isolation, and their combination. Note that crowding-out (in) means that the combined effect is smaller (larger) than the sum of the two isolated effects.
8. With regard to the trade-off between effectiveness and efficiency, the prices-vs-quantities debate started by Weitzman (1974) is relevant. It distinguishes between uncertainty about effectiveness of price instruments versus uncertainty about the costs of quantity instruments. While this debate is more about instrument choice and incentives than about a policy mix, it has been connected – even in the context of climate policy – to hybrid instruments such as tradeable permits with a price floor (kind of a policy mix). Such hybrids are found to perform better than each instrument alone (Pizer, 1997). Considering a setting with multiple pollutants, Ambac and Coria (2013) find that the desirable policy mix depends on whether pollutants are complements or substitutes.
9. We considered adding equity to the set of performance criteria. However, it has not received much attention in studies assessing synergy of policy instruments, while its assessment requires information about generally unknown factors, such as wealth and income distribution, prices, sector shifts and associated unemployment. In addition, it depends on how revenues of carbon pricing are used (Klenert et al., 2018; Hafstead, 2019).
10. One might, as a transition approach, combine a carbon tax for small emitters with a carbon market for large emitters, as already happens in various EU countries. This evidently complicates the policy mix while adding the challenge of multiple, incongruent carbon prices.
11. Among the various instruments, global carbon pricing enjoys the advantage that negotiating it is relatively simple as it means a one-dimensional negotiation challenge (Weitzman, 2014, 2017). Instead, negotiating national emission targets among 200 countries implies a 200-dimensional coordination problem, while negotiating technical standards for *n* products or technologies would mean an *n*-dimensional challenge (with *n* possibly being very large). In addition, a carbon market can harmonize national climate policies. Indeed, most current harmonized carbon prices are due to carbon markets (Haites, 2018).

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