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The role of carbon pricing in energy-transitions policy and research

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Abstract

We examine the relevance of carbon pricing for transition policy. It argues that carbon pricing should be a key element of a broader transition policy as it triggers multiple processes that critically matter to a low-carbon transition. Since carbon pricing has been criticized by various researchers in transition studies, their concerns and arguments are evaluated here. The paper further draw attention to the international dimension of a transition to a low-carbon economy, given that climate policy is a global public good and thus amenable to free riding by countries. In addition, it clarifies the need for a policy instrument that avoids counter-productive systemic effects, such as carbon leakage and energy rebound. It is explained that carbon pricing performs relatively well in both respects. In addition, the role of carbon pricing as part of a wider policy package is examined, accounting for positive and negative synergies between instruments. The paper ends with proposing that transition studies pay closer attention to carbon pricing, providing various recommendations for research.

Keywords: carbon tax, carbon market, transition studies, innovation policy, climate policy, energy policy, policy mix.

1. Introduction

There is currently considerably interest in energy transitions, interpreted as major changes in the way of producing, transporting and utilizing energy, aimed at contributing to an environmentally sustainable and socially equitable economy. Many scientific disciplines contribute insights about policies and institutions needed to foster such transitions, based on theoretical arguments and empirical lessons drawn from ongoing transitions. These insights tend to reflect distinct assumptions and methodological traditions, resulting in considerable disagreement about both the ideal policy package and the core instrument required to enforce major changes in energy-relevant behaviors, practices, organizations and technologies. We focus here on decarbonization, notably low-carbon behaviors and technologies, while connecting with the broader literature on sustainability transitions, notably its suggestions for policy design. Our concern is that this literature ignores, or at best downplays, carbon pricing. Instead, we forcefully argue in favor of giving this instrument a key role in transition policy, without denying an important complementary role for other instruments. Assessing the latter requires – as we will argue – a careful assessment of the positive and negative synergies of instrument combinations, to which we also devote attention. We evaluate studies that arrive at a negative judgment of carbon pricing to counter the neglect of, and aversion against, carbon pricing that still exists in many social sciences, and which has spilled over to sustainability-transition studies. In addition, we will give attention to the many advantages of the instrument, including overlooked ones such as its unique transparency offering an exclusive opportunity for international or even global harmonization of national climate policies. We will not hide that, like any effective instrument of climate policy, carbon pricing faces serious challenges, but suggest ways to overcome these.

Before we enter into arguments pro and contra carbon pricing, however, it is important to note that many policy-makers have already embraced it. One can even say it is on the rise. Almost 80 jurisdictions in the world have implemented, or are planning to implement, a carbon tax or a cap-and-trade scheme (World Bank, 2020; Haites, 2018). Taken together, they cover some 20% of global greenhouse gas emissions, while about 20 schemes already price emissions above US$20/tCO2. Internal carbon pricing by private companies and institutions is growing as well (Gillingham et al., 2017; CDP, 2017). In 2018, a carbon pricing proposal was even put on the table of U.S. legislators in the form of the Energy Innovation and Carbon Dividend Act, which enjoyed some bipartisan support across the aisle (HR7173, 2018). Early January 2019, a group of 3,554 economists, including 27 Nobel laureates, 4 former chairs of the US Federal Reserve, and 15 former chairs of the US Council of Economic Advisers, expressed strong support for carbon pricing and dividends (ESOCD, 2019). Importantly, even prominent conservatives advocate for it (Baker III et al., 2017).

In a recent article with many co-authors (van den Bergh et al., 2020), we argued that international, post-Paris climate negotiations should capitalize on the recent expansion of carbon pricing to harmonize and strengthen national climate policies. Without harmonization, one cannot expect countries to implement sufficiently stringent and effective policies, as witnessed by the current situation in which actual emission reductions and pledges for the Paris Agreement are grossly insufficient (Roelfsema et al., 2020). As the Paris Agreement did not harmonize policies, but instead focused on voluntary and ad hoc national emission targets, countries in effect are faced by the challenge of unilaterally implementing climate policies. This invites for free riding, which explains the extreme variety in country pledges (i.e. Nationally Determined Contributions – NDCs). These can be broadly categorised in four types (King and van den Bergh, 2019).[1] This is likely to translate into huge differences in the stringency of policies among countries, which in turn is likely to generate considerable carbon leakage (King and van den Bergh, 2021). The Paris Agreement did not opt for any joint policy approach, which at the time was the easy way out, i.e. politically expedient, given strong resistance from several main emitters (USA, Russia, China, Austrialia) along with others (fossil-fuel suppliers like Saudi Arabia) to seriously participate in the agreement. We claim in our study (van den Bergh et al., 2020) that initiatives outside the agreement, notably through a coalition or club of likeminded countries worldwide in terms of climate policy ambition, are urgently needed to overcome this extreme weakness of the Paris Agreement. This seems to be the only option to avoid an impasse characterized by insufficient global emissions reduction from which it is near impossible to escape. To overcome this impasse, we proposed a two-track, five-phase transition approach. This involves the UNFCCC climate negotiations being supplemented by an expanding coalition or club of national and possibly sub-national jurisdictions, implementing a uniform or gradually converging carbon price. Formation of a carbon-pricing coalition would enable the coalition to speak with a single, powerful voice at UN climate conferences. In addition, the coalition would put economic and moral pressure on non-members to join the coalition and adopt a constructive attitude in UN negotiations. A stick and carrot consisting of carbon border tax adjustments on imports and access to redistribution of tax revenues would incentivize joining the coalition. Such a growing coalition of ambitious countries would serve as the next stage of the Paris Agreement, necessary to overcome its fundamental flaws.

The focus on carbon pricing in achieving global policy harmonization for the purpose of a feasible path to strengthen national policies is not only logical as carbon prices can be easily compared and harmonized among countries. They will also moderate freeriding and fear of competitiveness losses. Additional advantages are that a global price can be gradually strengthened over time, that it limits national energy and carbon rebound and international carbon leakage, that it automatically generates revenues to compensate low-income households and countries, and that it enables reaching emission reduction objectives at low if not the lowest societal costs.[2] The point that other instruments lack such advantages is insufficiently recognized. For a more complete summary of unique advantages of carbon pricing, see Baranzini et al. (2017).

Incidentally, the effectiveness of carbon pricing is often questioned by critics (Rosenbloom et al. 2020a; Markard and Rosenbloom, 2020), but is clearly shown to be robust by rigorous empirical studies. Sen and Vollebergh (2018) estimate the long-run effect of a broad-based carbon tax on energy consumption for OECD countries. They find that one € increase in energy taxes is associated with a reduction of carbon emissions from fossil fuel consumption by 0.73 percent in the long run. A recent study by Best et al. (2020) uses data for 142 countries over a period of two decades, 43 of which had a carbon price in place at the national or sub-national level by the end of the study period. The authors find that the average annual growth rate of CO_2 emissions from fuel combustion has been around 2 percentage points lower in countries with a carbon price. In addition, they estimate that an additional € per tonne of CO_2 in carbon price is associated with a reduction in the subsequent annual emissions growth rate of approximately 0.3 percentage points. These results are for rather weak carbon prices. Imagine what can be achieved with high carbon prices as proposed by economists and expert panels (HLCCP, 2017; IMF, 2019; van den Bergh and Botzen, 2014), such as above 100€ according to these studies, one might expect emissions reduction on the order of 30-70 percent.[3] Under such a scenario, investments, technologies, firm routines, consumer habits and social influence will all be directed towards low-carbon options, making a full shift to a low-carbon economy realistic. Additional policy instruments, such as information provision, physical and social nudges and innovation support can overcome any remaining gaps.

In view of the foregoing, there can be no doubt about the effectiveness of carbon pricing. As a result, it should play a key role in a wider policy package if we want to stand a chance to solve climate change effectively and with minimal economic and social costs. Policy makers have realized this for a while – witness the many carbon prices implemented in countries and subnational states worldwide, with the EU-ETS already harmonizing carbon pricing in 30 countries (Appunn, 2021). In spite of all this, the importance of the instrument does not seem to be embraced by many transition researchers. Here we offer a self-contained discussion of relevant issues related to carbon pricing and wider policy for a low-carbon transition, motivated by a number of recent developments and discussion in both policy domains. We argue that more integration of insights about carbon pricing is needed to arrive at effective transition policy, and clarify that many critics show insufficient understanding of the intricacies of carbon pricing. In addition, we argue that the complementarity and synergy of distinct policy instruments, including carbon pricing, deserves a more rigorous and systemic analysis. We will end by providing a set of concrete suggestions for integrating carbon pricing in ongoing research within the field of sustainability-transition studies.

2. Scepticism about carbon pricing

Despite broad-spectrum support by most economists, many climate policy studies by social scientists ignore the unmatched effectiveness of reducing emissions through carbon pricing (Kallbekken et al. 2011; Sorrell, 2015; van den Bergh, 2008; IMF, 2000). This could be called 'carbon pricing denial'. Instead, they tend to suggest some form of bottom-up solution through voluntary and local action (Seddon and Ramanathan, 2013), or a rigid scheme of person carbon limits intended to promote global equity (Fawcett, 2010). As the latter would limit consumption by affluent households, regardless of income potential, it would face considerable political resistance, casting doubt on its political feasibility.

To illustrate, note that many travel organisations, flight companies and environmental NGOs recommend that air travellers offset their flight emissions voluntarily. However, evidence for countries with relatively environmentally-conscious citizens, such as in Sweden, shows that the relative amount of air traffic emissions offset remains negligible, and what is offset usually involves an unrealistically low implicit cost of carbon emissions (Gössling et al., 2009). On the other hand, air travellers are willing to pay more if they know that others pay as well, namely through a tax imposed on flight emissions (Brouwer et al., 2008). This illustrates a general problem: voluntary action happens as long as it is not too expensive, but even then remains rare. It suggests we should not put our hopes on voluntary action to solve climate change, but on policies that equally incentivize everyone to reduce carbon emissions. Moreover, voluntary action, or energy sufficiency, tends to result in considerable rebound which reduces its already small impact. In this context, Sorrell et al. (2020) find that sufficiency hardly affects aggregate energy use. One might think of bans and quotas on consumers (e.g. limits to flight frequency or kilometres) as a good alternative option, but these are overly costly in terms of foregone welfare, while there is no reason for optimism about their politically feasibility. An intermediate incentive solution, like carbon pricing, restricts firms and travellers while leaving them freedom on how exactly to reduce their emissions. This contributes to minimizing welfare costs, which together with leaving basic freedoms intact, contributes to political feasibility in a democracy – indeed, people will not easily vote for bans that interfere with their personal consumption.

If we consider other instruments, such as information provision or nudges, one can see broad support and little opposition, arguably because people consider their personal and administrative costs to be limited, as they leave people complete freedom regarding consumption and pollution, and as they affect everyone equally (Drews and van den Bergh, 2016). However, this is matched by a low effectiveness in terms of emissions reduction, namely on the order of 5-10% of prevailing emissions, according to various meta-analyses and reviews (Delmas et al. 2013; Andor and Fels, 2018; Wynes et al., 2018). Fortunately, such instruments can serve a complementary role by creating positive synergy with pricing or standards. One cannot count on this, though, as empirical and experimental studies offer mixed evidence on synergy – which can be as well absent or negative, for example, in case nudges backfire (Drews et al., 2020).

Although it is not uncommon to hear condescending remarks about carbon pricing in meetings and personal communications, few have written them down in an argumentative way. An exception is Ball (2018a) who seems to think that carbon pricing is about regulating industries. But this represents a clear misinterpretation of the literature on, and proposals about, carbon pricing. It is about a systemic change, a fundamental correction of all prices in the economy, by charging all fossil fuels for carbon content. This will seep through all prices of intermediate goods, capital goods, and final goods and services, affecting choices by all types of agents in the economy – consumers, producers, investors and innovators. In another article, the author criticizes implemented carbon prices for being low and not covering all emissions (Ball, 2018b). We agree, but this is no reason to set aside carbon pricing as an instrument. That many implementations have not followed the textbook advice is a reason to improve, not to give up. Moreover, the author should then be equally critical of other instruments which are also imperfect, weak and ad hoc in terms of implementation, explaining why climate policies worldwide have not achieved serious emissions reduction. The absence of significant climate-change mitigation efforts is more a reflection of a strong political resistance against stringent climate policy actions in general, instead of being a problem specific to carbon pricing. One needs also to take into account that lobbying is easier for ad hoc climate policies, focused on one sector, such as through negotiated technology-specific standards for which many exceptions and alternative technological specifications are possible, than for economy-wide policies such as a single carbon price. The only way so far we have been successful in integrating and harmonizing national policies has been through carbon pricing, notably carbon markets – with the EU as a prime example.

A widespread idea among social scientists is that ecolabels, supported by lifecycle analysis, will allow consumers to voluntarily reduce their carbon footprint (Baldo et al., 2009). However, limited human capacities of information processing and altruism means this approach cannot be counted on to achieve considerable emissions reduction (Waechter et al., 2015). In achieving local, bottom-up climate solutions, cities are also frequently mentioned (Watts, 2017). Not denying their potential contribution, one must realize that cities only exert direct control over a small portion of total emissions generated by industry, electricity production and consumption, and transport, while their control over emissions caused by agricultural production and land use change (deforestation) is largely absent (Satterthwaite, 2008). Moreover, the implementation of uncoordinated policies at the city level may generate carbon leakage. Complementing city strategies with carbon pricing will reduce their detrimental systemic effects, which will improve their effectiveness (van den Bergh, 2020). These lessons about the effectiveness of carbon pricing are also relevant for a vibrant branch of social science research which examined local, often urban scale, experimental initiatives for sustainability transitions (Bernstein and Hoffmann, 2018; Fuenfschilling et al., 2018; Grandin et al., 2018). However, these initiatives have been criticized for often being temporary (Grandin and Sareen, 2020), non-binding (Biermann et al., 2017), and challenging to diffuse and up-scale (Naber et al., 2017). Carbon pricing could overcome these shortcomings by acting as a long-term incentive for sustaining, diffusing and upscaling of niche experiments that have proven locally successful in reducing carbon emissions.

Subsidies for research and deployment of new technologies, such as electric vehicles[4], are often assumed to contribute to reducing emissions. However, without carbon pricing we cannot ensure that the full life cycle of new innovations will actually use less carbon (Popp, 2006). For instance, the production cycles of batteries for electric vehicles or solar PV panels might be unnecessarily intensive in carbon dioxide emissions, often relying on cheap coal power for manufacture, delaying a low-carbon transition. More generally, production of cleaner technologies generates emissions in an economy that is still running mainly on fossil fuel energy. To limit the carbon-intensity of such production, subsidies fall short – we need to penalise the dirty next to rewarding the clean if we aim for a quick low-carbon transition. One can see this by considering the following Kaya identity (Kaya and Yokoburi, 1997): *CO_2 emissions = carbon intensity of energy (CO_2/energy)* x *energy intensity of economy (energy/GDP)* x *income level (GDP/population)* x *population.* Subsidizing renewables will only affect the first factor, i.e. the *carbon intensity of energy*, while a carbon price will simultaneously influence the first and second factors, i.e. also the *energy intensity of economy*. Subsidizing R&D of clean technologies can still be desirable for various reasons: capturing positive externalities of knowledge spill-overs, keeping trajectories of promising but still expensive options open, and accelerating learning curves. But subsidies should be complemented with carbon pricing as otherwise emissions reduction will go far too slow.

In a very contentious article, Spash (2010) offers a very radical and ideological critique. He argues that claims by economists about the cost-effectiveness of carbon emission trading are not substantiated based on arguments that focus on uncertain marginal emission abatement costs, lobbying affecting the design of emission markets, and markets crowding out voluntary actions. Uncertain abatement costs are generally seen as a reason for favouring carbon taxes as a carbon pricing instrument over emission trading (as the latter can lead to high costs for firms), but not as a reason for preferring regulatory instruments over carbon pricing (Weitzman, 1974). Moreover, arguments by Spash that oppose emission trading because of lobbying are not convincing. We agree that lobbying can result in suboptimal emission control, but lobbying is likely to be worse with alternative climate policy instruments that are more sector-tailored as well as more costly for firms than carbon pricing. No convincing empirical evidence is given by Spash showing that carbon markets have a net effect of crowding out voluntary carbon reductions. A meaningful crowding out effect would contradict the aforementioned empirical evidence of emission reductions achieved because of carbon prices. Moreover, this argument does not recognize the limited potential of voluntary action in reducing emissions in the first place. Spash argues that direct regulations of emissions are much easier to implement. This reasoning neglects that almost all consumption and production decisions in reality involve carbon emissions, and regulating all involved technologies would be a huge, if not impossible task. Spash concludes that emission markets distract from the need to change human behaviour, institutions and infrastructure, but he does not detail the policies that should be put in place to trigger such a change. Carbon pricing which alters all relative prices of goods and services in the economy based on their carbon content is the only instrument that is able to have a widespread simultaneous influence on decisions by consumers, producers and investors in an economic system. Such widespread control is a good basis for setting in motion the required changes to move towards a low-carbon economy.

3. Responding to criticism of carbon pricing from a sustainability-transitions perspective

Recently, Rosenbloom et al. (2020a), wrote a critical article on carbon pricing[5] in relation to transition policy in which they downplay the role of carbon pricing in mitigating climate change and transitioning to a low-carbon economy. Despite the sympathetic title of their contribution, the authors say nothing positive about carbon pricing, instead emphasizing five supposed shortcomings. As this is the first and only published criticism, it is worthwhile to devote some attention to it here. This elaborates several points only touched upon in a necessarily brief response by van den Bergh and Botzen (2020), defending carbon pricing as having an essential and irreplaceable role in a wider policy package aimed at fostering a low-carbon economy. Moreover, in our argument we react to Rosenbloom et al. (2020b) which to a large degree repeats Rosenbloom et (2020a), but in addition raises some new arguments as a response to van den Bergh and Botzen (2020). Our hope is to contribute to a more nuanced, theoretically informed and evidence-based perspective on carbon pricing.

3.1 Market failure versus system problem

According to Rosenbloom et al. (2020a), framing climate change as a market failure fails to seriously appreciate its scope and depth. They suggest that it is better understood as a “system problem”. Unfortunately, they never enter into any details, and hence overlook that ‘market failures’ is a broad category that includes, among others, negative externalities of carbon emissions, positive externalities of innovation and knowledge generation, the public-bad nature of climate change, and the public-good nature of international policy coordination and agreement-formation. All of these are systemic issues central to the economic theory underlying carbon pricing (Perman et al., 2011). This underpins what economists well recognize as the systemic global nature of the climate-change externality that originates from consumption, production, and investment decisions in a large diversity of markets around the world (Stern, 2007; Aldy et al., 2010; Cramton et al., 2017). Hence, its complexity is not downplayed by framing it as market failure, as Rosenbloom et al. (2020a) argue.

Carbon pricing is moreover a systemic policy that matches well a systemic problem like climate change. Indeed, carbon emissions are generated by all kinds of productive, consumptive, investment, and transport activities. Moreover, who causes carbon emissions or where this occurs does not matter for the global warming effect. This feature strongly supports charging a uniform price on emissions.

An advantage of carbon pricing is that one can implement it in relatively few sectors, namely exploration and imports of fossil fuels, which then affects all other prices of goods, services, intermediate products, materials and electricity to signal societal costs of direct and indirect emissions over their respective product lifecycles. No other instrument is capable of achieving such consistent and precise system-wide control. It would shift choices by consumers, producers, investors and innovators in all sectors to low-carbon inputs, outputs and processes. This means it reaches everyone and every decision in the economy, without discrimination.

We agree with Rosenbloom (2020a) that lock-in of high-carbon technologies and practices is a serious system challenge. There are distinct types of lock-in, such as related to demand or supply sides, and to networks or complementary technologies or infrastructures. Incidentally, network lock-in is often conceptualized as an externality. Each lock-in type requires a particular policy, as recognized in both economics and innovation studies (Seto et al., 2016). A historical absence of high carbon prices has contributed to this lock-in by unintentionally steering investments towards high-carbon production and consumption, which in contrast to arguments in Rosenbloom et al. (2020a,b) suggests that carbon pricing should be part of a policy mix to un-lock these investments.

We disagree with the argument by Rosenbloom (2020b) that infrastructure, technological capacity, and routinized consumption practices are difficult to change with carbon pricing. One should realize that a sufficiently high carbon price could in principle unlock any high-carbon technology or practice. In fact, behavioural changes triggered throughout the economy by a carbon price can amplify through social interactions such as conformism, imitation and status-seeking (Konc et al., 2020), creating increasing returns that counteract the increasing returns underlying the existing lock-in of high-carbon options. By combining carbon pricing and un-locking policies, such as innovation support and information provision, one can escape lock-in using lower carbon prices. However, it is improbable that these alternative policies alone, i.e. without price signals, can achieve the large-scale reallocation of investments needed to escape lock-in of high-carbon infrastructure and technologies and achieve the "socio-technical" transition Rosenbloom (2020b) aim for.

3.2 Efficiency versus effectiveness

Rosenbloom et al. (2020a) suggest that carbon pricing means that efficiency is an overriding priority of climate policy. It is good to realize that a policy can only be cost-effective or efficient if it is effective in the first place, meaning that efficiency and effectiveness are not necessarily a trade-off as Rosenbloom et al. (2020a) argue. An ineffective policy will always be overly expensive, as it does not achieve much for a given effort. Probably, economic writings have not stressed this sufficiently and we should better clarify that carbon pricing is also among, if not *the* most effective instrument – on its own and especially if well combined with other instruments.

The effectiveness of carbon pricing is due to the fact that no decision in the economy escapes it influence, as already clarified in Section 3.1. It will steer both purchase and use decisions, and affect strategies by investors and innovators. It will work like an instrument that fills all the holes where carbon emissions could escape. A very important reason why carbon pricing is so effective, in comparison with other instruments, is that it can control energy and carbon rebound (Baranzini et al., 2017). This involves direct rebound due to more intense use of energy-efficient technologies, by pricing energy proportionally to carbon content. Regarding the challenge of avoiding indirect rebound, carbon pricing has the unique advantage of discouraging money savings due to energy conservation being spent on high-carbon goods and services. The reason is that it makes these goods and services relatively expensive compared with low-carbon alternatives. Regulatory measures, like emission standards proposed by Rosenbloom et al. (2020a) do not limit rebound effects, unless all production technologies and consumption goods that contribute to carbon emissions are regulated. This would require a huge set of standards – which likely will be inconsistent in terms of implicit carbon prices, hence resulting in much higher costs for society for the same emissions reduction. This said, it seems Rosenbloom et al. (2020a) do not value efficiency much. Inefficient policies contribute, however, to less emissions reduction than is feasible with carbon pricing. To limit rebound these regulations would also require continuous updating over time to account for any changes in technologies and consumer preferences, which is practically impossible.

This said, it is our impression that efficiency and cost-effectiveness are regarded as fairly unimportant criteria by Rosenbloom et al. (2020a). This is unfortunate, as it ignores that efficiency translates to higher employment and household income (Rengs et al., 2020), more emissions reduction for the same money, a higher government budget for distributional compensation, and – as a result – also more public support, while inefficient policies imply the opposite, in turn hampering stable political support. Efficiency is important in all times, but especially in the coming decade when rapid cuts in carbon emissions are needed and at the same time government policies will be focused on limiting impacts from the economic recession that is predicted to follow the COVID-19 pandemic (IMF, 2020).

3.3 Optimizing versus transforming

Rosenbloom et al. (2020a) suggest that carbon pricing cannot transform systems. Their statement is void of any proof. This is not surprising: if all purchase and use decisions by consumers and firms, investors and innovators in all production sectors are affected by a serious carbon price, transformation is likely to come about. Additional instruments – notably to support innovation and escape of lock-in, will help. In this respect we do not disagree with Rosenbloom et al. (2020b) that technology-specific deployment policies and green industrial policies have contributed to low-carbon solutions such as photovoltaics, wind energy, and electric vehicles. However, the historical absence of high carbon prices has implied that these innovations in low-carbon solutions, and their uptake, have been too slow for solving the climate problem. The systemic nature of carbon pricing provides more certainty that demand, supply, adoption and innovation decisions are altered in concert, which seems to offer a pretty good starting point for a major transition.

Rosenbloom et al. (2020a,b) further overlook the critical role of carbon pricing in realizing low-carbon innovations. In fact, carbon pricing contributes to steering low-carbon innovations of all kinds. Such innovation patterns will not unfold as quickly as is possible and neither in the right direction unless one implements uniform and serious carbon pricing. The reason is that many private innovators and investors are driven by expectations about prices as these co-determine future profit opportunities. In view of this, carbon pricing would help steer the direction of innovations towards energy-efficient and low-carbon production lifecycles (Aghion et al., 2016; Calel and Dechezleprêtre, 2016). Also the older evidence on energy prices clearly affecting the direction and speed of energy innovations is highly relevant given the close association between energy use and carbon emissions as well as energy and carbon prices (e.g., Popp, 2002). For a recent evaluation of the broader literature on this topic of low-carbon innovation see van den Bergh and Savin (2021).

The opinion that a carbon price only affects incremental innovations is debatable. Model studies indicate that a sufficiently high carbon price is able to enforce large changes in the economy (Jorgenson et al., 2009; Rengs et al., 2020). Carbon prices have the effect that low-cost solutions for reducing carbon are taken first as Rosenbloom et al. (2020a) rightly argue, and many would see as an attractive feature instead of a disadvantage. However, the authors fail to recognize that more expensive transformations become attractive when sufficiently high carbon prices are implemented. Anyway, most radical changes, if analyzed well, turn out to be composed of many incremental changes that happened in a relatively short period of time, or take the form of combining pre-selected technological modules. Nothing prohibits carbon pricing from triggering either type of innovation (van den Bergh, 2013a).

In addition, both economics and innovation studies recognize that it is important to support promising but still expensive technologies. This may be done through R&D subsidies to account for knowledge spill-over effects, which avoids foreclosing technological trajectories too early by a high carbon price (Jaffe et al., 2005).

Unlike other instruments, carbon pricing would be able to highlight carbon differences between the more and less 'clean' technologies: e.g., solar PV panels produced with different processes or electricity using distinct energy sources. It is difficult to know which products or technologies are more low-carbon over their lifecycle as production processes are complex and roundabout, involving many intermediate deliveries between firms and sectors. Through a cumulative carbon price signal, the high-carbon options would be effectively discouraged, which would be very challenging, if not impossible, to accomplish with regulatory instruments only (Liu and van den Bergh, 2020).

Finally, Rosenbloom et al. (2020a) suggest that we need policies that discourage carbon-intensive technologies and policies that encourage low-carbon innovations, suggesting that the latter are innovation policies and the first so-called "decline policies" (note that here the authors surprisingly suggest an entirely new and unclear term, the difference of which with traditional "regulatory policy" remains unclear), without assigning a concrete and specific role to carbon pricing. Moreover, this focus on technologies overlooks the link with demand. More importantly, the authors overlook that carbon pricing has both effects: it reduces use of high-carbon technologies and goods/services, and it promotes the use of low-carbon ones. Again, we agree support of low-carbon technologies is warranted under certain conditions, mainly through investment in public R&D, subsidizing cleverly relevant private R&D (when it clearly falls short), and (with moderation) subsidizing adoption of low-carbon technologies by firms and consumers. However, pricing the high-carbon options is generally better as it equally closes the gap between prices of low-carbon and high-carbon alternatives, but in a correct way, namely by punishing the polluter and not rewarding the adopter. Subsidies easily lead to expansion of energy use rather than substitution of high- by low-carbon options as they lower the cost of energy production and use.

3.4 Universal versus context sensitive policy

Rosenbloom et al. (2020a) prefer a context-sensitive over a universal approach. Two comments are relevant here. First, while not denying that attention for specific sector context can be relevant, such as agriculture policies that stimulate sustainable food production, sector-specific policies or strategies run the risk of being inconsistent and overly costly. This will translate in leakage among sectors, and in high costs and possibly unemployment, respectively. The costly nature of this approach is due to sector-specific policies not guaranteeing that the cheapest emission-reduction options in the economy are selected. Instead, arbitrary goals (considered fair somehow) are set for sectors, which will result in distinct marginal and average costs of emissions reduction between them.

Second, approaches tend to be ad hoc, costly and susceptible to lobbying, while causing inter-sectoral carbon leakage. Moreover, climate policy is bound to remain weak whenever implemented in a unilateral manner, that is, without coordination between jurisdictions, from cities through provinces to countries. The Paris Agreement was focused on voluntary pledges rather than coordinated policies. We need policy harmonization to overcome freeriding and concerns about competition and exports by national governments. Carbon pricing is our single hope to achieve policy harmonization. Its universal approach of putting a monetary price on CO_2 makes it relatively easy to harmonize, as shown by the various carbon markets around the world that cover multiple countries or provinces/states (World Bank Group, 2020). Also, carbon taxation has been convincingly argued to satisfy these advantages (Weitzman, 2014). Other instruments are less easily harmonized: for instance, technical standards for millions of products and technologies are difficult to coordinate, while countries with high stakes in certain industries will resist associated standards (e.g., countries with an important car industry will fight ambitious fuel-efficiency standards). Harmonization will not only allow for a gradual increase in the stringency of national policies, but also discourage carbon leakage. This means that emissions move from countries with strong to ones with weak climate policies, due to shifts in international trade and relocation of emitting firms. It is surprising that Rosenbloom et al. (2020a) highlight that carbon leakage is a problematic aspect of non-uniform carbon pricing, but fail to recognize that this policy coordination problem is likely to be worse with alternative regulatory policies. This also applies to other related arguments, like the absence of high levels of regulatory competences and monitoring systems in some countries, which would hamper implementing any type of climate policy. More generally, despite Rosenbloom et al. (2020a)'s first criticism (Section 3.1 above), the previous discussion suggests that the field of sustainability transitions lacks a genuine systemic approach that accounts for shifts and leakages between sectors, regions and countries.

It is good to add that especially fossil-fuel supplying countries will not come on board easily, and so far, have resisted a good climate deal. Hence, the way forward is not a full participatory agreement immediately, as Rosenbloom (2020b) interpreted our argument in van den Bergh and Botzen (2020) by saying our assumptions require all countries implement a unified carbon pricing framework. Instead, we propose a climate coalition or club of ambitious countries with a uniform carbon price and border carbon tariffs, which can put economic and moral pressure on non-members to join, leading to club expansion over time (Nordhaus, 2015; Victor, 2015). This is elaborated, extended and generalized for a carbon tax and carbon market (cap-and-trade or emissions trading) in van den Bergh et al. (2020).

3.5 Political realities

Regarding political realities, Rosenbloom et al. (2020a) suggest that carbon pricing faces a lot of resistance. Several other authors express the same view (Cullenward and Victor, 2020). Three considerations nuance this. First, all serious climate policies meet strong political resistance. In line with this, voters and politicians are attracted to less effective strategies and policies, such as information provision to trigger voluntary action or subsidies for solar PV and electric vehicles. Second, Rosenbloom et al. (2020a,b) do not provide any evidence that policy instruments other than carbon pricing, with similar effectiveness, can count on more political support. This is not surprising since even if other policy instruments would be as effective, they will be more limiting, costly and economically harmful, which is unlikely to appeal to lobbyists and voters (Baranzini et al., 2017). Third, carbon pricing is in fact already quite popular among policy instruments. Almost 60 jurisdictions have implemented some form of it (Haites, 2018). The 27 countries of the European Union (along with additional countries) even have a joint carbon emissions trading system (ETS)[6] which had a price between 50 and 60 €/ton CO_2 for most of 2021 and reach a value above 80 in 2022. Of course, the prices of current carbon taxes and ETS are still low due to climate policy lacking ambitions and being still unilateral in nature. An exception is the EU-ETS due to harmonizing carbon prices among 30 countries. That is exactly why we need more integration and harmonization worldwide. A carbon price has a clear advantage over other instruments in this respect (van den Bergh et al., 2020).

3.6 Other issues

It is not true, as Rosenbloom et al. (2020a) suggest, that carbon pricing is only supported by neoclassical economics and rational-agent assumptions. Many different types of empirical studies provide evidence for its capacity and effectiveness to enforce major changes that translate in significant emissions reduction (see references in Narassimhan et al., 2017). In addition, various agent-based models that allow for heterogeneous boundedly-rational and socially-sensitive behavior have studied carbon pricing, notably carbon markets, and provide further support for its effectiveness (Castro et al, 2020). However, regarding the effectiveness of transition policies, the jury is still out, as evidence here is thin, conceptual and anecdotal. This suggests a need for modesty in policy advice as well as application of research methods that provide stronger evidence.

So far, most applications of renewable energy do not replace fossil fuels but just add to growing energy demand. As long as we subsidize renewables but fail to implement a serious carbon price, this demand will continue to grow, and fossil/renewable substitution will remain disappointing. So, we need not just a carrot for low-carbon options, but also a stick for high-carbon ones.

Finally, many of the examples by Rosenbloom et al. (2020a) refer to changes in production or household sectors (e.g., "restoring peatlands", "mobility-as-a-service", "biobased materials") without clarifying how these are triggered by concrete policies. The same critique applies to the "green industrial policy" Rosenbloom et al. (2020b) call for. Such an approach falls short of arguing that carbon pricing is insufficient. Instead of talking about policy consequences, as Rosenbloom et al. (2020a) do, they would do better to directly compare the alternative policy instruments or mixes and their performance.

4. Positive synergy of carbon pricing and other instruments in the policy mix

Rosenbloom et al. (2020a) never clarify if and how carbon pricing can complement other instruments in a broader transition policy. Neither we nor most economists claim that carbon pricing should be the only instrument of climate policy or low-carbon transition policy. However, there is a tendency in transition studies to prefer many policy instruments, not always with a very solid analysis of synergies underpinning it (Kivimaa and Kern, 2016; Rogge and Reichardt, 2016; Howlett et al., 2017; Rogge et al., 2017). These studies often, ironically, ignore or give little weight to pricing. The same preference for many policy instruments can be seen in policy practice. To illustrate, the German government recently agreed on a climate policy package covering dozens of sectoral measures (Edenhofer et al., 2019).

Reasons for and against using multiple instruments are multifold. Important arguments in favour are (Lehmann, 2012; van den Bergh, 2013b): accomplishing multiple criteria, such as effectiveness, efficiency and equity; complementariness or even positive synergy in terms of the set goal (e.g., emissions reduction); or addressing distinct market failures such as negative environmental and positive innovation externalities (Jaffe et al., 2005). In more abstract terms, a policy mix often reflects a second-best (non-optimal) response to a first-best (theoretically optimal) single instrument not being feasible – due to political constraints or imperfect monitoring and hence compliance with policy (Bennear and Stavins, 2007). A policy mix can also result from political compromises between stakeholders with distinct policy preferences, or from a political strategy to camouflage insufficiency of core policy. Indeed, complex transition policy mixes run a serious risk that they focus on soft policies and lack destabilising policies. This is, in fact, a finding of various policy assessments, including for Finland and the UK (Kivimaa and Kern, 2016).

Arguments to limit the number of instruments in a policy mix include (van den Bergh et al., 2021): instruments overlap or create negative synergies; the risk of introducing potentially multiple distortions into the economy; each policy instrument generates a cost for the government in terms of human resources, transaction costs of political and policy processes until implementation, costs of monitoring and control, and sometimes serious budgetary sacrifices such as with subsidies. In the context of a global challenge, like climate policy, an additional concern is that policy stringency is comparable among regions and countries, which is not trivial (Schmidt and Sewerin, 2019) and which, in turn, may limit international policy harmonization (Howlett et al., 2017).

A variety of disciplines offer insights on reasons for, and composition of, policy mixes: economics, psychology, policy sciences, innovation studies and more recently transition studies (Jaffe et al., 2005; Bulkeley and Kern, 2006; Howlett and Rayner, 2007; Rogge and Reichardt, 2016; Rogge et al., 2017; Mundaca et al., 2019). However, they do not agree and tend to emphasize distinct criteria and motivations.

According to a recent survey of policy mixes by van den Bergh et al. (2021), the clearest evidence for positive synergy is based on theoretical-modelling and experimental studies. The reason is that these, unlike empirical studies, allow clearly separating between effects caused by each particular instrument. The literature suggests that combining a carbon tax with other regulatory instruments, such as sector-level targets or technical standards, has an advantage over doing this with carbon markets. The latter weaken a good functioning (i.e. a high price) and thus the effectiveness of such markets and may give rise to carbon leakage between sectors (Fankhauser et al., 2010). To understand this, note that (through other regulatory instruments) particular sectors reduce more than they would do with a carbon market only, and thus demand fewer permits, causing the permit price to drop, in turn allowing other sectors to pollute more. Likewise, combining carbon markets with stringent renewable-energy targets or quota can generate carbon leakage. Adoption subsidies are generally better combined with a carbon tax than market as they negatively affect the carbon price, hence reduce the effectiveness of the market. With carbon taxes this problem does not appear as the carbon price is exogenous. Two other important instrument types, namely innovation support and information provision, tend to be complementary to other instruments. Apart from what was said about information provision in Section 2, certain types of information provision can create positive synergy by reinforcing the effectiveness of regulation by prices through social network functioning, raising the social multiplier of carbon pricing (Konc et al., 2020). Innovation support, such as with R&D subsidies, can counter the short-term selection pressure against promising but still immature and thus expensive technologies created by regulatory instruments like standards, targets or carbon pricing, while also serving to enhance or speed up escape from lock-in of high-carbon technologies or practices. Other subtle issues of innovation support are well recognized in transition studies (Rosenbloom et al., 2020a).

A climate policy package that combines a carbon tax, adoption subsidies, innovation support and information provision scores well on the criteria of effectiveness, efficiency and potential for international harmonization, and also on equity if revenues are recycled inversely proportional with income. Another relevant policy mix is a carbon market with innovation support and information provision. This is possibly a better approach in the long run as international harmonization is easier given that this mix is simpler in structure: namely, it omits adoption subsidies since these interfere with the intended functioning of the carbon market. The great advantage is, then, that it in turn allows policy to be strengthened more easily over time.

Regarding the specific role of other instruments in this policy mix, information provision can garner understanding of, and support for, carbon pricing. Behavioural nudges can address informational failures and bounded rationality, for example, by presenting a low-carbon product as the default option for consumers (Ebeling and Lotz, 2015). So far, the discussion implicitly focuses on energy-related CO_2 or other greenhouse gas (CO_2-equivalent) emissions. In addition, non-price regulatory instruments are needed to control certain non-energy greenhouse gas emissions as from land conversion, deforestation and landfills. Innovation policies are required as well, to ensure further development of promising low-carbon technologies which are still too expensive to compete in markets. The main justification of public sector support is well-known, namely that R&D has positive externalities and knowledge spill-overs. But it cannot address negative environmental externalities – for this externality (i.e. carbon) pricing is the most effective climate policy. As a corollary, subsidies for technological innovation and adoption cannot stand alone.

Whereas carbon pricing was in the past often criticized for being inequitable, there is now wide agreement that it should be complemented by equitable revenue recycling, for both ethical reasons and political feasibility (Klenert et al., 2018). In fact, no other instrument allows for such automatic revenue compensation: technical standards, performance targets and quota impose costs on economic agents and have distributional effects but do not generate revenues, while subsidies use up revenues. Moreover, adoption subsidies for renewable energy and electric vehicle are rather inequitable as they tend to fall on relatively well-off households. The revenue-generating capacity of carbon pricing is increasingly relevant now that many governments around the world see their already high debt burdens rise rapidly. Moreover, pressures on employment and incomes strengthen the need to compensate households and companies for costs from additional climate policy measures. The equity issue has seen more conceptual and empirical elaboration for carbon pricing than for other instruments (Klenert et al., 2018; Maestre-Andrés et al., 2019). This is somewhat surprising given the expressed concern for equity by many social and policy scientists who seem more charmed about other instruments than carbon pricing.

Ironically, many writings on transition policy are not consistent with the basic idea of a gradual, multi-phase transition covering the stages of pre-development, take-off, acceleration and stabilization (Rotmans et al., 2001). The ambitious, complex policy mixes suggested are approached more from a static design perspective than from a dynamic and multi-phase transition angle. Instead, the literature on carbon pricing spends a great deal of attention on dynamics, adaptation and strengthening of prices of time (or tightening caps in emission trading systems), and even improving feasibility through a transition path. Regarding the latter, van den Bergh et al. (2020) propose a dual-track, five-phase transition approach to progressively harmonize and strengthen national climate-mitigation policies.

5. Conclusions and research suggestions

Sustainability-transition studies tend to ignore carbon pricing altogether (Savin and van den Bergh, 2021). As we hope to have shown, this is unwarranted. Carbon pricing has unmatched advantages, including consistent regulation of direct and indirect emissions (covering also adoption and use behaviour), limiting rebound and life-cycle effects, selecting for low-cost abatement options, generating revenues for compensating energy-poverty and other inequity effects, contributing to transparency and comparability between policies in distinct jurisdictions, and facilitating international harmonization as witnessed by the EU-ETS (i.e. it harmonizes carbon prices in 30 countries). This clearly indicates that carbon pricing has a unique and powerful capacity to effectively reduce emissions with minimal economic harm – in terms of costs, macroeconomic effects like employment, and income or purchase equity. The implication is that the function of carbon pricing cannot be taken over by any other instrument – something that is insufficiently valued in transitions research. Soft instruments like information provision or networking, aimed at encouraging voluntary action, or fostering community initiatives, will only create significant effects where alternative sustainable options for behaviour and technology are not burdensome or expensive, but will fall short in achieving deep decarbonization. In addition, large-scale bans and quotas on energy use not only will severely harm production and welfare but are politically infeasible in a democracy. Carbon pricing represents an intermediate solution that restricts firms and consumers in a gentle but effective way through clear price incentives, leaving them sufficient freedom to decide on how to reduce their emissions. In addition, carbon pricing of fossil fuels will seep through the economy to affect all prices of intermediate and final goods and services, and hence all decisions by consumers, producers, investors and service providers – and hence nothing will escape its influence which also means that social and economic harm will be maximally spread rather than concentrate in a few sectors or social groups.

Summarizing our assessment of the studies that are negative about carbon pricing (where we have not tried to be exhaustive since many studies/authors repeat the same arguments), a first observation is that most of these are qualitative in nature, instead of based on methods like modelling and statistical data analysis which arguably provide more definite and thorough insights. In addition, critics tend to offer unbalanced accounts where positive aspects of carbon pricing are ignored or downplayed, and shortcomings are exaggerated. They also often overlook that certain shortcomings – notably political resistance, inequity effects, or barriers to strengthening policy over time – apply equally or more strongly to other instruments. Reading into these studies we get a strong feeling that authors arrive at their conclusions based on an incomplete assessment of instruments and criteria, rather than by comparing systematically pros and cons of all instruments. Worse even, we find that some critics of carbon pricing show a superficial or erroneous knowledge of it. This all evidently contributes to unfounded and unfair resistance against carbon pricing, in turn hampering rather than promoting high-quality debate about how to solve climate change. We hope with this chapter to have clarified many issues surrounding carbon pricing and its connection with sustainability transitions and transition policy, as well as to have provided an entry into the broader and rich theoretical and empirical literature on carbon pricing.

All these considerations do not deny that we need a climate-policy package. Van den Bergh et al. (2021) examine how this can be best achieved, by employing positive and avoiding negative synergies between instruments. Innovation support on its own will not change consumer and firm behaviour quickly and sufficiently; technical standards or adoption subsidies for energy efficiency alone may, due to a focus on purchase decisions, lead to much energy and carbon rebound, which can only be limited by carbon pricing as it controls the use phase; and information provision alone will according to meta-analyses and surveys reduce energy use and emissions at most with 5-10% (Delmas et al. 2013; Andor and Fels, 2018; Wynes et al., 2018). Therefore, carbon pricing should be a key element of energy-transition policy. The reason is that the fundamental transformation needed is unlikely to be achieved through niche experimentation in the absence of carbon pricing. So-called "new business models for new technologies", which Rosenbloom et al. (2020a) mention, without detailing how they should be achieved, are unlikely to scale up towards a large scale transition to a low carbon economy without serious financial incentives that make these business models and low-carbon technologies economically attractive for investors and clients.

The above remarks do not deny the creative ideas one can find about policy in the literature on transitions thinking. It is surprising, though, that it has not undertaken a serious effort to integrate important and broadly supported insights from more established policy sciences such as environmental economics. This presents a challenge for future research. Based on the previous information, one can identify various research suggestions for transitions studies:

- We should give attention to a transition of policies themselves, i.e. how to achieve a more stringent and effective policy mix over time. Some ideas are provided in van den Bergh et al. (2020), about how to do this for carbon pricing in a multistage and dual-track stetting, with interactions between an expanding climate club and international (UNFCCC) climate negotiations. This could receive attention from different perspectives, using particular transition theories, such as innovations systems, multi-level perspective, strategic niche management, complex systems and evolutionary systems (Nill and Kemp, 2009; Rotmans and Loorbach, 2009; Jacobsson and Bergek, 2011; Geels, 2011; Safarzynska et al., 2012).
- Regarding the mix of policies, a widely accepted division into four main modes of urban climate governance is (Bulkeley and Kern, 2006): (a) self-governance of urban public sector activities; (b) provision of public services, such as public transport; (c) enabling emissions reduction by firms and households, such as through information or adoption subsidies; and (d) regulation of firms and households, such as through zoning, standards or carbon pricing. Transition policy could be clarified along these lines, and one could test if there is sufficient balance between the four modes at different points over the transition path. This should take into account the lessons from the literature as sketched in Section 4.

- A systemic approach to assess effectiveness of transition policy is missing yet. It was recently proposed to decompose effectiveness of emissions reduction into reach, ability and stringency (van den Bergh, 2020). Assessment of the effectiveness of transition policy could build on this decomposition approach, and possibly extend it with dynamic elements to capture the role of essential environmental technological innovations and slow societal transition processes.
- One could connect specific instruments in the transition policy mix to the different levels of action, systemic processes and governance, such as specified in the multi-level perspective (MLP) framework (niche, regime and landscape), economics (micro, meso and macro), or other fields (local, regional and global). Here the role of carbon pricing should be clarified – e.g., would it be relevant to multiple levels or not?
- A challenge of local niche experimentation with mitigation projects is that scalability is limited but essential to effectively reduce greenhouse gas emissions sufficiently across the economy and space. Future studies should give serious attention to whether and how carbon pricing can provide adequate financial incentives for the upscaling of niche projects.
- Finally, more attention is needed for the feasibility and international harmonization of effective transition policy, to assure that it is comparable between regions and countries so that it can be consistent in terms of regulatory strength. If this is not achieved, it is very likely that transition policies will remain too weak to solve climate change.

References

Aghion, P., Dechezleprêtre, A., Hémous, D., Martin, R., Van Reenen, J. (2016). Carbon taxes, path dependency, and directed technical change: evidence from the auto industry. *Journal of Political Economy* 124 (1): 1-51.

Aldy J., A. Krupnick, R. Newell, I. Parry, W. Pizer (2010). Designing climate mitigation policy. *Journal of Economic Literature* 48(4): 903-934.

Andor, M.A., Fels, K.M. (2018). Behavioral economics and energy conservation – A systematic review of non-price interventions and their causal effects. *Ecological Economics* 148, 178-210.

Appunn, K. (2021). Understanding the European Union's Emissions Trading System (EU ETS). Clean Energy Wire, 20 Jul 2021. https://www.cleanenergywire.org/factsheets/understanding-european-unions-emissions-trading-system

Baker III, J.A., M. Feldstein, T. Halstead, N.G. Mankiw, H.M. Paulson Jr, G.P. Schulz, T. Stephenson and R. Walton, 2017. The Conservative Case for Carbon Dividends. The Climate Leadership Council, February 2017, www.clcouncil.org.

Baldo, G.L., M. Marino, M. Montani, S.-O. Ryding (2009). The carbon footprint measurement toolkit for the EU Ecolabel. *The International Journal of Life Cycle Assessment* 14(7), 591-596.

Ball, J. (2018a). Hot air won't fly: The new climate consensus that carbon pricing isn't cutting it. *Joule* 2: 2491–2494.

Ball, J. (2018b). Why carbon pricing isn't working: Good idea in theory, failing in practice. *Foreign Affairs*, July/August 2018.

Baranzini, A, J. van den Bergh, S. Carattini, R. Howard, E. Padilla and J. Roca (2017). Carbon pricing in climate policy: Seven reasons, complementary instruments, and political-economy considerations. *WIREs Climate Change* 8(4), e462.

Baumol W.J., and W.E. Oates (1975). *The Theory of Environmental Policy*. (second edition 1988). Cambridge University Press, Cambridge UK.

Baumol, W.J. (1972). On taxation and the control of externalities, *American Economic Review* 62(3): 307-322.

Bennear, L.S., and Stavins, R.N. (2007). Second-best theory and the use of multiple policy instruments. *Environmental and Resource Economics* 37(1): 111-129.

Bernstein, S., Hoffmann, M., 2018. The politics of decarbonization and the catalytic impact of subnational climate experiments. *Policy Sciences* 51: 189–211.

Best, R., P.J. Burke and F. Jotzo (2020). Carbon pricing efficacy: Cross-country evidence. *Environmental and Resource Economics* 77: 69-94.

Biermann, F., Kanie, N., Kim, R.E., 2017. Global governance by goal-setting: the novel approach of the UN sustainable development goals. *Current Opinion in Environmental Sustainability*, 26–27: 26–31.
Brouwer, R., Brander, L. & Van Beukering, P. (2008). A convenient truth": air travel passengers' willingness to pay to offset their CO_2 emissions. *Climatic Change* 90, 299–313.
Bulkeley, H., and K. Kern (2006). Local government and the governing of climate change in Germany and the UK. *Urban Studies* 43(12): 2237-2259
Calel, R. and A. Dechezleprêtre (2016). Environmental policy and directed technological change: Evidence from the European carbon market. *Review of Economics and Statistics* 98: 173-191.
Castro, J., S. Drews, F. Exadaktylos, J. Foramitti, F. Klein, T. Konc, I. Savin, J. van den Bergh (2020). A review of agent-based modelling of climate-energy policy. *WIREs Climate Change*, e647.
CDP, 2017. Putting a price on carbon: Integrating climate risk into business planning. Carbon Disclosure Project, London.
Cramton, P., D.J.C. MacKay, A. Ockenfels and S. Stoft, 2017. *Global Carbon Pricing: The Path to Climate Cooperation*. The MIT Press, Cambridge, Mass.
Cullenward, D., and D.G. Victor (2020). *Making Climate Policy Work.* Polity Press, Cambridge, UK.
Dales, J. (1968). *Pollution, Property and Prices*. University Press, Toronto.
Delmas, M., Fischlein, M., Asensio, O. (2013). Information strategies and energy conservation behavior: A meta-analysis of experimental studies from 1975-2011. *Energy Policy* 61(C): 729-739.
Drews, S., and J. van den Bergh (2016). What explains public support for climate policies? A review of empirical studies. *Climate Policy* 16(7): 855-876.
Drews, S., F. Exadaktylos and J. van den Bergh (2020). Assessing synergy of incentives and nudges in the energy policy mix. *Energy Policy* 144, 111605.
Ebeling, F., and Lotz, S. (2015). Domestic uptake of green energy promoted by opt-out tariffs. Nature *Climate Change* 5(9): 868-871.
Edenhofer, O., C. Flachsland, M. Kalkuhl, B. Knopf and M. Pahle (2019). Assessment of the German climate package and next steps: Carbon pricing, social balance, Europe, monitoring. Mercator Research Institute on Global Commons and Climate Change, Berlin.
ESOCD, 2019. Economists' statement on carbon dividends: The largest public statement of economists in history. The Wall Street Journal, Thursday 17 January 2019, https://www.clcouncil.org/economists-statement.
Fankhauser, S., Hepburn, C. and Park, J. (2010). Combining multiple climate policy instruments: How not to do it. *Climate Change Economics*, 1(3), pp. 209-225.
Fawcett, T. (2010). Personal carbon trading: A policy ahead of its time? *Energy Policy* 38(11): 6868-6876.
Fuenfschilling, L., Frantzeskaki, N., Coenen, L., 2018. Urban experimentation & sustainability transitions. *European Planning Studies*, 27: 219–228.
Geels, F.W., 2011. The multi-level perspective on sustainability transitions: responses to seven criticisms. *Environmental Innovation and Societal Transitions* 1, 24–40.
Gillingham, K., Carattini, S. & Esty, D. Lessons from first campus carbon-pricing scheme. *Nature* 551, 27–29 (2017).
Gössling, S., L. Haglund, H. Kallgren, M. Revahl and J. Hultman (2009). Swedish air travellers and voluntary carbon offsets: towards the co-creation of environmental value? *Current Issues in Tourism* 12(1): 1-19.
Grandin, J., Haarstad, H., Kjærås, K., Bouzarovski, S., 2018. The politics of rapid urban transformation. *Current Opinion in Environmental Sustainability*, 31: 16–22.
Grandin, J., Sareen, S. (2020). What sticks? Ephemerality, permanence and local transition pathways. *Environmental Innovation and Societal Transitions*, 36: 72-82.Haites, E., 2018. Carbon taxes and greenhouse gas emissions trading systems: what have we learned? *Climate Policy* 18(8): 955-966.
Hahn, R.W., and G.L. Hester (1989). Marketable Permits: Lessons for Theory and Practice. *Ecology Law Quarterly* 16(2): 361-406.
Haites, E. (2018). Carbon taxes and greenhouse gas emissions trading systems: what have we learned? *Climate Policy* 18(8): 955-966.
Howlett, M., and Rayner, J. (2007). Design principles for policy mixes: Cohesion and coherence in new governance arrangements. *Policy and Society* 26(4): 1-18.

Howlett, M., J. Vince and P. del Rio (2017). Policy integration and multi-level governance: dealing with the vertical dimension of policy mix designs, *Politics and Governance* 5(2): 69-78.
HR7173 (2018). Energy Innovation and Carbon Dividend Act of 2018. 115th Congress (2017-2018) of the USA. https://www.congress.gov/bill/115th-congress/house-bill/7173
HLCCP, 2017. Report of the High-Level Commission on Carbon Prices. World Bank, Washington D.C.
IMF (2000). The impact of higher oil prices on the global economy. IMF Research Department, December 8, 2000. http://www.imf.org/external/pubs/ft/oil/2000/
IMF (2019). Fiscal Policies for Paris Climate Strategies—from Principle to Practice. Fiscal Affairs Department, International Monetary Fund, Washington D.C.
IMF (2020). World Economic Outlook, April 2020, https://www.imf.org/en/Publications/WEO/Issues/2020/04/14/weo-april-2020
Jacobsson, S.B., Bergek, A., 2011. Innovation system analyses and sustainability transitions: contributions and suggestions for research. *Environmental Innovation and Societal Transitions* 1, 41–57.
Jaffe AB, Newell RG, Stavins RN (2005). A tale of two market failures: Technology and environmental policy. *Ecological Economics* 54:164–174.
Jorgenson, D., R. Goettle, M. Sing Hoc, P. Wilcoxen (2009). Cap and trade climate policy and U.S. economic adjustments. *Journal of Policy Modeling* 31: 362-381.
Kallbekken S., S. Kroll and T.L. Cherry (2011). Do you not like Pigou, or do you not understand him? Tax aversion and revenue recycling in the lab. *Journal of Environmental Economics and Management* 62(1): 53-64.
Kaya, Y. and K. Yokoburi (1997). *Environment, Energy and Economy: Strategies for Sustainability*. United Nations University Press, Tokyo.
King, L., and J. van den Bergh (2019). Normalisation of Paris Agreement NDCs to enhance transparency and ambition. *Environmental Research Letters* 14 (2019) 084008.
King, L., and J. van den Bergh (2021). Potential carbon leakage under the Paris Agreement. *Climatic Change* 165, 52.
Kivimaa, P., and F. Kern (2016). Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. *Research Policy* 45(1): 205-217.
Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R., Stern, N., 2018. Making carbon pricing work for citizens. *Nature Climate Change* 8: 669–677.
Konc, T., I. Savin and J. van den Bergh (2020). The social multiplier of environmental policy: Application to carbon taxation. EVOCLIM working paper, ICTA-UAB, revised submission.
Lehmann, P. (2012). Justifying a policy mix for pollution control: A review of economic literature. *Journal of Economic Surveys* 26(1): 71–97.
Liu, F., and J. van den Bergh (2020). Differences in CO2 emissions of solar PV production among technologies and regions: Application to China, EU and USA. *Energy Policy* 138, 111234.
Maestre-Andrés, S., S. Drews and J. van den Bergh (2019). Perceived fairness and public acceptability of carbon pricing: A review of the literature. *Climate Policy* 19(9): 1186-1204.
Markard, J., Rosenbloom, D. (2020). Political conflict and climate policy: the European emissions trading system as a Trojan Horse for the low-carbon transition? *Climate Policy* 20(9): 1092-1111.
Mendelsohn, R. (1986). Regulating heterogeneous emissions. *Journal of Environmental Economics and Management* 13: 301-312.
Mundaca, L., Sonnenschein, J., Steg, L., Höhne, N., Ürge-Vorsatz, D. (2019). The global expansion of climate mitigation policy interventions, the Talanoa Dialogue and the role of behavioural insights. *Environmental Research Communications* 1, 061001.
Naber, R., Raven, R., Kouw, M., Dassen, T. (2017). Scaling up sustainable energy innovations. *Energy Policy*, 110: 342-354.
Narassimhan, E., K.S. Gallagher, S. Koester and J. Rivera Alejo (2017). Carbon Pricing in Practice: A Review of the Evidence. Center for International Environment & Resource Policy, The Fletcher School, Tufts University, Medford, Mass.
Newell, R.N., and R.N. Stavins (2003). Cost heterogeneity and the potential savings from market-based policies. *Journal of Regulatory Economics* 23(1): 43-59.
Nill, J., and R. Kemp (2009). Evolutionary approaches for sustainable innovation policies: from niche to paradigm? *Research Policy* 38(4): 668-680.

Nordhaus, William (2015). Climate clubs: Overcoming free-riding in international climate policy. *American Economic Review* 105 (4): 1339–70.
Perman, R., Y. Ma, M. Common, D. Maddison, J. McGilvray (2011). *Natural Resource and Environmental Economics*. 3rd ed. Pearson Education Limited, Harlow.
Pigou, A.C. (1920). *The Economics of Welfare*. MacMillan, London.
Popp, D. (2002). Induced Innovation and Energy Prices. *The American Economic Review* 92(1): 160-180.
Popp D. (2006). R&D subsidies and climate policy: Is there a "free lunch"? *Climate Change* 77: 311-341.
Rengs, B., M. Scholz-Wäckerle and J. van den Bergh (2020). Evolutionary macroeconomic assessment of employment and innovation impacts of climate policy packages. *Journal of Economic Behavior and Organization* 169: 332-368.
Roelfsema, M., van Soest, H.L., Harmsen, M. et al. (2020). Taking stock of national climate policies to evaluate implementation of the Paris Agreement. *Nature Communications* 11, article 2096.
Rogge, K.S. and K. Reichardt (2016). Policy mixes for sustainability transitions: An extended concept and framework for analysis. *Research Policy* 45(8): 1620-1635.
Rogge, K.S., Kern, F., Howlett, M. (2017). Conceptual and empirical advances in analysing policy mixes for energy transitions. *Energy Research & Social Science* 33: 1-10.
Rosenbloom, D., J. Markard, F.W. Geels, and L. Fuenfschilling (2020a). Opinion: Why carbon pricing is not sufficient to mitigate climate change—and how "sustainability transition policy" can help. *Proceedings of the National Academy of Sciences of the U.S.A. (PNAS)* 117(16): 8664-8668.
Rosenbloom, D., J. Markard, F.W. Geels, and L. Fuenfschilling (2020b). Reply to van den Bergh and Botzen: A clash of paradigms over the role of carbon pricing. *Proceedings of the National Academy of Sciences of the U.S.A. (PNAS)*, 117(38): 23221–23222.
Rotmans, J., R. Kemp and M. van Asselt (2001). More evolution than revolution: Transition management in public policy. *Foresight* 3(1): 15-31.
Rotmans, J., Loorbach, D., 2009. Complexity and transition management. *Journal of Industrial Ecology* 13 (2), 184–196.
Russell, C.S. (1979). What can we get from effluent charges? *Policy Analysis* 5(2): 155-180.
Safarzynska, K, K. Frenken and J.C.J.M. van den Bergh (2012). Evolutionary theorizing and modelling of sustainability transitions. *Research Policy* 41: 1011-1024.
Satterthwaite, D. (2008). Cities' contribution to global warming: Notes on the allocation of greenhouse gas emissions. *Environment & Urbanization* 20(2): 539-549.
Savin, I., and J. van den Bergh (2021). Main topics in EIST during its first decade: A computational-linguistic analysis. *Environmental Innovation and Societal Transitions* 41: 10-17.
Schmidt, T.S. and S. Sewerin (2019). Measuring the temporal dynamics of policy mixes – An empirical analysis of renewable energy policy mixes' balance and design features in nine countries. *Research Policy* 48(10): 103557.
Seddon, J., and V. Ramanathan (2013). Bottom-up solutions to mitigating climate change. *Stanford Social Innovation Review* 11(3): 48-53.
Sen, S., and H. Vollebergh (2018). The effectiveness of taxing the carbon content of energy consumption. *Journal of Environmental Economics and Management* 92: 74-99.
Seto, K.C., S.J. Davis, R.B. Mitchell, E.C. Stokes, G. Unruh, and D. Ürge-Vorsatz (2016). Carbon lock-in: Types, causes, and policy implications. *Annual Review of Environment and Resources* 41: 425-452.
Sorrell, S. (2015). Reducing energy demand: A review of issues, challenges and approaches. *Renewable and Sustainable Energy Reviews* 47, 74-82.
Sorrell, S., B. Gatersleben and A. Druckman (2020). The limits of energy sufficiency: A review of the evidence for rebound effects and negative spillovers from behavioural change. *Energy Research & Social Science* 64, 101439.
Spash, C.L. (2010) The Brave New World of Carbon Trading. *New Political Economy* 15(2): 169-195
Stern, N. (2007). *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge, UK.
Tietenberg, T.H. (1985). *Emissions Trading: An Exercise in Reforming Pollution Policy*. Resources for the Future, Washington D.C.

van den Bergh, J. (2008). Environmental regulation of households? An empirical review of economic and psychological factors. *Ecological Economics* 66: 559-574.
van den Bergh, J.C.J.M. (2013a). Environmental and climate innovation: Limitations, policies and prices. *Technological Forecasting and Social Change* 80(1):11-23.
van den Bergh, J.C.J.M. (2013b). Policies to enhance economic feasibility of a sustainable energy transition. *Proceedings of the National Academy of Sciences of the U.S.A. (PNAS)* 110(7): 2436-2437.
van den Bergh, J.C.J.M. (2020). Systemic assessment of urban climate policies worldwide: Decomposing effectiveness into 3 factors. *Environmental Science and Policy* 114: 35-42.
van den Bergh, J.C.J.M., and W. Botzen (2014). A lower bound to the social cost of CO_2 emissions. *Nature Climate Change* 4(April): 253-258.
van den Bergh, J., and W. Botzen (2020). Low-carbon transition is improbable without carbon pricing. *Proceedings of the National Academy of Sciences of the U.S.A. (PNAS)*, forthcoming.
van den Bergh. J.C.J.M., A. Angelsen, A. Baranzini, W.J.W. Botzen, S. Carattini, S. Drews, T. Dunlop, E. Galbraith, E. Gsottbauer, R.B. Howarth, E. Padilla, J. Roca, R.C. Schmidt (2020). A dual-track transition to global carbon pricing. *Climate Policy* 20(9): 1057-1069.
van den Bergh, J., and I. Savin (2021). Impact of carbon pricing on low- carbon innovation and deep decarbonisation: Controversies and path forward. *Environmental and Resource Economics* 80: 705-715.
van den Bergh, J., Castro, J., S. Drews, F. Exadaktylos, J. Foramitti, F. Klein, T. Konc and I. Savin (2021). Designing an effective climate-policy mix: Accounting for instrument synergy. *Climate Policy* 21(6): 745-764.
Victor, D. (2015). The Case for Climate Clubs. E15 Expert Group on Measures to Address Climate Change and the Trade System, January 2015, International Centre for Trade and Sustainable Development (ICTSD) and the World Economic Forum, Geneva, Switzerland.
Waechter, S., Sütterlin, B., and Siegrist, M. (2015). The misleading effect of energy efficiency information on perceived energy friendliness of electric goods. *Journal of Cleaner Production* 93: 193-202.
Watts, M. (2017). Cities spearhead climate action. *Nature Climate Change* 7, 537-538.
Weitzman, M.L. (1974). Prices vs. quantities. *Review of Economic Studies* 41(4), 477-491.
Weitzman M.L. (2014). Can negotiating a uniform carbon price help to internalize the global warming externality? *Journal of the Association of Environmental and Resource Economists* 1:29-49.
World Bank (2020). State and Trends of Carbon Pricing 2020. Washington, DC: World Bank.. https://openknowledge.worldbank.org/handle/10986/33809
Wynes, S., Nicholas, K.A., Zhao, J., Donner, S.D. (2018). Measuring what works: quantifying greenhouse gas emission reductions of behavioural interventions to reduce driving, meat consumption, and household energy use. *Environmental Research Letters* 13, 113002.

[1] These four categories of pledges/NDCs (Nationally Determined Contributions) are: absolute emission reduction targets vs. (distinct) base years; reduction relative to future emissions growth under BAU scenario; reduction of emission intensity of national income (GDP); and projects without identifying associated emissions reduction. For more details see King and van den Bergh (2019).

[2] Newell and Stavins (2003) provide a good entrance to the theoretical and empirical literature supporting cost-effectiveness of pricing instruments in environmental policy. Classic contributions are Pigou (1920), Dales (1968), Baumol (1972) and Baumol and Oates (1975). Other influential contributions are Russell (1979), Tietenberg (1985), Mendelsohn (1986) and Hahn and Hester (1989).

[3] For instance, the World Bank (2020) expects that carbon prices should be at least US$40–80/tCO2 by 2020 and US$50–100/tCO2 by 2030 to reduce emissions in line with the objectives of the Paris Agreement.

[4] E.g. https://www.bmwi.de/Redaktion/EN/Artikel/Industry/electric-mobility-r-d-funding.html.

[5] According to one of the co-authors the article was inspired by the interview of Jochen Markard with Jeroen van den Bergh about "Carbon pricing" in the STRN newsletter nr. 31, March 2019, pp. 8-11 (https://transitionsnetwork.org/wp-content/uploads/2016/09/31st-STRN-Newsletter.pdf). Interestingly, Markard concluded from the interview that: "It has become clear that there are many subtle aspects to carbon pricing. Transitions research could pay more attention to, and learn from, the debate on carbon pricing. Given 'our' experience with the innovation dimension of policies, the relevance of industry and market creation, as well as politics and the formation of coalitions, there is certainly much we can contribute. Also, the interaction of e.g.

carbon pricing and innovation policies, together with ongoing changes in policies and policy mixes as transitions progress, deserve our attention." Unfortunately, a similar message cannot be found in Rosenbloom et al. (2020a).

[6] Although Rosenbloom (2020b) argue that carbon pricing is difficult to implement for heavy industry, the EU-ETS covers energy-intensive industrial sectors.