Evaluating policy packages for a low-carbon transitions – Principles and applications

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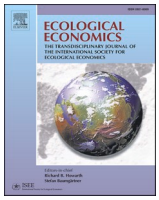

Evaluating policy packages for a low-carbon transition – Principles and applications

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ABSTRACT

The low carbon transition has become a major challenge for countries in order to limit global temperature increase to acceptable levels. Steering this transition is a very challenging task and the topic of this Special Issue. Transitions require change at system level which asks for a search of appropriate change agents and a proper design of incentives. Economic analysis could be particularly helpful here by focusing on i) descriptive instead of normative analysis of the complexities of the system, and ii) evaluation of policy packages instead of single policy instruments due to the multiple market failure context. In addition I introduce the different contributions in this Special Issue showing how they add to a better understanding of the steering question and how this should help policy makers to improve policies along the transition path.

1. Introduction

Global warming has become the key challenge of humankind. Even though it is far from being the only environmental challenge, global warming is held responsible for both gradual and more dramatic changes in weather patterns and natural disasters (IPCC, 2023). These changes also seem to come faster, both in pace and intensity, then previously expected, According to the Paris agreement in 2015 the global community has recognized this threat and agreed upon the need to mitigate emissions of greenhouse gases (GHGs) to limit the temperature increase to a level well below 2 °C and even pursue efforts to limit it to 1.5 °C above pre-industrial levels. Fighting climate change is one of the focal points of policy discussions on cooperation among countries nowadays.

Aiming for this rather strict temperature target requires dramatic cuts in GHG emissions such as those implied by a 'net zero' or 'low carbon' strategy.[1] Such changes are very challenging because this requires fundamental changes in how humankind has exploited energy resources and land since the Industrial Revolution. Fossil fuel use has been a key input for this revolution and the growth of GDP in many regions across the globe, but also causes the principal GHG responsible for global warming, CO_2-emissions. Similarly, land use changes and improvements have been the key driver for the global food revolution, but also contributes to the very strong GHG methane.

The changes at system level required by predefined (long term) policy goals are often called 'transitions' nowadays. Transitions are indeed associated with such a complete reset of our production and consumption system. Drastic cuts in GHG emissions require fundamental changes in the most important emission sectors such as electricity production, industry, transport, built environment and agriculture, while they are also interlinked. Moreover, no clear picture of the ultimate outcome yet exists because many different possibilities of future development paths are thinkable. For instance, a low carbon energy future might be based on large amounts of renewables with or without a role for nuclear and biomass to generate electricity. Similar uncertainties exist with respect to the role of carbon capture, energy storage through batteries, the role of hydrogen, land us change, etc., etc.

Even though agreement exists on the ultimate goal as implied by the Paris agreement, the question *how* to induce this fundamental change is a much more tacit one. The main focus of the contributions to this *SI* is related to this steering question. The steering question reflects the need to implement Nationally Determined Contributions (NDCs) – which reflect promises by countries to meet their low carbon objectives within the IPCCC framework – into practical behavorial changes and policies. Implementing such policy goals through NDCs typically requires leverages to induce change towards low carbon trajectories.[2] Many countries also already implement instruments or instrument packages that aim at lower carbon emissions (Nachtigall et al., 2022), although the overall effectiveness of these instruments is often challenged as the GHG emission trajectories of most sectors and countries still fall short relative to the trajectory needed to implement the Paris agreement. This *SI* contributes to this challenge in a variety of ways which will be explained in this introduction.

[1] 'Carbon' in this paper simply refers to all GHGs among which carbon dioxide emissions is only one. Concepts like 'net zero' or 'low carbon' refer to system goals where all GHGs are balanced not just 'carbon'.

[2] The OECD recently initiated a process to not only coordinate on policy goals but also on implementation packages which typically contain different instruments (see OECD, 2023).

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2. Understanding transitions

Disagreement exists as to whether economics would be helpful in answering this steering question of transitions. Some even argue that economics has little to offer in understanding system change and by implication also transitions. For instance, the literature on innovation and policy studies claims that transitions are very special while economics would be focused on a simplistic linear representation of system change (e.g. Rotmans and Loorbach, 2009; Schot and Geels, 2008; Hekkert et al., 2020). According to this view social and economic systems would be complex and develop over time in a hardly predictable way. Accordingly transitions would also not follow a linear, but a non-linear and unpredictable path instead. And steering transitions could therefore not boil down to a simple adage of repairing market failures as economists suggest. Instead a transition would require the promotion of innovation in so-called "niches and arenas" with an emphasis on front-runners, stimulating variation and selection through incremental steps and learning processes in a multi-actor and multi-level environment.

It is beyond the scope of this introduction to evaluate the validity of this criticism. The contributions in this *SI* all focus on the transition path towards an ultimate aim of a low carbon outcome in the future. In this respect no real difference exist with the alternative view. Such a starting point simply defines the low carbon transition as a social goal. The system broad implications just follow from this ambition. Whether or not higher temperature levels then 1.5 °C could be considered 'optimal' or not, is beyond the scope of this *SI* (Stern et al., 2022).[3] In the economist' language: such an approach just takes a specific goal for society as given.[4]

Most economists would also agree that social and economic systems are complex and can be characterized by hard-to-predict developments over time. At the same time, they also provide ideas that keep transitions 'traceable' while at the same time answering the steering question along this path. In particular the endogenous growth literature provides such helpful ideas (e.g. Bovenberg and Smulders, 1995; Acemoglu et al., 2012).[5,6] Technological change also plays a key role in this literature and it is understood as a dynamic process at the same time as well. It is no coincidence that the endogenous growth literature in economics has been inspired by similar sources such as Schumpeter's well-known analysis of the dynamics of capitalism and Nelson and Winters' ideas on evolutionary theory and economic change (Aghion and Howitt, 1998).[7]

Answers, or perhaps the better term is guidance, typically follows from the 'traditional' market failure approach. The dynamic process that characterizes the economy could also run into a suboptimal system if market externalities exist. These market externalities become system failures if the scale of the externalities cuts deep enough in the economic system. And this is precisely the case of climate change as explained before. Therefore the existing 'allocation' of resources is misdirected towards overexploitation of the climate and innovation should be directed to internalize the global warming 'externality'.

Building such notions into ideas about transitional change helps to better understand what is required to steer the low carbon transitions. Moreover, this literature also explicitly allows for externalities within the innovation and adoption process itself assuming patents may not be sufficient to internalize 'spillovers' and other information failures. By keeping an eye on traceable individual decisions, in particular on the invention and adoption decisions related to (radical) new technologies, also an explicit link is drawn with agents and incentives that could be changed if one aims for system change.

3. Steering transitions

Still a large gap exists between this rather abstract scientific literature and the challenges that policy makers usually face when considering how to direct the social and economic system towards a low carbon path. As noted before, all key emission sectors, such as electricity production, industry, transport, built environment and agriculture should re-invent themselves. Finding appropriate 'kicks' for system change is essential here (Farmer et al., 2019; Hepburn et al., 2020). To further discuss identification issues of proper leverages of change to steer transitions, in particular in relation to the market economy we live in, I explicitly separate this 'how question' into two different subquestions:

i) which (change) *agents* should be targeted to direct change?
ii) which *incentives* should be changed and how?

Subsequently I discuss both questions in more detail.

3.1. Finding change agents

The first question asks for identification of the *agents of change* in relation to the relevant processes that could induce the required transition. Society consists of many agents varying from firms, consumers and citizens, to governments, and other private and public institutions. All of these agents coordinate their activities using different methods of exchange such as markets, voting mechanisms, legislation or lobbying and negotiations.

Clearly change agents are required for a transition. The policy and innovation literature focuses on the role of 'niche' markets and its stimulation here (e.g. Schot and Geels, 2008; Rotmans and Loorbach, 2009). In the 'mission oriented' approach the government should help to guide this search process (see Mazzucato, 2021, but also Hekkert et al., 2020). Finally, Farmer et al. (2019) suggest that such a search process should not exclude any agent upfront and even look broader to find so called Sensitive Intervention Points or SIP's. Such points could be any actor that might be able to contribute to the transition. So identification of those who might lead the process of change is important in all these approaches.

Interestingly, these views are not so different from the economists perspective that market failures provide guidance here. The search process for proper change agents using a market failure approach to the low carbon transition would be directed by the idea that some markets produce 'dirty' goods while others produce or could start producing 'clean' goods instead (Acemoglu et al., 2012). Existing 'markets', i.e. firms, their buyers and the regulatory environment within which they operate, are hold responsible for the production and consumption of 'dirty goods'. So the behaviour of all of these agents is misdirected by the characteristics of the system *in the status quo* including (lack of or existing) regulation and the (existing) distribution of property rights. Finding change agents here also amounts to finding SIPs that are responsible for this behaviour, in particular those agents who are responsible for the largest impacts on the externality.

[3] Although in particular economists still discuss the level of emission reduction required and some believe higher temperature levels then 1.5 °C might even be 'optimal', others defend the approach followed by policy makers which is based on insights from climate science (see Stern et al., 2022).

[4] Tinbergen (1952) already explored welfare evaluations of economic systems with given multiple social goals long ago.

[5] These models reduce complexity by using microfoundations and closure rules. The closure rules guarantee proper inclusion of accounting rules that represent the economic system while microfoundations introduce decision-making processes of agents that optimize within cost constraints, such as the amount of effort necessary to produce new ideas or prototypes.

[6] It is remarkable that the literature on innovation and policy studies does not at all refer to this important contributions by economists. At the same time economists also do not refer to the other literature as well. See also the paper by Vollebergh et al. (2023) in this *SI*.

[7] See Kemfert and Vollebergh (2005) for a discussion of state of the art contributions on the analysis of complexity and technological change in relation to sustainability issues in another *SI* of this journal.

Perhaps the main difference here is that economists tend to look first at agents responsible for the existing market failure, i.e. those responsible for producing the dirty goods. Moreover, these agents are not just particular firms or households, but also others responsible in the production and consumption chain such as banks, upstream producers delivering basic materials or other inputs to downstream firms. From this perspective it makes sense to not only target the agents that potentially could produce clean substitutes such as those agents in the niche markets, but also those responsible for the existing outcome of the system. Also the government is an obvious change agent here as this institution is responsible for *existing* laws and incentives that determine this 'suboptimal' market behaviour.

This search processes for change agents should also be linked explicitly to differences between markets. For instance energy markets are usually characterized by networks, digitalization and physical infrastructure, while markets for food are more traditional and flexible in terms of what and how production is organized. In addition, some agents are indeed more willing to change their behaviour than others and could probably best be targeted first. But also the bulk of the followers matter and should be targeted by other policies. In fact, the followers often face social dilemmas and solving such dilemma's ask for other strategies to produce the public good (see also Vringer et al., 2017).

3.2. Incentivizing transitions

The second question asks which *incentives* should be changed and how. Incentives relate directly to stimuli that guide behaviour and decisions taken in the status quo. Current outcomes with their above target level of emissions are called – in the economist language – 'suboptimal' and a signal of a 'market failure'. Understanding current outcomes of system developments and why they 'fail', perhaps even despite specific interventions, helps to identify which policies or, more precisely, instruments might provide potential incentives to steer the system towards a more sustainable 'equilibrium'.

Indeed, when incentives change, behaviour is likely to change too. The low carbon transition requires agents to switch away from the currently profitable business models causing the global warming 'market failure'. And also consumers of these dirty goods have to switch away from their pollution-intensive consumption towards cleaner alternatives.[8] To induce this change incentives should be in line with the aim of the transition and facilitate change agents to deliver clean behaviour.

This is precisely where the idea of 'kicks' to SIPs is relevant. Once knowing where these 'points' are located, 'kicks' to the current state of socioeconomic, technological and political systems should be given, as well as 'shifts' to the underlying system dynamics (see also Hepburn et al., 2020). Proper kicks should shift systems away from their existing paths towards new and cleaner horizons. They can be provided by governments and their policies, though certainly not exclusively. Other change agents play a role here as well such as banks, firms, NGOs and citizens as well as procedures or standardization processes (Vollebergh and van der Werf, 2014). Even market forces themselves provide such kicks as is illustrated by the hick up of natural gas and other fossil fuel prices in 2022 and the strong impact this has had on the transition process.

A key set of kicks relevant for the low carbon transition are certainly the regulatory interventions by the government using 'policy instruments' in particular. Policy instruments are tools through which governments implement policies such as taxes, (tradeable) permits, standards, covenants and information provision. Such instruments create important incentives to agents as shown by economists both in theory and empirically (Duflo, 2017).[9] Indeed, introducing or changing existing policy instruments provides leverages for agents to change their behaviour. Selection of proper instruments for the low carbon transition by the government is far from obvious, however. Instruments typically differ from each other and even the same instrument can be designed in many different ways.

Finding appropriate incentives for system change could benefit from a careful analysis of behaviour in the status quo responsible for current emissions. Economics has a lot to offer here too by directing policy makers to better understand the causes of the misallocation. Finding out where this misallocation comes from precisely helps governments to implement more effective and even more efficient policies. Understanding lock-ins to particular polluting production and consumption processes helps to better translate the required direction into supporting policies and translate them into the design of specific instruments, or the government 'kicks' that are needed for the required transition.

Directed change such as implied by the low carbon transition requires a coherent, consistent and persistent approach based on well-designed policies and instruments in particular. Due to the complexity of the low carbon transition usually instrument *packages* are required, however. Even an instrument that addresses a single market externality, such as un(*der*)priced carbon emissions, may require multiple government interventions in practice, such as a tax or excise on mineral oil plus an excise on natural gas plus a carbon emission permit system for large emitters, etc. Moreover, policy interventions cannot be limited to the market failure related to the underpricing of carbon emissions as several other market failures are likely to hinder a swift transition as well, such as innovation externalities, lock-in problems, network externalities and lack of competition.[10] Finally, distributional issues matter for transitions as adaptation cost are unlikely to be distributed in a fair or just way.

Traditional criteria for evaluating policy instruments on the transition path, such as effectiveness, efficiency and fairness of interventions remain very important in the case of instrument packages. *Effectiveness* relates to the question whether particular incentives produce their desired effects. *Efficiency* requires no more than that spending resources on the process of change ('transition') would be best with least 'waste' of scarce means. And finally, *fairness* accounts for the idea that the unavoidable distributional consequences of change are distributed in a 'fair way'. Using these criteria explicitly in assessments of transitional instrument packages helps to better understand the loopholes of change along the transition path and how policy makers could deal with them to improve acceptability. So incentivizing the low carbon transition asks for policy packages that typically account for different types of market failures and their distributional consequences *at the same time*.

This *SI* is divided in three parts. The first part contains two papers that discuss instrument design in relation to practical policy making in more detail. These papers illustrate that design of proper instruments is a challenging task and indeed requires careful examination as to why the existing system is producing dirty outcomes from the perspective of the transition and how existing instruments could be reformed to better address this shortcoming. The second part contains three papers that assess instrument packages using the three key criteria discussed in the previous paragraph. They clearly illustrate why these criteria still matter for instrument package design. Finally, the third part is more reflective on the fundamental idea of transitional change itself and evaluates this whole idea in a wider framework where also individual and social

[8] Such alternatives might not always be available. In that case consumers can only respond by buying less of the dirty goods.

[9] Whereas a huge literature exist on instrument selection in economics, its importance has attracted more attention in the innovation and policy literature only recently (see also the contribution by Vollebergh et al. (2023) in this *SI*).

[10] Broad agreement exist among policy makers that such policies should go beyond carbon price alone. The current European Green Deal and its instrument pais just one example of how comprehensive such transitions are (see https://climate.ec.europa.eu/eu-action/european-green-deal/delivering-european-green-deal_en).

preferences matter as well as the distributional aspects of change.

4. Instrument package design meets the real world

Finding proper change agents and (re)designing incentives is a tacit task. As noted before the most important change agent is probably the government. Governments affect behaviour through their 'policies', in particular through their menu of tax and other regulatory instruments as well as through their spending decisions including tax expenditures, subsidies or other governmental programs. Indeed, government instruments change the constraints that other agents, like firms, households and institutions, face, and may work through a variety of mechanisms including changes in beliefs, information, prices and formal and informal rules.

The setting for practical policy making, however, is far from the textbook world that economists usually consult for their normative advice. Here a market economy is assumed to work again properly once the externality is 'restored'. Transitions, however, face a multitude of adaptations when the system as a whole is locked-in a development path that produces an externality that has consequences at the system level. This is why the two papers in this SI that focus explicitly on instrument design focus on packages indeed. Not only do they recognize complications of implementing policies to address the emission externality in practice, they also account for other distortions at the same time, in particular externalities related to innovations and networks.

First of all, the paper by Vollebergh et al. (2023) starts from the same premises discussed in this introduction and asks how to help policy makers with a useful strategy to answer the steering question in practice. They emphasize the importance of a proper descriptive analysis before focusing on the choice of change agents and relevant incentives. Their descriptive framework consists of two parts, namely *stock-taking* of design characteristics of existing instruments ánd a *mapping* exercise to link these characteristics to the market failures they are supposed to address.

Stock taking of existing instruments helps to better understand why particular decisions of (change) agents are taken in the status quo. The authors claim that four key attributes could characterize each instrument separately. These attributes are focus, scope, strictness and timing and are codified in (e.g. fiscal) law. Together they reflect the incentive or 'kick' provided by an existing instrument and also guarantees comparability across instruments as well as a better understanding of their joint interaction.

Furthermore, they argue that it is particularly helpful to also *map* these attributes of instruments both directly and jointly to the underlying low carbon related market failures. Instruments that already price in carbon explicitly or implicitly could be mapped to the underlying activities directly. For instance, existing (carbon) pricing instruments could be linked explicitly to fossil fuel related energy products causing these emissions. This is what the OECD does in their calculations of effective carbon pricing of different types of (implicit and explicit) carbon pricing instruments (OECD, 2021). In addition, Vollebergh et al. (2023) account for technology market failures and instruments that already address this failure in the status quo. Overall their mapping exercise allows to more explicit describe and discuss the coherence of a mix or package of policy instruments.

This stock taking and mapping analysis could be used to evaluate whether and how an existing set of policy instruments can be improved with an eye on selecting proper change agents as well as improving upon existing incentives. To illustrate this potential the paper applies the framework to the aim of deep carbonization in the residential and commercial (buildings) in an ambitious country, Austria. Sectoral GHG emissions are used as indicators for the environmental market failure and revealed technological advantage (RTA) as an indicator for current eco-innovation performance. The results of their descriptive exercise are used to suggest improvements in the existing instrument package from the carbon transition perspective.

The contribution by Anderson and his co-authors targets an important change agent, i.e. the industrial sector in the Netherlands, and how this sector is currently incentivized (Anderson et al., 2023). Also this paper focuses on an instrument package but also addresses context specific characteristics that matter for this change agent in particular before evaluating existing instruments that aim to help the carbon transition in this important emission sector. The industrial sector in the Netherlands is characterized by a deep lock-in of the energy-intensive industry in fossil energy use, in particular natural gas but also oil. Two key conditions explain this lock-in, i.e. the large natural gas fields both on- and off-shore discovered in the 1960s and its location in a delta of several rivers close to the sea. This delta connects its easily accessible harbor to Germany. For this reason the Dutch economy is also a typical small open economy with high import and export rates.

These context related key characteristics matter a lot to better understand the choice of existing instruments, partly because governments tend to favor country specific industries because of international specialization. Transition of a fossil fuel based specialized industrial sector – which is the case in the Netherlands – is a very challenging task for that reason. Moreover, it is likely to require a strong redirection of current government incentives to better align them towards the low carbon aim (see also Criscuolo et al., 2022). The paper by Anderson et al. (2023) uses models of potential pathways to net-zero emissions by 2050 in the Dutch manufacturing sector to guide their instrument evaluation. These pathways illustrate the difficulties and also the need for technologies that are not (market) mature today. Such as (green) hydrogen, a massive increase of renewable electricity generation, a role for Carbon Capture and Storage even around 2050, and the need for expanding existing and building new energy infrastructures to facilitate this transition.

Using this broad and context specific perspective the paper identifies the broad range of instruments needed to incentivize the major shift of the Dutch industrial sector properly. Apart from the two-pillar strategy related to effective carbon pricing and technology support, the paper argues that also incentives are needed to the broader environment that is conducive to the low-carbon transition. Therefore the paper also discusses complementary policies, such as regulatory instruments and the deployment of public infrastructure.

Together both papers clearly demonstrate that economic science could play a role in answering both steering questions related to the low carbon ambition. Policy evaluations benefit from a much more thorough and tacit analysis of the status quo including instrument and context specific characteristics. Careful analysis of the causes of current system failures and the ways in which governments have responded or not responded to them in the past also helps to provide better guidance in finding proper incentives to steer agents towards a low carbon goal. After all, existing behaviour is precisely the cause of the problems the transition aims to solve. And it is precisely existing practice that does not change by itself as lock-ins are not easily changed.

5. Instrument package assessments

The challenge to find appropriate change agents and how to incentivize them properly towards the low carbon transition through the deployment of instrument packages could also benefit from experiences in the past as well as from ex ante evaluation of instrument packages. The effectiveness of instruments could be measured by finding out whether particular incentives produce their desired effects. Because of the explosion of empirical research of actual behaviour the last decade context specificity has become much better recognized in the recent economic literature (Duflo, 2017). At the same time this literature raised the bar for determining causal impacts from leverages such as a specific instrument (re)designed by the government. Not all studies on ex post effectiveness pass the test of controlling appropriately for omitted variables or factors that may actually be responsible for reverse causality. So far little attention has been paid to study causal impacts of instrument

packages.

Similar observations apply to the question how to determine (cost) efficiency and distributional consequences of transitional change. What matters for cost efficiency, for instance, is to what extent the design of particular instrument packages induces change at least cost. Usually, however, also a dynamic impact is related to such leverages such as new research. Inducement of innovation matters for cost efficiency over time, i.e. the intertemporal welfare effects. Also distributional consequences are related to such impacts. Switching away from the deployment of existing 'money making' business models with highly polluting assets and technologies towards new and less polluting models always creates winners and losers. Proper insight in the distributional dimension of transitions is a prerequisite to discuss its *fairness*.

Identification of the effectiveness, efficiency and distributional impacts of instrument packages is therefore a huge challenge and deserves much more attention. In their contribution Hille and Oelker (2023) focus on an *ex post assessment* of the effectiveness of a large set of (support) instruments on renewable energy capacities across the world. They consider effectiveness of instruments in expanding the international diffusion of renewable energy and which role innovation has had in this context. This paper employs rich policy and patent data for 189 countries and territories to investigate this effectiveness question for wind and solar photovoltaic capacities.

By explicitly separating between innovation ('patents') and adoption ('increasing capacities') the paper studies how in particular renewable energy support policies both individually and in clusters affect the invention-innovation-diffusion frontiers of both wind and solar. Increasing capacities reflect a growth in the adoption of particular cleaner technologies. Scaling up such technologies reduces the lock-in of fossil fuels in the electricity market in particular. This, in turn, may have a feedback effect on innovation as well. Potential endogeneity is controlled for using lags and knowledge stocks which is standard in this literature. So change agents are identified implicitly by looking at outcomes of researchers through patents, while the role of governments is reflected in their use of different policy instruments that address the different externalities in the innovation process. Accordingly they evaluate individual policies' effectiveness in a broad instrument-country context while controlling for the inherent endogeneity of policy instruments and innovation.

The findings of the paper are interesting. They report that innovation in renewable energy appears to be largely policy-induced, but also contributes to the increase of renewable energy capacities. Assessment of differences between instruments in this context shows that the most effective policy instruments tend to be quotas with certificate trading, tendering, and fiscal instruments that provide specific investment support, i.e. investment tax credits and capital subsidies. Less tangible and projectable measures, such as the most commonly implemented sales-related tax reductions and renewable energy targets, are least effective. Differences between technologies seem to matter as well. These results illustrate that instruments are more effective if directly targeted to change agents and their day-to-day decisions. The paper also has interesting lessons in the global context as differences in the policies' effectiveness and role of innovation depends on the countries' level of development too.

Assessments of the interlinkages of effectiveness, efficiency and distributional impact typically requires other methodologies. Such socio-economic ex ante impacts can be assessed using another toolbox of economics, i.e. applied general equilibrium models. This type of modelling framework captures macro-economic and sectoral impacts through price inducements of the instrument packages by using a proper accounting framework of the economy. Such models account explicitly for price and income effects in existing markets and therefore match with observable money and income flows in the system as measured by the National Accounts. Representation of change agents and incentives, however, is usually at a somewhat high level of aggregation and not always allows for heterogeneity that characterize agents.

Two papers in this *SI* aim to improve precisely both type of limitations. The paper by Weitzel et al. (2023) explicitly assesses policy instrument packages while being aligned as closely as possible to energy system modelling. Also further decompositions of aggregate labour market outcomes is allowed for to account for heterogeneity in skill and occupation types. And, finally, the classic 'representative household' has been enriched with micro-level household data to also capture distributional effects across income groups with heterogeneous expenditure patterns. This combination of models and datasets provides much more insight into transitional change than the more traditional general equilibrium framework.

The focus of this paper is on the so called European Green Deal which aims to put the EU on track towards climate neutrality by 2050 (European Commission, 2019). One of the key elements of this policy is a more stringent carbon reduction target of 55% below 1990 levels by 2030. Alternative policy pathways consisting of different compositions of policy instruments to reach that target are studied, in particular packages that rely more on regulatory standards, on carbon pricing, or a mix of both. These different packages use different leverages and address agents in different ways, which causes differences in economic and distributional consequences including differences in abatement cost. Moreover, the international context for the EU matters a lot, in particular if other regions impose packages despite the Paris agreement later or even not at all.

Carbon pricing and regulatory measures are both important elements to incentivize agents in the system on their pathway towards lower carbon emissions ('effectiveness'). The paper considers different mixes of both regulatory and pricing elements that provided the starting point for the design of the "Fit for 55" policy package. Impacts on (consumer) prices and distribution are studied including revenue recycling as a means to mitigate some adverse effects for both policies.

Implications of the different policy packages to reach the corresponding targets can be substantial and depend on the exact design. As usual with these models GDP impacts of the different packages are fairly similar. Weitzel et al. (2023) rich framework, however, highlights the substantial heterogeneous impacts of climate policy packages across sectors, worker skill types and income groups. Their assessment shows that the outcomes strongly depend on policy design but also on modelling assumptions. Robustness checks across this variation in results is used to find which outcomes are robust, such as job losses related to coal. Other industry effects seem to depend more on policy design choices, e.g. to what extent a policy package mitigates adverse effects for sectors, for instance by lowering labour taxes (recycling of revenues), or by antileakage measures such as the provision of free allowances or carbon border adjustments.

Also the case study of France by Ravigné et al. (2022) in this *SI* enriches the standard way of looking at transitions by such applied CGE models. The focus of this paper is the dynamic impact of policy package interventions aiming for low carbon emissions of the change agent 'households'. The distributional consequences of such policies are a major issue for the public acceptability of the energy transitions or the just transition. Households are typically change agents who invest (or cannot invest themselves) in durable cleaner technologies, in particular electric vehicles and technologies related to energy-efficient housing. However, distributional consequences of efforts to change incentives towards purchasing more energy and carbon-efficient durable technologies are very likely to differ strongly among households.

By using an innovative numerical method that combines micro-simulation and macroeconomic modelling techniques they are able to also more precisely represent technology heterogeneity among households. In particular the paper offers insights in fair transition ambitions such as the one promoted by the EU Fit-for-55 proposal and which typically consists of an instrument package. This package includes carbon taxation, technology adoption subsidies and compensating lump-sum transfers. The representation of households by their technology adoption decisions instead of their income levels provides an interesting

new twist to the discussion on the distributional consequences of the low carbon transition policy. Results are provided for two successive versions of the French low-carbon strategy.

The paper also discusses how potential adverse distributional effects could be addressed by (additional) instruments. For instance, targeting of policies to the largest energy consumers not only maximizes emission reductions ('effectiveness'), but also reduces the discrepancy of impacts between rural and urban households ('fairness'). Unfortunately, this policy is likely to aggravate the regressivity of carbon taxation if no rebate is provided for households for their carbon tax payments. Recycling schemes favoring poorer households are also a powerful mean to offset the regressivity of carbon taxation in the short term. In parallel, policies supporting electric vehicles and thermal renovation are effective in reducing households' tax payments at further horizons. No simple conclusion can be drawn from this richer analyses as well. Like the paper by Weitzel et al. (2023) this paper illustrates also nicely how the choice of climate policy instrument and revenue recycling mechanisms determine equity outcomes, contributing to the broader debate on inequality-sensitive optimal policy design (Stiglitz, 2019).

6. The complex role of preferences along the transition path

The elephant in the room of the low carbon transition is typically support by citizens for the low carbon transition. Support is likely to depend on the consequences of the problem at stake, i.e. climate damage, as well as the impact of efforts – the instrument packages – to mitigate climate change and how this has an impact on our daily way of life. A key difference of climate change with several other environmental issues is its gradual change and its impact delay. The growing amount of carbon dioxide in parts per million in the atmosphere cannot be observed or smelled. Also climate related specific disasters may appear as unrelated and unpredictable. As a consequence beliefs and scientific evidence are key inputs to preference formation and what is usually called 'support' for carbon mitigation measures..[11,12] Moreover, carbon mitigation efforts have consequences in terms of their distributional burden on change and non-change agents as well, while these burdens depend on how the leverages of change are designed as has been shown in this *SI*.

The concept of 'climate justice' captures the idea that carbon mitigation policies should be fair or just. Unfortunately, there is no clear definition of what fairness means exactly and therefore also not in the context of instrument package evaluation along the transition path. If efforts impose serious consequences on private choices in terms of income and the price and type of products sold at the market, adverse effects on support are very likely. Also differences in distributional outcomes between countries and within countries as well as across firms and households may impair support for climate mitigation policies.

At least two major approaches exist as far as distributional fairness is concerned (Rawls, 1971). The first approach looks for procedural principles which can be applied to instrument packages and their design as well. For instance, citizens may support a general principle such as the 'polluter should pay'. If accepted as a key procedural principle for carbon mitigation policies, it could be applied as a key design element for such packages. As long as a particular policy package design follows this principle it would be evaluated as 'fair'. The other approach focuses on outcomes and would look at the consequences of such instrument packages. Applied to the case of pricing instruments for carbon mitigation the focus is on consequences, for instance in terms of income losses or gains. In addition the evaluation also requires operational criteria in order to determine whether a particular package can be called 'just' or 'fair'.

Fairness, or its perception, and public acceptability are also closely connected. When policies are perceived as unfair, in particular from a distributional perspective, their acceptance is likely to suffer. Indeed, citizens have preferences about what they consider a fair or just process or outcome of climate mitigation policies. These preferences in turn often depend on how the distribution of the *costs* of these policies differs among citizens within a single country.[13] Fanghella et al. (2023) in their contribution to this *SI* also focus on distributional fairness within a country by looking at burden sharing rules, but they also take *environmental benefits* associated with different policies into account. They focus in particular on how these benefits affect individual citizens' acceptability or support, and to what extent a so called self-serving bias may play a role here.

Specifically, this paper analyzes burden sharing rules in the context of energy efficiency policies by using a discrete choice experiment on nationally representative household samples of Sweden, Italy, and the United Kingdom. Policies that aim to increase energy efficiency typically rank high in terms of climate mitigation policies even though they are not primarily focused on reducing carbon emissions. These policies reduce carbon emissions as long as the energy input is fossil fuel related. Benefits are operationalized through (assumed) improvements in environmental quality and differ according to location. Respondents would be selfish if they prefer burden sharing policies that tend to benefit themselves most, either in terms of the distributional consequences of how the policy is funded, or in terms of the location where any possible side benefit may accrue to them. The paper does not look at instrument packages but at 'policies' represented at a more aggregate level, and which could be assumed to reflect the combined distributional impact of several instruments instead.

Fanghella et al. (2023) examine four burden sharing rules reflecting ideas about procedural justice. The four rules ask for a contribution of the costs to the policy: i) proportional to individual energy use ('accountability rule'); ii) increasing more than in proportion with individual income ('progressive-share rule'); iii) equal to the costs of the policy at individual level ('equal-amount rule'); and, iv) fixed as a share of individual income ('equal-share rule'). Valuation of the various attributes of these rules clearly differs between different subgroups in society (income groups, as well as location of residence - rural or urban) and is also clearly linked to self-interest. These results suggest that the accountability rule is the most popular and the equal-amount rule the least popular burden-sharing rule. Further, policies with environmental benefits accruing primarily in rural areas are least preferred. Also some correlation with self-interest is determined, though perhaps less convincing then one might have expected. The presence and intensity of self-serving bias also appears to vary across countries while this presence still holds in their experiment where they prime randomly assigned groups of participants to feel either rich or poor.

Finally Vona (2023) discusses the many channels through which distributional fairness of climate mitigation policies is affected. Assessments of the just transition in relation to the implementation of specific instruments or instrument packages usually only focus at the use and changes of consumer goods, in particular energy use and its taxation. In contrast to this simplified and 'traditional' view this paper allows for a much broader impact assessment and identifies several other channels through which climate mitigation policies affect the distribution. 'Standard' incidence analysis is particularly helpful here to identify such

[11] As a consequence climate change and its mitigation suffers from wickedness (see also Vringer et al., 2009). A social problem is more wicked (i) the less consensus there is regarding the (perceived) urgency of the problem, and – not unrelated— (ii) the larger the distance (geographically, or temporally) between beneficiaries of sustainability actions and those who bear the costs of providing them.

[12] Note that the situation for climate adaptation measures is different as impacts like floods or droughts are more visible and immediate.

[13] Traditionally climate justice relates to the fairness of distributional impacts of climate change damage and climate mitigation efforts across countries (IPCC, 2023).

channels (Fullerton and Muehlegger, 2019). Indeed, incidence analysis explicitly relates systemic changes to transitional issues such as effectiveness, efficiency and distribution. Such systemic changes. However, are not always easy to determine and usually work in the background. An example is the impact through changes in factor markets – such as the labor and capital markets – where large differences may exist in ownership of skills and assets.

In a transition some agents will loose because of the reduction in demand for dirty goods but also through reduced demand for 'dirty' labor and capital. Assets might even become 'stranded' if the change is fast enough. At the same time transitions also create 'winners', i.e. those who switch to the clean alternatives, in particular if the dirty 'lock-in' becomes more expensive and outdated. Winners are also those who benefit from the reduction in the environmental bads as a result of the transition, in particular also from the (co)benefits from policy interventions. Some of the papers in this *SI* already illustrate the relevance of such broader assessments such as the papers by Fanghella et al. (2023) and Ravigné et al. (2022). Also the Green Deal in the EU stresses the importance of fair complementary distributional policies. Finding a subtle balance between providing the right incentives for change and compensating the losers is one of the challenges of the low carbon transition.

Vona (2023) extends this discussion on distributional issues even further and highlights the importance to indeed also consider heterogeneity in *the capacity and willingness to adjust*. Using a broad conceptual framework along the dimensions of time, space, and preferences, he explicitly considers multidimensionality, adjustment dynamics and multiple market failures simultaneously in his contribution. Distributional effects of standalone climate policies are clearly regressive on income and progressive on nonpecuniary benefits, while they become even more regressive in the long-run and across regions in the absence of compensatory measures. Therefore it is always preferable to explicitly design broader 'green' policy packages that include offsetting policies (rebates, environmental tax reforms, green deal plans, place-based policies, progressive green subsidies). The Green Deal in the EU is a good example of such a broader package. However, even such broader packages would still not entirely solve all adverse impacts. Vona concludes that the path to a just transition is still narrower than previously thought. Green deal plans appear the most sensible option also in terms political acceptability, but political acceptability might still suffer because inequality in the status quo hampers support of green policy packages.

7. Conclusion

Along the transition path towards low carbon this *SI* contributes to a better understanding as to why current 'system problems' exist and how this understanding might provide guidance for transition policies to be implemented by change agents such as the government and by designing proper incentives. There is no need to hoover in the dark here with trial and error only because unpredictable forces would always make a more predictable endeavour impossible. The papers in this *SI* illustrate that descriptive, evidence based and even model based analysis of 'system changes' helps to better understand who would be key agents and which changes in incentives might be appropriate to steer the transition.

A shift towards a low carbon society is unlikely to be produced by the market alone, and even if so, might come too late. Without government intervention it is unlikely that emission reductions and eco-innovations will be supplied by the market at a level that provide change fast enough. Fortunately, changes can already be observed and illustrate that 'shifts' in the underlying system dynamics are on their way. Indeed some sectors, like the electricity sector, are changing already in a fundamental way in several countries. Other sectors such as the industry, built environment, transport and agriculture still face huge challenges. Selection of proper change agents and kicks to the current system is still very important. Level playing fields, certainly in the international arena, matter too but are often not chiseled in stone and market forces tend to stimulate low cost and price solutions. However, as long as such solutions do not reflect all relevant social cost and benefits, i.e. impacts on other than the market participants involved, they are likely to remain suboptimal and could even exacerbate the transition by externalizing important effects,

Severe system failures such as climate change require coherent policy responses and instrument design. Coherent policies ask for a deep enough understanding of existing incentives and their characteristics relevant for the transition at stake. The *SI* also shows that effectiveness, efficiency and even distributional impacts of instrument packages matter for such ambitions. Currently, evaluation of instrument packages is rather limited however. The theoretical literature on design and evaluation of specific policy instruments, such as taxes and (tradeable) permits, is voluminous, but usually focuses on the simple quantity-price dimension of a single instrument as if they are always substitutes (Vollebergh and van der Werf, 2014). Also empirical analysis is often limited to a partial case in order to identify causal interventions (which is otherwise very difficult to detect). Determining a causal impact of an instrument is certainly helpful but usually depends on the context in which it was applied and shown to be causally effective. What one learns exactly from such findings in other circumstances is still an open question. The same holds for the extent to which such a particular instrument contributes to the coherence of steering question as a whole.

The lesson of this *SI* though is that economists could certainly be of much help in steering transitions. Finding appropriate change agents and how to incentivize them towards the low carbon transition properly is a real challenge, but also a core question within this profession. Even though applications to the design of instrument packages are currently limited, economic analysis might help to better understand how the design of instruments or instrument packages matters for providing the right incentives including their distributional consequences. Indeed, several papers in this *SI* have also shown that in particular laggards – to be identified in terms of income, technology or space – are likely to be the losers of the transition without much outside options even if they benefit most of the mitigation effort in the long run. Even though these benefits are also more likely to be concentrated with them, this effect will go unnoticed or being noticed too late. Although such distributional impacts remain a concern, they are minor compared to the impacts that humankind would face if we wouldn't embark on policies that aim for a low carbon future.

Declaration of Competing Interest

None.

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