Carbon Pricing and the 1.5°C Target: Near-Term Decarbonisation and the Importance of an Instrument Mix

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Carbon pricing is routinely presented as the most efficient way to reduce greenhouse gas emissions, and therefore as an indispensable pillar of ambitious climate policy. For incremental emission reductions on the margin, this static perspective may be correct, expressing the ability of carbon pricing to identify and spur abatement options with the lowest cost. At the same time, meeting the 1.5°C target requires achievement of zero net emissions in the relatively near term, implying a need for full decarbonisation rather than marginal abatement. To date, there is only limited empirical evidence suggesting that carbon pricing has produced deep emission cuts. Emission reductions triggered by carbon taxes and emissions trading systems are typically modest or relate to a baseline rather than absolute levels, even in cases where price levels are relatively high. Consequently, we posit that deep decarbonisation in line with the 1.5°C target can only be ensured by drawing on a portfolio approach, in which carbon pricing operates alongside other instruments including regulation and legal mandates.

I. Carbon Pricing and its Hegemony in the Climate Policy Debate

Economists almost unanimously recommend that emitters of greenhouse gases (GHGs) pay a price for every ton of carbon dioxide equivalent (CO_2e) emitted, and that such a price on carbon be the 'logical foundation of any policy regime' to avert dangerous anthropogenic climate change.[1] A recent article, for instance, argues that 'among all instruments carbon pricing deserves the most serious attention from researchers, politicians, and citizens.'[2] Unsurprisingly, therefore, carbon pricing is being advanced in multiple venues as the single most important policy instrument to address climate change, dominating political debates and benefitting from substantial public resources for stakeholder outreach, public diplomacy and capacity building.

Carbon pricing has been defined as 'initiatives that put an explicit price on greenhouse gas emissions, ie, a price expressed as a value per ton of carbon dioxide equivalent (tCO_2e)',[3] and is commonly implemented through a corrective price set politically in the form of taxes, charges, and other levies,[4] or

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1 On the 'logical foundation', see World Economic Forum (WEF), *Green Investing: Towards a Clean Energy Infrastructure* (WEF 2009) 39; see also Nicholas H Stern, *The Economics of Climate Change: The Stern Review* (Cambridge University Press 2007); Thomas Sterner, 'Fuel Taxes: An Important Instrument for Climate Policy' [2007] 35 Energy Pol'y 3194; Joseph E Stiglitz and others, *Report of the High-Level Commission on Carbon Prices* (World Bank 2017).

2 Andrea Baranzini and others, 'Carbon Pricing in Climate Policy: Seven Reasons, Complementary Instruments, and Political Economy Considerations' [2017] 8 WIREs Clim Change 1, 13.

3 World Bank, *Carbon Pricing Watch 2017* (World Bank 2017) 20.

4 William J Baumol, 'On Taxation and the Control of Externalities' [1972] 62 Am Econ Rev 307, drawing on Arthur C Pigou, *The Economics of Welfare* (Macmillan & Co 1920).

through quantity controls with a market for tradable permits, in which the dynamic of supply and demand reveals the price.[5] Underlying the broad appeal of this policy instrument is the observation that different emission abatement options have different costs, and that a price signal is the most efficient policy option because it relies on market forces to identify and trigger the abatement options with the lowest cost. In an ideal state, this will level marginal abatement costs across emitters in all sectors and jurisdictions.

In addition to this instrumental function, carbon pricing also has an epistemic dimension, where it is regularly used as a proxy for policy efforts in economic modelling. Models used in climate and energy projections calculate the marginal costs of emission reductions, typically expressed as implicit carbon prices.[6] A common starting point of global integrated assessment models is a 'ubiquitous price on carbon and other GHGs' in every country and sector, which 'rises over time in a way that minimizes the discounted sum of costs over time'.[7] Numerous model runs have been completed for numerous GHG concentration levels at various times. What these models express are the marginal costs of reducing the final ton of CO_2e at a given level of ambition, whether that reduction be achieved through taxes, emission caps, subsidies, direct regulations or any combination of these.

As the foregoing passages underscore, carbon pricing plays a pervasive role in discourses on climate change, both as a prominent policy recommendation and as an epistemic tool. Yet another manifestation of the concept relates to the optimal price level: economists have long sought to calculate the social cost of carbon, that is, the expected damage arising from one additional ton of CO_2e emitted.[8] Assuming optimal carbon pricing and perfect market conditions for emitters worldwide, a price on all GHG emissions equalling the social cost of carbon should theoretically result in an optimal emission level: low enough to ensure the functioning of human society and ecosystems, but without curtailing those emissions that contribute the highest value to social welfare. Such estimates of the social cost of carbon are widely used to support public policy decision making through quantified assessment of the benefits of climate mitigation efforts, and, more specifically, to inform the design of carbon pricing policies.[9]

II. Tensions between Carbon Pricing and the 1.5°C Target

1. Welfare Maximisation vs. Politically Agreed Targets

Already at a conceptual level, the compelling premise of carbon pricing as an instrument to quantify the environmental externalities of carbon emissions – and internalise these into the economic cost of underlying behaviour[10] – reveals a tenuous correlation with the politically agreed objective of deep decarbonisation within specified timelines. Even if we knew the correct social cost of carbon, and had the political support needed to implement a corresponding pricing policy, we could still not guarantee global carbon neutrality during the second half of the century as required by the Paris Agreement and many national and subnational legislative or policy acts. Nor would that carbon price necessarily ensure the rapid and steep decarbonisation pathways called for

5 Thomas D Crocker, 'The Structuring of Atmospheric Pollution Control Systems' in Harold Wolozin (ed), *The Economics of Air Pollution: A Symposium* (W W Norton, 1966) 61; John H Dales, *Pollution, Property & Prices: An Essay in Policymaking and Economics* (University of Toronto Press 1968); David W Montgomery, 'Markets in Licenses and Efficient Pollution Control Programs' [1972] 5 J Econ Theory 395, drawing on Ronald H Coase, The Problem of Social Cost [1960] 3 JLE 1.

6 Christoph Bertram and others, 'Complementing Carbon Prices with Technology Policies to Keep Climate Targets within Reach' [2015] 5 Nat Clim Change 235; Massimo Tavoni and others, 'Post-2020 Climate Agreements in the Major Economies Assessed in the Light of Global Models' [2015] 5 Nat Clim Change 119.

7 Intergovernmental Panel on Climate Change, *Climate Change 2014: Mitigation of Climate Change* (eds Ottmar Edenhofer and others, Cambridge University Press, 2014) 449.

8 David Anthoff and Richard SJ Tol, 'The Uncertainty about the Social Cost of Carbon: A Decomposition Analysis Using FUND' [2013] 117 Clim Change 515; William Pizer and others, 'Using and Improving the Social Cost of Carbon' [2014] 346 Science 1189.

9 See the survey in Stephen Smith and Nils A Braathen, 'Monetary Carbon Values in Policy Appraisal: An Overview of Current Practice and Key Issues' (2015) OECD Environment Working Papers No 92 <http://www.oecd-ilibrary.org/docserver/download/5jrs8st3ngvh-en.pdf> accessed 8 March 2018.

10 Such externalities are described by economists as a market failure, denoting an inefficient allocation of goods and services by the market, see Francis M Bator, 'The Anatomy of Market Failure' [1958] 72 Q J Econ 351. Internalising the social cost of pollution in the private cost of underlying economic activity has been proposed as one way to correct the market failure, see William J Baumol and Wallace E Oates, *The Theory of Environmental Policy* (2nd ed, Cambridge University Press 1988) 155.

by climate science to achieve the 1.5°C objective: under virtually all scenarios, net emission levels have to reach zero during this century,[11] requiring all or close to all abatement options to be realised, including those with higher cost.[12]

As long as the private benefit of emitting behaviour exceeds its (internalised) social cost, however, rational economic actors will continue to emit. Since present estimates of the social cost of carbon are relatively low, pricing policies based on them will still be eclipsed by the private benefit of many types of emitting behaviour. That is not a flaw of the concept as such, but a condition of its ability to maximise social welfare by guiding mitigation to activities where the benefits of abatement outweigh its cost. It does, however, show that the theoretical notion of a social cost of carbon is not aligned with the political objective of full decarbonisation during this century, as scientific uncertainties preclude establishing with sufficient confidence that zero or negative emissions are economically optimal.

Proponents will rightly counter that the social cost of carbon is not static, and is expected to rise over time.[13] Some have also argued that the risk of catastrophic climate outcomes is insufficiently reflected in present estimates, justifying considerably higher values and a much steeper increase.[14] Given such uncertainties in calculating the accurate social cost of carbon, some jurisdictions have altogether abandoned it as the primary metric for policy choices.[15] Instead, they have opted to work backward from an agreed emissions or temperature target to infer a carbon price consistent with a pathway towards target achievement. Such an approach aligns well with aspirational or legally binding climate targets, and also underpins the 1.5°C target contained in the Paris Agreement.[16] Rather than pursuing welfare maximisation through Pareto efficient allocation of abatement efforts, thus, this approach relies on political negotiation, aligning scientific and economic considerations with equity concerns and the preferences of diverse constituencies.[17]

Working back from politically agreed targets leads to carbon prices that are considerably higher than mainstream estimates of the social cost of carbon, albeit again subject to uncertainty. Projections of the carbon prices required to achieve the 2°C target, for instance, range from USD 15 to 360 per tCO_2e in 2030, USD 45 to 1,000 per tCO_2e in 2050, and USD 750 to 8,300 per tCO2e in 2100.[18] No comparable analysis has yet been published for achievement of the 1.5°C target, although an initial study of mitiga-

11 Joeri Rogelj and others, 'Scenarios Towards Limiting Global Mean Temperature Increase Below 1.5°C', [2018] 10 Nat Clim Change <doi:10.1038/s41558-018-0091-3> (online first); for the 2°C target: Detlef P van Vuuren and others, 'RCP2. 6: Exploring the Possibility to Keep Global Mean Temperature Increase Below 2°C' [2011] 109 Clim Change 95.

12 Asbjørn Torvanger and James Meadowcroft, 'The Political Economy of Technology Support: Making Decisions about Carbon Capture and Storage and Low Carbon Energy Technologies' [2011] 21 Global Envtl Change 303.

13 See, for instance, William D Nordhaus, *A Question of Balance: Weighing the Options on Global Warming Policy* (Yale University Press 2008).

14 Arguing that high-cost, low-probability events justify a considerably higher social cost of carbon, see Robert B Litterman 'What Is the Right Price for Carbon Emissions?' (2013) 36:2 Regulation 38; more generally, Martin L Weitzman, 'On Modeling and Interpreting the Economics of Catastrophic Climate Change' [2009] 91 Rev Econ & Statistics 1. One influential effort to quantify the social cost of carbon – developed by the U.S. Interagency Working Group on the Social Cost of Carbon – therefore included a separate, higher value to capture the damages associated with extreme climate outcomes, although the central estimate used for policy making purposes remained in the much lower range found in other mainstream estimates, see the 95th percentile value ('High Impact') for the social cost of carbon in United States Environmental Protection Agency, 'The Social Cost of Carbon: Estimating the Benefits of Reducing Greenhouse Gas Emissions' <https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html> accessed 8 March 2018. Under the current administration, the United States has abandoned use of the social cost of carbon as a metric altogether.

15 Specifically, they point to the considerable uncertainties about climate sensitivity and climate-induced damage functions, as well as disagreement about the appropriate discount rate, see Robert S Pindyck, 'Pricing Carbon When We Don't Know the Right Price' (2013) 36:2 Regulation 43, 44.

16 See, for instance, for the United Kingdom: Department of Energy and Climate Change (DECC), 'Carbon Valuation in UK Policy Appraisal: A Revised Approach' (2009) <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/245334/1_20090715105804_e____carbonvaluationinukpolicyappraisal.pdf> accessed 8 March 2018; similarly, the European Union has moved away from relying purely on the social cost of carbon for long-term climate policy design, see Paul Watkiss, 'The Social Costs of Carbon (SCC) Review: Methodological Approaches for Using SCC Estimates in Policy Assessment' (2006) Final Report to Defra <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/243816/aeat-scc-report.pdf> accessed 8 March 2018.

17 Kevin Anderson and Alice Bows, 'A New Paradigm for Climate Change' [2012] 2 Nat Clim Change 639.

18 In 2005 USD, respectively, based on scenarios that limit warming to below 2°C with a greater than 66% probability, see Stiglitz and others (n 1) 32, based on Intergovernmental Panel on Climate Change (IPCC), *Mitigation of Climate Change: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2014) 450.

tion cost differential between 1.5°C and 2°C scenarios suggests that, all else equal, carbon prices to achieve the 1.5°C target need to be about 2 to 3 times higher than in 2°C scenarios, and – because keeping temperatures below 1.5°C requires much more rapid decarbonisation of the economy – up to 5 times higher in the near term, by 2030.[19] In other words, if carbon pricing is the only policy relied upon for decarbonisation in line with the 1.5°C target, price levels would have to lie between USD 75 to 1800 per tCO_2e in 2030.

2. Political and Behavioural Constraints

Such high prices will unquestionably deliver substantial emission reductions. Outside the realm of economic theory and modelling, however, it is doubtful that carbon prices can ever achieve these levels. Already at much lower levels, persistent challenges related to the political economy of carbon pricing have been documented across multiple jurisdictions, leading commentators to write about 'binding political constraints'.[20] Such constraints are highly consequential, having thwarted the passage of many carbon pricing proposals[21] or, in some cases, prompted the repeal of carbon pricing systems already in place.[22] Unlike other climate policy instruments, carbon pricing makes the cost of compliance fully transparent, and tends to impose it disproportionately on a limited group of articulate, politically influential emitters while spreading out a weakly benefit[23] – the incremental mitigation of climate change – among many diffuse and poorly organized constituents.[24] As such, therefore, carbon pricing epitomises a policy susceptible to regulatory capture and the failure of collective action in the common interest.[25] Where higher carbon prices can be politically implemented, however, they give rise to equity concerns, as poorer households will be disproportionately impacted. Redistributive mechanisms can correct that, but further complicate the politics around carbon pricing, and, by extension, its elegant conceptual simplicity as a policy instrument.

Even if carbon pricing at prescribed levels were politically viable, increasing steeply in line with decarbonisation targets, or imposing a steadily declining cap that signals future allowance scarcity, it would still not automatically result in the emission reductions projected by economic models. Behavioural economics and psychology are continuously improving our understanding of human responses to different types of policy incentives, and suggest that economic actors are not only frequently irrational, but react to price signals in complex and unpredictable ways.[26] Economic theory itself acknowledges that market failures other than the externalities of pollution contribute to climate change, including knowledge and adoption spillovers, informational failures, myopia and bounded rationality, time-inconsistencies, moral hazard, and

19 Joeri Rogelj et al, 'Energy System Transformations for Limiting End-of-Century Warming to Below 1.5 °C' [2015] 5 *Nat Clim Change* 519, 525.

20 Jesse D Jenkins and Valerie J Karplus, 'Carbon Pricing Under Political Constraints: Insights for Accelerating Clean Energy Transitions' in Douglas Arent and others (eds), *The Political Economy of Clean Energy Transitions* (Oxford University Press 2017) 39; Jesse D Jenkins, 'Political Economy Constraints on Carbon Pricing Policies: What Are the Implications for Economic Efficiency, Environmental Efficacy, and Climate Policy Design?' [2014] 69 Energy Pol'y 467.

21 Examples include a failed carbon and energy tax proposal in the European Union during the 1990s, see Frank J Convery, 'Origins and Development of the EU ETS' [2009] 43 Envtl Res Econ 391; a United States federal tax on energy that also aimed to reduce GHG emissions, see Dawn Erlandson, 'The BTU Tax Experience: What Happened and Why It Happened' [1994] 12 Pace Envtl L Rev 173; a Canadian federal carbon tax proposal in 2008, see Kathryn Harrison, 'A Tale of Two Taxes: The Fate of Environmental Tax Reform in Canada' [2012] 29 Rev Pol'y Res 383, 397; the volatile evolution of subnational carbon pricing proposals in the United States, see Barry G Rabe, 'The Durability of Carbon Cap-and-Trade Policy' [2016] 29 Governance 103, and, most recently, press coverage of the recurring defeat of carbon tax legislation in Washington State.

22 Examples include the Australian Carbon Pricing Mechanism, revoked in 2014 following a federal election, see Christopher Rootes, 'A Referendum on the Carbon Tax? The 2013 Australian Election, the Greens, and the Environment' [2014] 23 Envtl Pol 166, and the withdrawal of New Jersey from the Regional Greenhouse Gas Initiative in 2011.

23 Sander van der Linden, Edward W Maibach and Anthony A Leiserowitz, 'Improving Public Engagement with Climate Change: Five "Best Practice" Insights from Psychological Science' [2015] 10 Perspect Psychol Sci 758.

24 In the typology of public policies set out by Theodore J Lowi, 'American Business, Public Policy, Case Studies, and Political Theory' [1964] 16 World Pol 677, this would reflect 'regulation'. Equity considerations and concern about the social impacts of carbon pricing on disadvantaged or vulnerable groups tend to prevent redistribution of the compliance burden away from large emitters to the broader public.

25 Mancur L Olson, *The Logic of Collective Action: Public Goods and the Theory of Groups* (Harvard University Press 1965); George J Stigler, 'The Theory of Economic Regulation' (1971) 2:1 Bell J Econ Mgmt Sci 3.

26 Damien Bazin, Jerome Ballet and David Touahri, 'Environmental Responsibility versus Taxation' [2004] 49 Ecol Econ 129.

split incentives.[27] Pricing is not ideally suited to correct such market failures, which tend to be behavioural or institutional in nature, and which create barriers to mitigation that a mere increase in the private cost of emitting behaviour may not easily overcome.

3. Dynamic Efficiency and Transformative Potential

Collectively, the foregoing observations about theoretical premises and political economy constraints of carbon pricing contribute to yet another property that affects its suitability as a driver of decarbonisation within strict timelines: its *dynamic* – rather than *static* – efficiency.[28] When it comes to static efficiency, that is, the ability to prompt refinement of *existing* technologies, processes and capabilities, carbon pricing is unrivalled in the way it channels abatement to the options with least cost: by allowing flexibility across space and time, it lets the market decide when and where to mitigate, equalizing marginal abatement cost across the economy in a Pareto-efficient equilibrium.[29]

Its ability to foster dynamic efficiency, however, and spur development of *new* technologies, processes, and capabilities is less clear.[30] By design, carbon pricing is meant to favour the most affordable emission reductions at any given point in time, rather than spur early investment in research, development, and deployment of advanced abatement technologies. As we progress towards full decarbonisation of the economy, however, such mitigation options with long lead times will successively be indispensable at commercial scale. Carbon pricing, which targets the negative externalities of emitting behaviour, is not ideally suited to capture the positive externalities of innovation, such as knowledge diffusion.[31] Accordingly, innovation levels under existing carbon pricing systems have been modest at best.[32]

Another dynamic challenge relates to how carbon pricing influences investment behaviour. In existing carbon pricing systems, investors in emitting assets and infrastructure have been shown to make myopic choices that discount future compliance obligations and imply scepticism[33] about the durability of climate policies over the longer term.[34] Because such investments have a normal economic life of years or even decades, they result in carbon lock-in and impede decarbonisation of affected sectors.[35] Already, research has suggested that no new emitting electricity infrastructure should be built if the 2°C threshold is to be met,[36] a hard constraint that would apply all the more on a pathway towards 1.5°C. Only abandoning such investments before the end of their useful economic life would still allow adherence to the 1.5°C target, leading to stranded assets and significant destruction of capital.[37]

For these reasons, backloading of mitigation effort can result in considerably higher aggregate welfare impacts over time, even without counting the impact of climate change itself.[38] Within current political re-

27 Adam Jaffe, Richard Newell and Robert Stavins, 'A Tale of Two Market Failures: Technology and Environmental Policy' [2005] 54 *Ecol Econ* 164.

28 For a detailed definition, see Pankaj Ghemawat and Joan E Ricart Costa, 'The Organizational Tension between Static and Dynamic Efficiency' [1993] 14:S2 Strat Mgmt J 59.

29 Carolyn Fischer and Richard G Newell, 'Environmental and Technology Policies for Climate Mitigation' [2008] 55 J Envtl Econ Mgmt. 142; Baran Doda and Samuel L Fankhauser, 'Energy Policy and the Power Sector in the Long Run' (2017) Grantham Research Institute on Climate Change and the Environment Working Paper No 276 <http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2017/09/Working-Paper-276-Doda-Fankhauser-1.pdf> accessed 5 March 2018.

30 Benjamin Görlach, 'Emissions Trading in the Climate Policy Mix: Understanding and Managing Interactions with Other Policy Instruments' [2014] 25 Energy & Env 733.

31 Daron Acemoğlu and others, 'The Environment and Directed Technical Change' [2012] 102 Am Econ Rev 131.

32 Raphael Calel and Antoine Dechezleprêtre, 'Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market' [2016], 98 Rev Econ Stat 173; see also Margaret R Taylor, 'Innovation under Cap-and-trade Programs' [2012] 109 Proc Nat'l Acad Sci 4804.

33 On the concept of policy durability, see Eric Patashnik, *Reforms at Risk* (Princeton University Press 2008).

34 Uncertainty about the future evolution and ambition of carbon pricing in the European Union, for instance, has contributed to investment decisions that are incompatible with a deep decarbonisation pathway, see William Acworth and others, *Emissions Trading and the Role of a Long Run Carbon Price Signal: Achieving Cost Effective Emission Reductions under an Emissions Trading System* (International Carbon Action Partnership 2017).

35 Karen C Seto and others, 'Carbon Lock-In: Types, Causes, and Policy Implications' [2016] 41 Ann Rev Env & Resources 425.

36 Alexander Pfeiffer and others, 'The '2°C Capital Stock' for Electricity Generation: Committed Cumulative Carbon Emissions from the Electricity Generation Sector and the Transition to a Green Economy' [2016] 179 Appl Energy 1395.

37 A recent report estimates that USD 1.6 trillion in capital expenditure will be at risk by 2025 if the world implements climate policies consistent with the targets of the Paris Agreement (assuming a 1.75°C scenario), see Andrew Grant, Mind The Gap: The $1.6 Trillion Energy Transition Risk (Carbon Tracker 2018).

38 Adrien Vogt-Schilb, Guy Meunier and Stéphane Hallegatte, 'When Starting with the most Expensive Option Makes Sense: Optimal Timing, Cost and Sectoral Allocation of Abatement Investment' [2018] 88 J Envtl Econ and Mgmt, 210.

alities, therefore, the static efficiency which renders carbon pricing superior to other instruments in the short run is also its weakness in a longer, dynamic perspective. Altogether, carbon pricing appears better suited for incremental emission cuts at the margin, not for the systemic transformation required for achievement of the 1.5°C target. It is premised on notions of marginal cost and benefit, placing it at conceptual odds with an issue of the scale and temporal sensitivity of climate change.[39] By promoting incremental optimisation of existing systems, it may bind investment and render incumbent practices and technologies more resilient to change.[40] Instead of spearheading innovation and systemic transformation, carbon pricing may thus be most useful where it can incentivise marginal optimisation in specific contexts, such as fuel switching in the electricity sector.[41]

III. Experiences with Carbon Pricing in the Real World

While carbon pricing has been amply shown to offer static efficiency for emission reductions at the margin, there has been little evidence to date that it can leverage the deep emission cuts required for full decarbonisation within this century. Leaving aside complex questions about research methodologies to discern and measure the effects of carbon pricing policies amidst other factors affecting emissions,[42] the track record of carbon pricing does not document any examples of abatement in excess of single-digit percentages. While past observations do not necessarily rule out improved performance of carbon pricing going forward, they still offer an indication of how carbon pricing fares in the real world. One common theme across virtually all case studies are political constraints that prevent higher price levels, substantiating the vulnerabilities of carbon pricing described in the previous section, and casting doubt on its suitability as a sole or primary instrument of deep decarbonisation.

1. Carbon Taxes in the Real World

The World Bank Carbon Pricing Dashboard has exhaustive data on carbon pricing systems implemented around the world, affirming a steady expansion in the share of global emissions covered by carbon prices, albeit with significant variation in price levels.[43] According to this dashboard, a total of 47 separate carbon pricing initiatives were in place as of 2018.[44] They are found at the national, sub-national, and supra-national level, and comprise taxes, emissions trading systems, hybrid carbon pricing systems, and emission crediting mechanisms. A majority of these carbon pricing systems are based on some form of taxation, which are commonly defined as 'compulsory, unrequited payments to general government.'[45] Several jurisdictions, including Japan and British Columbia, have imposed uniform, economy-wide carbon taxes. About as many jurisdictions have implemented varying carbon taxes on different sectors and products, for instance Sweden and Mexico.

In many countries, emissions from transport and, to a lesser extent, from heating and electricity generation are subject to a fiscal burden in the form of excise or consumption taxes imposed on fuel sales. When these taxes are not expressly based on the carbon content of the fuels, they are not considered carbon taxes *strictu sensu*, yet because they still increase the cost of GHG emissions – and thereby contribute to internalising their environmental externalities – they are often included in carbon tax assessments,

39 Nicholas Stern, 'Ethics, Equity and the Economics of Climate Change. Paper 2: Science and Philosophy' [2014] 30 Econ Phil 397, 398: 'Risks on this scale take us far outside the familiar policy questions and standard, largely marginal, techniques commonly used by economists.' Nicholas Stern, 'Ethics, Equity and the Economics of Climate Change. Paper 2: Economics and Politics' [2014] 30 Econ Phil 445: 'Issues of this scale and temporal sensitivity cannot be convincingly represented as the integral of a collection of marginal changes in a static model or where the clock is conceptually stopped whilst the tatonnement process edging towards some optimum takes place.'

40 Howard A Latin, *Climate Change Policy Failures: Why Conventional Mitigation Approaches Cannot Succeed* (World Scientific 2012).

41 Michael Grubb, *Planetary Economics: Energy, Climate Change and the Three Domains of Sustainable Development* (Routledge 2014).

42 For a good discussion of alternative methodologies to ascertain mitigation effects and distinguish causation from correlation, see Misato Sato and others, 'Methods for Evaluating the Performance of Emissions Trading Schemes' (2015) Climate Strategies Discussion Paper <http://climatestrategies.org/publication/methods-for-evaluating-the-performance-of-emission-trading-schemes> accessed 8 March 2017.

43 See <http://carbonpricingdashboard.worldbank.org> accessed 28 February 2018.

44 World Bank, Ecofys and Vivid Economics, *State and Trends of Carbon Pricing* (World Bank 2017).

45 Organisation for Economic Co-operation and Development (OECD), *Revenue Statistics 2017: Tax Revenue Trends in the OECD* (OECD Publishing 2017) 1.

occasionally under the designation of 'effective carbon rates.'[46] Data from the International Energy Agency (IEA) shows that excise taxes paid by the electricity sector are substantially lower than those paid by households, with industry placed in the middle. A breakdown of excise taxes by fuel shows that road transportation is taxed most heavily, with median rates often in the range of 200-400 USD per tCO_2e. By contrast, taxes on coal, fuel oils, and gas used in industry and power generation are taxed more lightly, with the median rate often in the single digits and in any event below USD 100 per tCO_2e.

A survey of excise taxes, carbon taxes, and other relevant forms of pricing in Member States of the Organisation for Economic Co-operation and Development (OECD) and other major economies finds clear divergences between real-world carbon prices, on the one hand, and modelled carbon price projections or the social cost of carbon on the other.[47] In the 41 countries included in this survey, carbon prices cover only 40% of emissions, with the remainder of emissions exempt from a price signal; 90% of emissions subject to a carbon price face prices below 30 EUR per tCO_2e. Reflecting the foregoing observation, emission taxes related to road transport fuels are, as a general rule, much higher than taxes applied to stationary sources.

Although no comprehensive survey has tried to quantify the mitigation performance of these diverse carbon taxes and, more broadly, the effective carbon rates in place around the world, assessments of individual jurisdictions tend to identify statistically relevant abatement effects. Generally, however, even those carbon taxes considered particularly effective from a mitigation perspective have only been shown to spur moderate emission reductions, at least relative to the efforts required for deep decarbonisation in line with the 1.5°C target.[48] Even there, moreover, the causal role of carbon taxes alongside other climate policies has been debated, potentially further detracting from their performance.[49]

In the transportation sector, where effective carbon rates are typically highest – and often well above current estimates of the social cost of carbon – statistical data again reflects mostly incremental emission reductions. An instructive example is Sweden, which is noteworthy for having implemented the highest carbon tax at currently USD 163 per tCO_2e. Emissions from the Swedish transport sector, however, declined only four percent between 1990 – the year before the carbon tax was introduced – to 2015.[50] As importantly, new gasoline and diesel vehicle registrations in Sweden have grown in recent years,[51] locking in continued emissions for a decade or more.

All this should not suggest that carbon taxes have not limited or reduced emissions compared to a counterfactual scenario. But what the empirical track record shows is a high willingness to pay for certain benefits such as individual mobility, and conversely a price elasticity in key sectors that is insufficient to guarantee decarbonisation at a rate consistent with the 1.5°C target, at least in any realistic political scenario.

2. Emissions Trading in the Real World

Emissions trading systems appear to fare somewhat better than carbon taxes when measured against their ultimate goal: emissions are declining, often significantly. Less clear, however, is whether the reductions have actually been caused – or are merely correlated – with introduction of the emissions trading system. In the case of the European Union, for instance, decreasing emissions in covered sectors have been ascribed to several causes other than emissions trading, including broader economic weakness and mitigation pressure from complementary policies, such as programmes to promote renewable energy and energy efficiency.[52] In recent years, moreover,

46 Organisation for Economic Co-operation and Development (OECD), *Effective Carbon Rates: Pricing CO_2 through Taxes and Emissions Trading Systems* (OECD Publishing 2016).

47 OECD (n 9).

48 In British Columbia, for instance, which is often portrayed as a 'textbook example' of carbon taxation, the carbon tax (currently at CAD 30 per tCO_2e) is only estimated to have reduced emissions between 5% and 15%, see Brian Murray and Nicholas Rivers, 'British Columbia's Revenue-Neutral Carbon Tax: A Review of the Latest 'Grand Experiment' in Environmental Policy' [2015] 86 Energy Pol'y 674.

49 See Ekaterina Rhodes and Mark Jaccard, 'A Tale of Two Climate Policies: Political Economy of British Columbia's Carbon Tax and Clean Electricity Standard' [2013] 39 Can Publ Pol'y S37.

50 Julius Andersson, *Cars, Carbon Taxes and CO_2 Emissions* (Grantham Research Institute on Climate Change and the Environment, 2017).

51 Trafikanalys, 'Fordon 2016' (2017) <http://www.trafa.se/globalassets/statistik/vagtrafik/fordon/2016/fordon_2016_blad.pdf> accessed 25 February 2018.

52 Michael Mehling, 'Between Twilight and Renaissance: Changing Prospects for the Carbon Market' [2012] 6 CCLR 277; Endre Tvinnereim, 'The Bears are Right: Why Cap-and-trade Yields Greater Emission Reductions than Expected, and what that Means for Climate Policy' [2014] 127 Clim Change 447.

the European carbon market has proven unable to prevent new construction of coal-fired power plants.[53]

One difference between the two pricing mechanisms relates to their scope and coverage in practice: emissions trading typically covers large, stationary installations, whereas taxes are more often aimed at consumers. Such differences in design can significantly affect abatement performance: electricity generators and heavy industry respond differently to price signals, and have the requisite capacity and resources for strategic, long-term planning. Also, they can often substitute technologies, raw inputs, and processes more easily with clean alternatives than individual consumers. Occasionally, marginal abatement costs will simply be lower in large emitters, or emissions might fall due to emissions displacement into other regions. Known as leakage, such displacement occurs through shifting production, investment, and energy flows.[54]

Emissions trading has also proven more susceptible to uncertainty and interactions with other policies. Although uncertainty about fundamentals, such as technology cost, fuel and resource cost, and economic cycles, as well as adverse policy interactions can affect all climate policy making, they have been shown to effect dramatic impacts in the case of emissions trading,[55] translating into price volatility and what has been euphemistically termed an 'imbalance of demand and supply',[56] with prices that are, on average, much lower than carbon taxes around the world.

Over a decade of experience with pure emissions trading systems has shown that the absence of any price or supply intervention mechanism results in an untenably short and uncertain planning horizon for investments in long-lived capital assets such as electricity generation facilities. New design features, such as carbon price floors, auction reserve prices, and market stability reserves, are becoming increasingly prevalent to avoid the unintended outcomes witnessed in practice, such as increased dispatch of or new investment in coal-fired generation. Instrument hybridization therefore marks a logical and perhaps inevitable evolution of emissions trading.[57] Still, as with individual behaviour, corporate behaviour is not always predictable: in the emissions trading pilot systems introduced in several Chinese cities and provinces starting in 2013, for instance, the largely state-owned participants failed to respond to market signals, undermining an indispensable condition for cost effectiveness of this instrument.[58]

IV. Instrument Portfolios and the Role of Regulation

As mentioned earlier, different market failures contribute to anthropogenic climate change, from the negative externality of carbon emissions to the positive externalities of innovation spill overs, information asymmetries, bounded rationality, and split incentives.[59] Also, climate policies can pursue objectives other than emissions abatement, such as promoting innovation, inducing structural transformation, increasing energy security, or building resilience to climate change.[60] A widely accepted notion in economic theory, the 'Tinbergen Rule', states that each policy objective requires at least one policy instrument,[61] and provides the theoretical justification for a variety of policy instruments in an instrument portfolio.

Given the theoretical constraints and empirical track record of carbon pricing described in the previous sections, it becomes clear that deep decarbon-

53 European Network of Transmission System Operators for Electricity (ENTSOE), *Yearly Statistics and Adequacy Retrospect 2015* (ENTSOE 2017).

54 John Ward and others, 'Carbon Leakage: Theory, Evidence and Policy Design' (2015) Partnership for Market Readiness Technical Note 11 <https://openknowledge.worldbank.org/bitstream/handle/10986/22785/K8516.pdf> accessed 25 February 2018.

55 Mehling (n 52).

56 Commission, 'Report from the Commission to the European Parliament and to the Council: Report on the Functioning of the European Carbon Market' COM (2017) 693 final, 23.

57 Georg Grüll and Luca Taschini, 'Cap-and-Trade Properties Under Different Hybrid Scheme Designs' [2011] 61 J Envtl Econ Mgmt 107; Cameron Hepburn, 'Regulation by Prices, Quantities, or Both: A Review of Instrument Choice' [2006] 22 Oxf Rev Econ Pol'y 226; William A Pizer, 'Combining Price and Quantity Controls to Mitigate Global Climate Change' [2002] 85 J Publ Econ 409.

58 Anatole Boute and Hao Zhang, 'The Role of the Market and Traditional Regulation in Decarbonising China's Energy Supply' [2017] 30 J Envt'l L <https://academic.oup.com/jel/advance-article-abstract/doi/10.1093/jel/eqx028/4644814?redirectedFrom=fulltext>; Clayton Munnings and others, 'Assessing the Design of Three Carbon Trading Pilot Programs in China' [2016] 96 Energy Pol'y 688.

59 David M Driesen, 'The Limits of Pricing Carbon' [2014] 4 Clim L 107.

60 Dieter Helm, 'Economic Instruments and Environmental Policy' 36 Econ Soc Rev 205, 214.

61 Jan Tinbergen, *On the Theory of Economic Policy* (North Holland Publishing Co 1952) 37; Leif Johansen, *Public Economics* (North-Holland Publishing Co 1965) 12.

isation within current political realities and stringent timelines will necessitate reliance on other policy instruments. Performance and technology standards, directed subsidies and price supports, licensing and planning, information and suasive instruments, and public investments in infrastructure and innovation all play useful and important roles alongside carbon pricing to ensure achievement of the 1.5°C target. Research on these policy alternatives, however, including their conditions, impacts, and interactions, has lagged behind research on carbon pricing. A short overview of research on portfolios of climate policy instruments follows in the next sections, along with a case study on technology phase-out mandates in the transportation sector.

1. Research on Instrument Portfolios

Research on instrument portfolios for climate policy mitigation remains a relatively narrow field. Several studies have affirmed the superiority of instrument combinations over reliance on individual policies. Daron Acemoglu and others, for instance, recommend a balance between moderate carbon taxes and innovation subsidies.[62] Christoph Bertram and others argue that an instrument portfolio can have fewer distributional effects and smaller efficiency losses relative to an 'optimal' carbon price.[63] Similarly, Jesse Jenkins has favoured a combination of instruments, including incentives for technological innovation, notably through creative use of carbon pricing revenues.[64] Such observations have also informed a recent high-level report on carbon pricing, which expressly acknowledges the importance of complementary instruments to reduce overall welfare impacts and address market failures for which carbon pricing would be inefficient.[65]

Focusing on the political economy of climate policy, Jonas Meckling and others have acknowledged that carbon prices are unlikely to reach levels high enough to induce the deep emission cuts implied by politically agreed targets.[66] Based on their analysis, targeted support policies with concentrated winners – such as subsidies for renewable energy deployment – are more likely to display policy durability, as they create constituencies supportive of robust climate policy.[67] Opinion surveys have confirmed that such policy alternatives are also more popular with the broader public, despite their overall cost.[68] Such support can, in turn, expand the political opportunity space for higher carbon prices,[69] leading some commentators to argue for a sequential approach, in which the timeline of policy implementation sees carbon pricing following other policy instruments.[70] Altogether, distributional concerns are important for the success or failure of climate policy, calling for additional research.[71]

Instrument portfolios allow combining instruments to harness their respective strengths, but bad portfolio design can result in policy interactions and pose considerable challenges to climate policy performance.[72] Such interactions are particularly likely where policies pursue more than one objective, or un-

62 Daron Açemoglu and others, 'The Environment and Directed Technical Change' [2012] 102 Am Econ Rev 131.

63 Bertram and others (n 6)

64 Jesse D Jenkins, 'Political Economy Constraints on Carbon Pricing Policies: What Are the Implications for Economic Efficiency, Environmental Efficacy, and Climate Policy Design?' [2014] 69 Energy Pol'y 467; the substantial impact of strategic revenue recycling relative to the behavioural effect of the carbon price itself has been borne out in practice with the U.S. Regional Greenhouse Gas Initiative, see Paul J Hibbard and others, *The Economic Impacts of the Regional Greenhouse Gas Initiative on Nine Northeast and Mid-Atlantic States: Review of RGGI's Second Three-Year Compliance Period (2012-2014)* (Analysis Group 2015), and is also key to fostering enduring public support, see David Amdur, Barry G Rabe and Christopher P Borick, 'Public Views on a Carbon Tax Depend on the Proposed Use of Revenue' [2014] 13 Issues Energy Envtl Pol'y 1.

65 Stiglitz and others (n 1) 37, 47-9.

66 Jonas Meckling and others, 'Winning Coalitions for Climate Policy', [2015] 349 *Science* 1170, pointing to the example of climate policy combined with industrial and labour policy underlying the growth of the German wind industry.

67 Axel Michaelowa, 'The German Wind Energy Lobby: How to Promote Costly Technological Change Successfully' [2005] 15 Eur Env 192.

68 Jon A Krosnick and Bo MacInnis, 'Does the American Public Support Legislation to Reduce Greenhouse Gas Emissions?' [2013] 142 Daedalus 26.

69 Gernot Wagner and others, 'Energy Policy: Push Renewables to Spur Carbon Pricing' [2015] 525 Nature 27; Generally Brian J Cook, 'Arenas of Power in Climate Change Policymaking' [2010] 38 Policy Stud J 465.

70 Jonas Meckling, Thomas Sterner and Gernot Wagner, 'Policy Sequencing toward Decarbonization' [2017] 2 Nat Energy 918; Michael Pahle and others, *What Stands in the Way Becomes the Way: Sequencing in Climate Policy to Ratchet Up Stringency Over Time* (Resources for the Future 2017).

71 Diana Ürge-Vorsatz and others, 'Measuring the Co-Benefits of Climate Change Mitigation' [2014] 39 Ann Rev Env & Res 549.

72 Samuel Fankhauser, Cameron Hepburn and Jisung Park, 'Combining Multiple Climate Policy Instruments: How Not to Do It' [2010] 1 Clim Ch Econ 209; Carolyn Fischer and Louis Preonas, 'Combining Policies for Renewable Energy: Is the Whole Less Than the Sum of Its Parts?' [2010] 4 Int'l Rev Envtl Res Econ 51.

dermine each other and necessitate tradeoffs.[73] Given its economic rationale of promoting mitigation at least cost, carbon pricing is particularly prone to adverse interactions when implemented alongside other instruments that address the same market failure. Performance and technology standards, for instance, can interfere with the ability of carbon pricing to equalize abatement cost across the economy and identify the most cost-effective abatement options.[74] In the case of emissions trading systems, meanwhile, where the overall emissions level is determined by the number of units in circulation, emissions reductions achieved under other policies can displace emission units which will then serve to offset emissions elsewhere in the system, effectively only shifting the location and timing of emissions under the politically determined limit.[75] Instrument portfolios therefore require careful design, and deserve greater attention in climate policy research and analysis.

2. Case Study: Individual Mobility

A particular need for high-cost initial investment can be found in the transport sector, where decarbonisation requires both a replacement of the existing vehicle stock and the provision of alternative technologies and infrastructure. Although the expected economic life of vehicles is lower than that of power generation facilities, the natural retirement of aging combustion engine vehicles constitutes an excellent opportunity to replace fossil with low carbon capital stock at renewal.

As mentioned in an earlier section, however, price signals are not always effective in the transport sector, given low price elasticities and a high willingness to pay for individual mobility. Research has shown that vehicle choice depends less on price signals than on a variety of preferences related to vehicle performance, size, familiarity, and range.[76] Entering information on customer preference heterogeneity into integrated assessment models (IAMs) has been shown to produce results where electric vehicle penetration is delayed by several decades, increasing emissions relative to the scenario where only price matters.[77] Performance standards for new investments offer an alternative policy approach, yet their widespread adoption has not only incurred substantial cost,[78] but also failed to curb transport emissions in line with mandated decarbonisation targets.

Political economy constraints are, again, a central factor in the observed intractability of emission reductions in this sector, with a limited number of highly organized and vocal actors on the part of both vehicle manufacturers and consumers capturing the political debate. Faced with the need to achieve substantial emission reductions in the near term while also ensuring that new capital stock in the transport sector is channelled towards technologies and infrastructure with zero direct emissions, policy makers are increasingly turning to another policy category: technology mandates.

Accordingly, several countries have recently proposed future bans on the sale of new vehicles with internal combustion engines. For instance, in July 2017, the French government announced an intention to phase out the sale of new diesel- and gasoline-fuelled cars by 2040, and the city of Paris is even contemplating an earlier ban on existing conventional vehicles by 2030. Similar statements have been made by China, India, Norway, and the United Kingdom.[79]

73 William A Knudson, 'The Environment, Energy, and the Tinbergen Rule' [2009] 29 Bullet Sci Tech Soc 308, 309-311.

74 If the carbon price is higher than the marginal abatement cost under such complementary policies, it becomes redundant, whereas if it is lower, the simultaneous application of directed technology mandates will curtail the compliance flexibility of emitters and increase the cost of achieving the same environmental outcome, see IPCC (: Reference source not found) 1182.

75 Dallas Burtraw and William Shobe, *State and Local Climate Policy under a National Emissions Floor* (Resources for the Future 2009); Lawrence H Goulder and Robert N Stavins, 'Challenges from State-Federal Interactions in US Climate Change Policy' [2011] 101 Am Econ Rev 253; additionally, the increase in unit supply will, *ceteres paribus*, exert downward pressure on unit prices until all units in circulation are again demanded, thereby weakening the price signal in the market, see Lawrence H Goulder and Andrew Schein, 'Carbon Taxes vs. Cap and Trade: A Critical Review' [2013] 4 Clim Ch Econ 1, 16.

76 See, for instance, James Archsmith and others, 'Attribute Substitution in Household Vehicle Portfolios' (2017) NBER Working Paper No 23856 <https://www.nber.org/papers/w23856> accessed 5 March 2018.

77 David L McCollum and others, 'Improving the Behavioral Realism of Global Integrated Assessment Models: An Application to Consumers' Vehicle Choices' [2017] 55 Transp Res Pt D: Trans & Env 322.

78 Academic analysis has widely concluded that fuel economy and emissions standards are costly relative to the achieved emission reductions, see Valerie J Karplus and Sergey Paltsev, 'Proposed Vehicle Fuel Economy Standards in the United States for 2017 to 2025: Impacts on the Economy, Energy, and Greenhouse Gas Emissions' [2012] 2287 Transp Res Record 132.

79 Alanna Petroff, 'These Countries Want to Ban Gas and Diesel Cars' *CNN Money* (11 September 2017) <http://money.cnn.com/2017/09/11/autos/countries-banning-diesel-gas-cars/index.html> accessed 8 March 2018.

Vehicle manufacturers are already responding, for instance with the announcement by Volvo that it will phase out production of purely fossil-fuelled cars by 2019. Accompanying such phase out efforts are mandates for electric vehicle penetration by specified deadlines, incentive and transition assistance programmes, as well as public investments in charging infrastructure. Deep decarbonization of the transport sector passenger cars does not appear likely to be primarily tax-driven in practice, although taxes play a part in making some types of vehicles more attractive than others. Rather, regulations, standards, and public infrastructure are the principal instruments.

This surge in blunt technology mandates begs important questions about the political economy of alternative climate policy instruments, and their role in an instrument portfolio for deep decarbonisation within stringent timelines. Despite their documented inferiority in terms of static cost-effectiveness,[80] for instance, regulatory policies, when implemented alongside carbon pricing, have been shown to have a reliable abatement effect.[81] Politically, they are aided by the fact that costs of their achievement – both social and private – are less visible than with carbon pricing policies. Conceptually, their promise of a guaranteed outcome make them particularly attractive in cases where achievement of binding policy objectives within specified timelines takes precedence over static cost-effectiveness. Pressure to adopt dramatic measures after a sequence of visible policy failures are also what is prompting consideration of phase out mandates in the transport and electricity sectors. But as past experience with phase out policies shows, hasty or uncoordinated action can have judicial repercussions and result in stranded assets,[82] justifying further research to understand the conditions and effects of carbon pricing and alternative climate policy instruments in instrument portfolios.

3. A Research Agenda for Instrument Portfolios

More research is needed on the effects of portfolio approaches that combine various instruments, including the contributions of each constituent policy. An example of such a study is seen in the case of British Columbia, where a comparison of the widely lauded carbon tax and a clean electricity standard adopted simultaneously in the province showed that the latter reduced 4 to 6 times more emissions than the former, enjoying greater public acceptance, but also incurring higher average abatement costs than the carbon tax.[83] While various instruments may spur emission reductions in the same sector, their effects can be shown to work along different dimensions, with research subsidies, for instance, promoting development and uptake of specific technologies over the long term, while carbon pricing tends to leverage abatement much more broadly and in the shorter term.[84]

Political economy constraints and unforeseen policy interactions have fundamental implications for the viability and performance of climate policy instrument portfolios. As the foregoing example of technology phase out mandates shows, knowledge gaps and misplaced faith in theoretically optimal instruments can result in costly policy corrections. Besides the conventional vehicle phase out initiatives mentioned in the previous section, for instance, a number of countries are also introducing policies to limit or phase out coal use in electricity generation,[85] including the United Kingdom, which already has one of the highest carbon prices for electricity generators due to its domestic carbon floor price. But as that last example also shows, uncoordinated unilateral action can have unintended consequences, in this case by displacing emission allowances that have become available for continued emissions in other parts of Europe.

Preventing carbon lock-in through long-lived capital assets may necessitate blunt policies such phase

80 Fischer and Newell (n 28).

81 Olivier Gloaguen and Emilie Alberola, 'Assessing the Factors Behind CO2 Emissions Changes over the Phases 1 and 2 of the EU ETS: An Econometric Analysis' (2013) CDC Climate Research Working Paper No 2013-15 <http://www.cdcclimat.com/IMG/pdf/13-10_cdc_climat_r_wp_13-15_assessing_the_factors_behing_co2_emissions_changes.pdf> accessed 8 March 2018; Rhodes and Jaccard (n 48).

82 Karoline S Rogge and Phil Johnstone, 'Exploring the Role of Phase-out Policies for Low-carbon Energy Transitions: The Case of the German *Energiewende*' [2017] 33 Energy Res Soc Sci 128.

83 Rhodes and Jaccard (n 48).

84 For an example related to carbon capture and storage, see William Blyth and others, 'Policy Interactions, Risk and Price Formation in Carbon Markets' [2009] 37 Energy Pol'y 5192.

85 See the recent pledge by over 20 countries to end coal use by 2030, Powering Past Coal Alliance, 'Declaration' (16 November 2017) <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/660041/powering-past-coal-alliance.pdf> accessed 8 March 2018.

outs mandates for achievement of deep decarbonisation,[86] yet research into the design, effects and interactions of such policies has lagged far behind the study of carbon pricing. As a result, policymakers may lack the information needed to apply these instruments in a way that avoids unnecessary cost and other detrimental effects. Additional research on the different effects of various mitigation instruments in an instrument portfolio is therefore needed.

V. Outlook

For all its beneficial effects, a price on carbon does not guarantee that emitting activities will cease within committed timelines of deep decarbonisation. We have therefore argued that more attention needs to be directed toward climate change mitigation instruments other than those based on pricing carbon emissions, including regulatory approaches such as technology mandates and phase out policies. Such attention needs to come from policymakers and researchers alike. Otherwise, reliance on carbon pricing alone may lead to substantial sunk costs in fossil-bound infrastructure, due to the numerous market failures and particularly onerous political economy constraints facing any attempt to impose sufficiently high prices on carbon emissions.

Altogether, non-price instruments should be pulled out from subordinate compartments in the mitigation toolbox, and be presented not as 'second best' or 'auxiliary' policies, but rather as integral parts of a portfolio. Because of their stigma as suboptimal policy approaches, these instruments may not receive the attention they deserve in a process of deliberate, strategic policy making, contributing to abrupt and costly policy corrections down the line as supposedly 'first best' instruments underperform or are finally proven to lack political feasibility. With current carbon prices mostly lingering at modest levels and with patchy coverage, their role may have to be redefined to that of a backstop measure, leveraging their ability to curb emissions from existing capital stock and, in particular, to incentivise abatement in areas that other instruments are unable to reach. But to achieve deep decarbonisation in line with the 1.5°C target, such other instruments will be needed, including regulation.

86 Frank W Geels and others, 'Sociotechnical Transitions for Deep Decarbonization' [2017] 357 Science 1242.