Environmental Research Letters

LETTER • OPEN ACCESS

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To cite this article: Elmar Kriegler *et al* 2018 *Environ. Res. Lett.* **13** 074022

Environmental Research Letters

OPEN ACCESS

RECEIVED
24 February 2018

REVISED
2 May 2018

ACCEPTED FOR PUBLICATION
15 May 2018

PUBLISHED
6 July 2018

LETTER

Short term policies to keep the door open for Paris climate goals

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Keywords: mitigation pathway, integrated assessment, regulatory policies, carbon pricing, political implementability, Paris Agreement, 1.5 °C and 2 °C temperature limits

Supplementary material for this article is available online

Abstract

Climate policy needs to account for political and social acceptance. Current national climate policy plans proposed under the Paris Agreement lead to higher emissions until 2030 than cost-effective pathways towards the Agreements' long-term temperature goals would imply. Therefore, the current plans would require highly disruptive changes, prohibitive transition speeds, and large long-term deployment of risky mitigation measures for achieving the agreement's temperature goals after 2030. Since the prospects of introducing the cost-effective policy instrument, a global comprehensive carbon price in the near-term, are negligible, we study how a strengthening of existing plans by a global roll-out of regional policies can ease the implementation challenge of reaching the Paris temperature goals. The regional policies comprise a bundle of regulatory policies in energy supply, transport, buildings, industry, and land use and moderate, regionally differentiated carbon pricing. We find that a global roll-out of these policies could reduce global CO_2 emissions by an additional 10 $GtCO_2eq$ in 2030 compared to current plans. It would lead to emissions pathways close to the levels of cost-effective likely below 2 °C scenarios until 2030, thereby reducing implementation challenges post 2030. Even though a gradual phase-in of a portfolio of regulatory policies might be less disruptive than immediate cost-effective carbon pricing, it would perform worse in other dimensions. In particular, it leads to higher economic impacts that could become major obstacles in the long-term. Hence, such policy packages should not be viewed as alternatives to carbon pricing, but rather as complements that provide entry points to achieve the Paris climate goals.

Introduction

The Paris Agreement aims to collectively hold warming to well below 2 °C and pursue efforts to limit warming to 1.5 °C through progression of nationally determined climate policy plans (called nationally determined contributions, or NDCs). Nevertheless, countries have already raised their concern that the current NDCs would only slow the growth of global greenhouse gas (GHG) emissions and that short term ambition would need to be ratcheted up swiftly in order to keep the long-term goals in reach (UNFCCC 2015). This concern was further supported by recent analyses (Rogelj *et al* 2016). Following an NDC trajectory until 2030 would imply larger mitigation challenges in terms of the need for even faster and deeper emissions reductions after 2030 in view of an increased carbon lock-in compared to cost-effective well below 2 °C scenarios (Riahi *et al* 2015, Fawcett *et al* 2015).

Ratcheting up NDCs requires identifying concrete policies that could be effectively implemented in the real world. Economic theory has frequently emphasized the importance of carbon pricing as the least-cost policy to achieve emission reductions (Edenhofer *et al* 2015). However, climate policy needs also to be socially and politically acceptable while providing credible long-term pathways for climate stabilization (Vogt-Schilb and Hallegatte 2017). This requires to take into account other societal objectives, such as reducing local air pollution, in the policy choice. Implementing a carbon price alone would entail clearly visible costs that would immediately affect specific actors such as energy-intensive industries. Such actors might have the power to veto necessary policy reform and undermine the political feasibility of carbon pricing (Trebilcock 2014, Jenkins 2014). This may compel governments to look for alternative mitigation policies that may be politically more feasible but economically more costly.

Despite their importance for policymakers, rigorous analyses of politically feasible policies to strengthen the NDCs to keep the Paris climate goals in reach is limited (den Elzen *et al* 2015, Fekete *et al* 2015, IEA 2015), and in the context of the 1.5 °C limit practically absent. This study investigates how rolling out a set of existing 'good practice' policies, as well as additional policies aiming to achieve carbon neutrality in individual sectors ('net zero' policies), would strengthen emissions reductions until 2030 and serve as entry points for achieving the Paris temperature goals. The novel element is to integrate such detailed policy packages until 2030 into pathways that reach long-term targets until 2100 using an integrated assessment modelling framework. This allows us to evaluate the consistency of these policy packages with the long-term Paris ambition, including to what extent they keep the door open for limiting warming to 1.5 °C (Rogelj *et al* 2015). Specifically, we assess how multiple dimensions that influence medium- to long-term political feasibility (Gambhir *et al* 2017), including transition speed, scale, and disruptiveness, are affected by the choice of short-term policy package until 2030 and the availability of carbon dioxide removal (CDR) measures.

Methods

We use a global multi-sector, multi-region integrated assessment modelling (IAM) framework, REMIND-MAgPIE (Popp *et al* 2014, Luderer *et al* 2015, Kriegler *et al* 2017) to assess the extent to which the strengthening of NDCs with additional policy packages would help keeping the Paris temperature goals within reach. The IAM framework consists of the energy-economy-climate model REMIND (Bauer *et al* 2008, Leimbach *et al* 2010a, 2010b, Luderer *et al* 2013, 2015) coupled to the land-use model MAgPIE (Lotze-Campen *et al* 2008, Popp *et al* 2010, 2014). Both models cover the globe with 11 regions and run scenarios until the year 2100. Further details of the modeling framework can be found in the supplementary material, section S3 available at stacks.iop.org/ERL/13/074022/mmedia.

Scenario design: in this study, we compare 13 climate policy scenarios which all assume middle-of-the road socio-economic developments as described in Shared Socio-Economic Pathway 2 (SSP2) (Riahi *et al* 2017). The scenarios are differentiated along the three dimensions of near-term policy, long-term climate target and CDR availability (see table 1 for an overview of the scenario set).

The scenario set considers four different cases of **near-term policy** developments. The two benchmark cases of moderate and high near-term ambition are commonly used mitigation scenario designs (Fawcett *et al* 2015). They comprise a scenario following the conditional NDCs until 2030 and thereafter transitioning to global carbon pricing towards the Paris goals (called '*NDCs*' in the following), and a scenario with a near-term phase-in (2020–2040) of cost-effective global carbon pricing to reach the Paris goals without pursuing additional policies as suggested in the NDCs ('**Cost-effective pricing**'). The cost-effective pricing scenario shows greater emissions reductions until 2030 due to the earlier adoption of global carbon price levels in line with the Paris goals (supplementary material figure S2). Such scenarios have been used as near-cost-optimal benchmark to evaluate the emissions gap of the NDCs (UNEP 2016). The other two near-term policy cases explored in this study represent intermediate levels of near-term ambition. These policy scenarios pursue '*Good Practice*' and '*Net Zero*' policy packages, respectively, on top of the conditional NDCs until 2030 and thereafter transition to cost-effective global carbon pricing to reach the Paris temperature goals. The formulation of the two policy packages is motivated below.

The NDC scenarios as well as the Good Practice and Net Zero scenarios assume that until 2030, all countries follow their respective mitigation targets and anticipate a continuation of national ambition level afterwards, and only from 2035 onwards act with full foresight towards the long-term target. Cost-effective pricing scenarios already allow for anticipation of the long-term climate target after 2020.

We consider **two different long-term climate goals** in the scenario design. 2 °C targets are implemented as a bound on cumulative total CO_2 emissions from 2011–2100 of 1000 $GtCO_2$, implying a high likelihood (>66%) of staying below 2 °C if non-CO_2 GHGs are

Table 1. Overview of the scenario set that is differentiated along the three dimensions of near-term policy (horizontal), as well as long-term climate target and CDR availability. Please note that the three 1.5 °C scenarios with limited CDR and less than optimal short-term policies cannot be solved within our modeling framework, as even with diverging high carbon prices the long-term budget is exceeded.

		Near-term policy Increasing near-term policy ambition →			
Long-term climate target ↓	CDR assumption ↓	NDCs until 2030	Good Practice	Net Zero	Cost-effective carbon pricing
2 °C (1000 $GtCO_2$ 2011–2100)	Full availability	NDC-2 °C	GoodPractice-2 °C	NetZero-2 °C	Cost-effective-2 °C
	Reduced availability	*NDC-2 °C-redCDR*	*GoodPractice-2 °C-redCDR*	*NetZero-2 °C-redCDR*	*Cost-effective-2 °C-redCDR*
1.5 °C (400 $GtCO_2$ 2011–2100)	Full availability	NDC-1.5 °C	GoodPractice-1.5 °C	NetZero-1.5 °C	Cost-effective-1.5 °C
	Reduced availability	[n.a.]	[n.a.]	[n.a.]	*Cost-effectice-1.5 °C-redCDR*

mitigated in line with CO_2 (Clarke *et al* 2014). 1.5 °C targets are implemented as a more stringent bound of 400 $GtCO_2$, implying a greater than 66% likelihood of holding 2100 temperatures below 1.5 °C, but allowing for temporary overshoot of this temperature limit (Luderer *et al* 2018). Each of the two CO_2 budget are achieved by iteratively adjusting a global carbon price that is assumed to grow with 5% p.a. until 2060 and linearly thereafter. Regionally fragmented carbon prices in 2020 (for the cost-effective scenarios) or 2030 (for the other scenarios) converge to the globally harmonized carbon price over a 20 year period (see figure S2 in the supplementary material). GHGs other than CO_2 are priced equivalently to CO_2 throughout the 21st century based on 100 year global warming potentials from IPCC's Fifth Assessment Report.

Since the large-scale deployment of CDR technologies in deep mitigation pathways has raised a number of feasibility and sustainability concerns (Smith *et al* 2015), we calculated the scenarios for two different assumptions on the availability of CDR technologies. The full CDR scenarios allow the full use of the potential of afforestation and BECCS as endogeneously emerging from the REMIND-MAgPIE model. In the limited CDR scenarios, we limit the total amount of global land area available for afforestation to 375 million ha, the available purpose-grown biomass to 100 EJ yr^{-1}, and the maximum yearly CCS injection to 8 $GtCO_2$ (instead of 16 $GtCO_2$ in the full CDR cases).

Development of policy packages: the 'good practice' and 'net zero' policy packages identified in this study constitute a significant strengthening of the policy ambition of the NDCs. An overview of the two strengthened policy packages along with sector-level benchmark values are presented in table 2. The implementation of these strengthened policies is often driven by multiple factors including social, economic, competitiveness and development-related factors in addition to climate policy considerations. Since many of these policies include a broader set of priorities than GHG abatement, they supplement the typical carbon pricing policies in least-cost emission scenarios (Bertram *et al* 2015, von Stechow *et al* 2015).

The 'good practice' policy package assumes a global roll out of selected policies that are currently implemented successfully in some countries (Fekete *et al* 2015, Roelfsema *et al* 2018). The development of a good practice policy package for this study is an extension of (Fekete *et al* 2015, Roelfsema *et al* 2018), where benchmarks were derived for each (sub-)sector from countries that have implemented the best-in-class policies and that have resulted in significant deviation from business-as-usual emission development. By design, the good practice policy package can be regarded as implementable at least in some parts of the world because it is based on actions that some countries are already undertaking. However, policy plans and targets in some countries may not be immediately compatible with the political environment in other countries. A global roll-out of these policies would therefore need to be nationally determined and adapted to national circumstances. To this end, we assume some regional variation in the roll-out of selected policies with potentially high public costs (Inchauste and Victor 2017).

We here update and refine the 'good practice' benchmark values by examining existing policies mainly for major emitting countries, e.g. China, the EU, India, Japan and the U.S. First, existing policies were identified per (sub-)sector based on Kuramochi *et al* (2016) and CD-LINKS (2017), which conducted surveys to in-country experts to identify important policies for GHG emissions reductions including other relevant policies that were not primarily motivated by energy and climate policy goals. Other studies reviewed include Healy *et al* (2016) and den Elzen *et al* (2015). We then reviewed the literature on the impact of the identified policies. We also examined five–ten year historical trends of (sub-)sector-level energy and GHG emission indicators because it is often difficult, or not possible in some cases, to quantify net impact of policies. Based on this analysis, we selected policies that are effective and at the same time replicable in different parts of the world. The (sub-)sector benchmarks that are assumed achievable under the selected policies were used as 'good practice' values. Where the impact of key policies could not be directly quantified,

Table 2. Overview of sector-level benchmarks under strengthened policy packages. The rationale for these benchmarks are explained in the methods section as well in the supplementary online material. Corresponding values as resulting under the NDC and least cost well below 2 °C scenarios are shown as reference and can be compared to the numbers in paranthesis for good practice and Net-zero ranges are given for benchmarks that are differentiated across regions, specifications are given in supplementary material, section S2.

Sector	Current level (global values in 2015 given if not stated otherwise)	Good practice value (in 2030 if not stated otherwise)	Net-zero value toward 2030 (in 2030 if not stated otherwise	Conditional NDC value (moderate-ambition reference)	Value in well below 2°C cost-effective scenario (high-ambition reference)
Energy supply: renewables share in power generation	0.45 %-point/yr share increase	1.25–1.45 %-point/yr share increase	same as good practice	1.0%-point/yr (2020–2030 average)	2.5%-point/yr (2020–2030 average)
Energy supply: fossil fuel-fired power	270 GW coal power under construction	No new unabated coal power plants after 2023 (→123 GW coal 2020–2030 new installations)	No new unabated coal after 2018 beyond units under constr.; no new unabated gas after 2022–2032 (→24 GW coal 2020–2030)	278 GW of new unabated coal power (2020–2030)	24 GW of new unabated coal power (2020–2030)
Industry	Approx. 1%/yr energy efficiency (EE) improvement;	0.5%/yr additional EE improvement (→9% reduction of total final energy (FE) in 2030);	0.5%/yr additional EE improvement (→9% reduction in total FE in 2030);	5% reduction of total FE rel. to current policy in 2030;	14% reduction of total FE rel. to current policy in 2030
	No full scale commercial CCS	Approx. 200 MtCO_2 /yr CCS in industry.	Approx. 500 MtCO_2 /yr CCS in industry.	70 Mt CO_2/yr CCS in industry	200 Mt CO_2/yr CCS in industry
Buildings	1%/yr retrofit; Approx.	1.5-2.1%/yr retrofit; new buildings on average near zero energy by 2020–30;	3%/yr retrofit; new buildings on average near zero energy by 2020–25;	6% reduction of total FE rel. to current policy in 2030	15% reduction of total FE rel. to current policy in 2030
	1%/yr energy efficiency (EE) improvement for appliances and lighting	0.5%/yr additional EE for appliances and lighting; (→13% reduction of total final energy (FE))	0.5%/yr additional EE for appliances and lighting; lighting (→20% reduction of total FE)		
Passenger transport; freight transport; international shipping and aviation	EV share in new sales: <1%;	20–30% EV share in new sales;	65–75% EV share in new sales;	16% EV share;	33% EV share;
	LDV fuel economy: 20 km/l (Japan, 2013, test mode);	38 km/l for new LDVs; strengthened new freight vehicle fuel efficiency;	Fuel efficiency as good practice;	3% reduction of total FE rel. to current policy in 2030	9% reduction of total FE rel. to current policy in 2030
	1.4%/yr increase in bunker CO_2 emissions	Aviation EE improvement up to 2%/yr by 2020, cap emissions at a max of 2020 values for years >2020 (→13% reduction of total final energy (FE))	2.6%/yr aviation EE improvement and scale-up of biofuels use (→22% reduction of total FE)		
Agriculture	Anaerobic digester adoption: 10%;	30% adoption of anaerobic digesters;	same as good practice	Anaerobic digester adoption:20%	Anaerobic digester adoption:20%
	Nitrogen (N) use efficiency: 52%	10%-point increase of N use efficiency	same as good practice	N use efficiency: 4%-point increase	N use efficiency: 4%-point increase
Forestry and land use	6 million ha/yr net forest loss	End natural forest loss; 10 million ha/yr afforestation	same as good practice	End of natural forest loss in some countries; 7 million ha/yr afforestation	End of natural forest loss in 2020; 4 million ha/yr afforestation
Carbon pricing	Low to moderate carbon pricing in a few regions	at least 5$/t CO_2 in 2025, increase at 1$/year (higher for countries with existing carbon pricing) (→average price in 2030 at 22$)	at least 5$/t$CO_2$ in 2025, increase at 2$/year (higher for countries with existing carbon pricing) (→average price in 2030 at 27$)	Minimum price of 1$ until 2030, average price at 13$	Carbon prices between 47–50$/t CO_2 in 2030

we selected benchmarks based on techno-economic potential studies from the literature.

The 'net zero' policy package is more ambitious than the 'good practice' package, as it adds policies pushing for zero emission technologies particularly in energy end-use sectors in line with the Paris Agreement's goal to reach net zero CO_2 emissions in the second half of the century (Kriegler *et al* 2014, Rogelj *et al* 2015). It assumes global roll out of ambitious policy plans, strategies and targets that have been announced in recent years as well as a range of techno-economic studies on deep decarbonisation pathways, and represents the level of ambition of at least some of the actors. 'Net zero' benchmark values were set only for selected (sub-)sectors that are most relevant (Kuramochi *et al* 2018). The selection of (sub-)sector 'net zero' policies was conducted in similar steps as with 'good practice' policies.

The result (table 2) is an indication of the rate of change that may be achievable with sector-specific policies, many of which already successfully implemented in some countries. This is different to the technical mitigation potential that is shown in other studies (UNEP 2017).

REMIND-MAgPIE implementation of policy packages: the conditional NDCs are represented in REMIND-MAgPIE by a range of sector-level targets in the energy- and land-use systems, plus regional emissions targets on total GHG excluding land-use change CO_2 emissions where applicable (Roelfsema *et al* 2018). In regions where the sector targets by themselves are not sufficient to meet the emissions constraint, a region-specific residual carbon price to initiate the required additional emissions reductions is imposed. The Good Practice and Net Zero policy packages also represent a range of sector-level targets, and additionally assume regionally differentiated carbon prices that exceed those resulting from the NDC emission constraints (figure S2 in the supplementary material). We decompose the effect of strengthening carbon pricing vs. strengthening sectoral policies in the supplementary material (section S1.2). Both contribute roughly equal to the strengthening of 2030 emissions reductions in the Good Practive and Net Zero cases compared to the conditional NDCs (figure S3 in the supplementary material).

All sector-specific policies in the Good Practice and Net Zero policy packages are implemented as respective lower or upper bounds or additional equations, constraining the solution space of the model. So instead of representing direct national policies (for example feed-in tariffs for renewables), the desired outcome of such policies is represented (increasing renewable shares in power generation). This approach does not yield direct insights into distributional implications of different policy instruments, or other questions of policy design (e.g. whether or not feed-in tariffs, auctions, or performance standards work best for renewable support). Nevertheless, it leads to a more detailed representation of the near-term trajectories than a mere variation of carbon prices as sectoral mitigation shares are affected by the policy choice. In particular, our approach captures to what extent carbon lock-in can be avoided in the different sectors and how well upscaling of alternatives is prepared for by supporting policies. These are key features for analysing the benefits of strengthened near-term action for keeping long-term targets within reach (Bertram *et al* 2015).

It is important to note that efficiency targets in the buildings, transport and industry sectors are implemented by setting a maximum on total final energy use in the respective sectors. This forces the model solution away from the equilibrium energy use of the production function, leading to rather high GDP and consumption losses. These are most likely overestimated, given that some of the efficiency policies will, at least in the medium- to longer term, also have an effect on the autonomous energy efficiency improvement in these sectors which is not represented in the model.

Further information on the selection of policies as well as the translation of their impact into REMIND-MAgPIE calculations can be found in section S2 of the supplementary material.

Implementability assessment: the ability to implement climate polices can be affected by a range of factors which we group in five dimensions: the speed and the *scale* of the transition such policies aim to induce, the *disruption* they cause to existing trends and patterns, their economic *efficiency*, and their *distributional impacts* on socio-economic actors. For the first four dimension we identify a small set of indicators that serve as proxies for key implementation challenges and at the same time can be meaningfully implemented in the REMIND-MAgPIE model. The fifth dimension, distributional impacts, is a critical factor for assessing the political feasibility of implementing climate policy measures. The ability of evaluating distributional impacts of mitigation pathways derived from integrated assessment models is still limited, and an active area of research (see Bauer *et al* (2016), for an example). Here we look at a more narrow category, price changes for basic household goods, that are often drivers of distributional impacts.

Changes occurring at unprecedented pace (category '*speed*') might entail large adjustment costs or simply overwhelm the capabilities of societies as well as legal and institutional frameworks to adapt. An obvious high-level indicator for transition speed in the energy sector is *annual average emissions reduction rates from fossil fuel combustion*. But, also the land use sector may face rapidly *increasing demand for bioenergy and afforestation* in deep mitigation scenarios.

It may be difficult to undertake large-scale changes without new strains on society and the environment (category '*scale*'). *Deployment of CCS* has repeatedly been faced with public resistance even in the case of small-scale pilot projects. A wide variety of technically feasible CDR technologies, but also other decarbonization technologies could face similar resistance. The political acceptability of overshoot pathways relying on *net negative emissions* is particularly questionable in this respect. In addition, using large areas of *land for afforestation or bioenergy production* can be limited by sustainability concerns, such as biodiversity.

Costs that arise for concentrated interest groups, such as owners of fossil fuel reserves, coal-fired power plants, or energy intensive industries, as a result of disruptive changes in the energy system and other GHG-emitting sectors can make it politically difficult to trigger the necessary changes (Inchauste and Victor 2017) (category '*disruption*'). A high-level indicator for disruptive changes is the *change in CO_2 emissions growth rate* from one decade to the next. In addition, we consider *idle capacities of coal-fired power plants* as a disruption indicator.

In terms of '*efficiency*', we consider the overall macro-economic costs of mitigation policies as implied by the discounted stream of losses in household consumption. These are only direct economic costs that do not include economic benefits and co-benefits of mitigation policies from avoided damages due to reduced warming.

Table 3. Overview of implementability indicators. The indicator selection is discussed in the methods section and detailed definitions are provided in section 1.3 in the supplementary material. Maxima of decadal averages are taken over the period 2020–2050 (first six indicators). Please note that a visual representation of this data that more clearly shows the relative relationships is offered in figure 3.

Indicator		Disruption		Speed		Price Impacts		Efficiency	Scale		
		CO_2 trend break	Idle coal	CO_2 reduction	Landbio+aff inc	CO_2 price increase	Foodprice increase	ConsLoss	Cum CCS	Cum neg CO_2	Land bio+aff
Unit		Maximum change in gross CO_2 emissions reduction rate between decades [pp]	Maximum idle capacity of coal power plants in a given year [GW]	Maximum annual average emissions reduction rate per decade [%/yr]	Maximum annual average increase of land for affor. and bioen. crops [mha/yr]	Maximum annual average increase of carbon price per decade [$/t$CO_2$/yr]	Maximum annual average increase of food price index per decade [%/yr]	Cumulated discounted consumption loss expressed in % of cumulated baseline consumption	Cumulative CCS deployment over 21st century ($GtCO_2$)	Cumulative net negative emissions over 21st century ($GtCO_2$)	Global area for affor. and bioenergy crops (in 2050) [mha]
Implementation challenge		Employment, costs for concentrated interest groups	Employment, costs for concentrated interest groups	Adjustment costs, adoption of legal and institutional frameworks	Adoption of legal and institutional frameworks	Costs for concentrated interest groups as well as the broad public	Food security	Overall mitigation costs	Public attitudes, risk perception	Public attitudes, risk perception, finance	Additional sustainability concerns (e.g. biodiversity)
NDCs	2°C Full CDR	**3.4**	985	4.3	25	9.1	3.1	1.9	722	393	557
Good Practice	2°C Full CDR	2.5	820	3.8	23	7.6	2.7	1.9	719	312	533
Net Zero	2°C Full CDR	3.3	812	3.3	20	6.7	2.3	2.1	718	251	504
Cost-effective	2°C Full CDR	3.8	976	2.9	18	4.6	2.5	1.8	691	207	437
NDCs	1.5°C Full CDR	**4.6**	985	5.6	43	20.0	6.1	3.4	878	825	909
Good Practice	1.5°C Full CDR	3.2	820	5.1	38	17.3	5.3	3.2	864	745	839
Net Zero	1.5°C Full CDR	3.3	814	4.6	34	15.0	4.9	3.3	861	698	775
Cost-effective	1.5°C Full CDR	4.7	1051	4.0	23	8.2	3.8	3.0	826	557	661
Scenarios with reduced CDR availability											
NDCs	*2°C Red CDR*	***4.9***	985	5.8	31	31.2	6.9	3.6	457	224	546
Good Practice	*2°C Red CDR*	3.5	821	5.3	25	24.0	5.8	3.3	451	155	536
NetZero	*2°C Red CDR*	3.3	814	4.6	24	19.8	5.6	3.2	457	117	525
Cost-effective	*2°C Red CDR*	4.6	1051	3.8	22	8.4	3.8	2.6	454	20	506

Finally, concerns about who bears the costs of emission reductions and how quickly affected actors may be able to adapt to price increases determine whether mitigation polices are seen as equitable, which can be expected to influence their implementability (category '*price impacts*'). For instance, rising *food prices* resulting from competition for arable land for biomass and food production could endanger food security. Energy price inceases predominantly affect low income household. We use the *decadal increase in carbon prices* as proxy for the price impact of climate policies. The exact definitions of the implementability indicators are described in the supplementary material.

Results

Global warming can be limited to likely below 2 °C throughout the 21st century in all four policy scenarios with both full and reduced CDR availability. Limiting warming to 1.5 °C by 2100 can also be achieved in all four policy scenarios by our modeling framework if CDR is fully available. However, when restricting CDR, 1.5 °C pathways could only be identified for the cost-effective pricing scenario introducing comprehensive carbon pricing directly after 2020. Mid-century global carbon prices are about twice as high in 1.5 °C pathways than in well below 2 °C pathways with full CDR (table S1 in the supplementary material). For both temperature goals, strengthening near term ambition from 'NDCs' to 'Net Zero' can reduce mid-century carbon prices by around 30% to levels comparable to those found in the cost-effective scenarios. Restricted CDR availability rewards the strengthening of near term action more strongly and pushes 1.5 °C to the limit of what can be reached even with comprehensive carbon pricing after 2020 (Luderer *et al* 2013, Strefler *et al* 2018).

Impact on emissions: the 'good practice' and 'net zero' policy scenarios provide significant additional emissions reductions in 2030 compared to the NDC scenario (figures 1 and S1). We project the NDCs to reach 43 $GtCO_2$ and 57 $GtCO_2$equivalent emissions (including non-CO_2 GHGs) in 2030 within the range of literature estimates (Fawcett *et al* 2015, Rogelj *et al* 2016, 2017, den Elzen *et al* 2016, UNEP 2017, Benveniste *et al* 2018). The additional emissions reductions of ca. 8 $GtCO_2$ / 10 $GtCO_2$eq in 2030 in the 'net zero'scenario (figure S3 in the supplementary material) close a large part of the emissions gap to the cost-effective scenarios in this study and the benchmark value of 40 $GtCO_2$eq emissions stated in the Paris Decision (UNFCCC 2015) and based on the IPCC's Fifth Assessment Report (Edenhofer *et al* 2014). This is achieved with a very different policy mix than in the cost-effective carbon pricing scenarios.The mix is characterized by a substantial strengthening of technology and efficiency policies while regional carbon pricing is only moderately strengthened compared to the NDC scenario (see figure S2 in the supplementary material for regional carbon price levels in the four policy scenarios). Strengthened regulation and strengthened carbon pricing contribute roughly equal to the additional emissions reductions in 2030 (section S1.2 in the supplementary material and figure S3). In the cost-effective pricing scenarios, emission levels fall to 30 $GtCO_2$ / 41 $GtCO_2$eq in 2030 for the likely below 2 °C with full CDR availability, 26 $GtCO_2$ / 37 $GtCO_2$eq for both the likely below 2 °C with restricted CDR and 1.5 °C with full CDR, and 15 $GtCO_2$ / 25 $GtCO_2$eq for 1.5 °C with restricted CDR. One of the lowest emission pathways put forward in the literature to date reach levels of 20 Gt of CO_2 emissions in 2030 (Rockström *et al* 2017), in between what we obtain for the cost-effective 1.5 °C pathways with full vs. restricted CDR as well as in between the cost-effective 1.5 °C vs. 2 °C pathways with restricted CDR.

The 'Good practice' and 'Net Zero' policy scenarios mitigate the trend break in the NDC scenario between the periods 2020–2030 and 2030–2050 (figure 1, lower panel). This is also true for economic quantities like electricity sector investments (figure 2). A more steady increase in low carbon electricity investments over the next decades enhances the implementability of the electricity sector transformation compared to more rapid redirectioning of investments around 2020 (in the case of the cost-effective scenarios) or 2030 (in the case of the NDC scenario).

Implementability of pathways: we assess the political implementability of the mitigation scenarios with the indicators introduced above relating to *speed*, *scale*, *efficiency*, *price impacts*, and *disruptiveness* of the transition (table 2 and figure 3). They display clear trends across the four policy scenarios. The NDC scenario performs worst in almost all implementability dimensions, confirming earlier findings that a delay of mitigation action until 2030 implies disruptive changes in 2030, very large transition speeds after 2030 and substantial CDR deployment in the second half of the century to limit warming to 1.5 °C–2 °C by the end of the century (Kriegler *et al* 2013, Luderer *et al* 2013, Riahi *et al* 2015, Fawcett *et al* 2015, Strefler *et al* 2018). In contrast, the cost-effective pricing scenario performs best in most dimensions, with the notable exception of disruptiveness. Here it performs similar or even worse than the NDC scenario due to a rapid increase in carbon prices during the period 2020–2030.

The 'Good practice' and 'Net zero' scenarios are less disruptive than both the 'NDC' (in 2030) and 'Cost effective' scenarios (see also the example of annual changes in investments in renewable power technologies, supplementary material section S.1.3.2). This points to their ability to smooth transitional breaks and serve as entry points to ratcheting up climate policy plans. However, they score less favorable than cost-effective pricing in other dimensions. While 'Good practice' and in particular 'Net zero' can

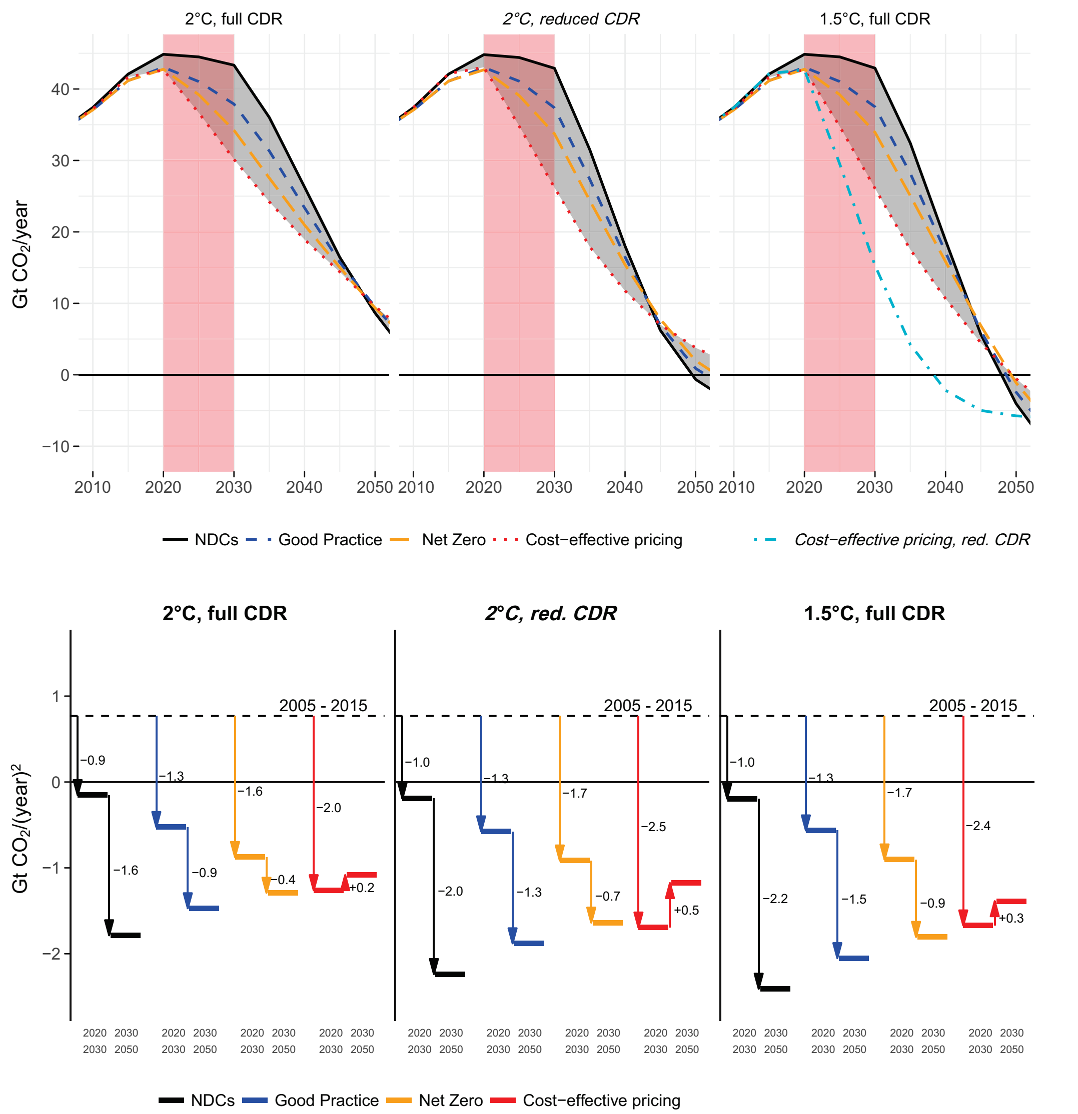

Figure 1. The upper panel shows global net CO_2 emissions trajectories towards the well below 2 °C target with full (left) and limited CDR availability (center) and towards the 1.5 °C target with full CDR availability (right). The lower panel highlights the associated annual net CO_2 emissions growth rates for the periods 2020–2030 and 2030–2050 and the change in growth rates between the two periods and the reference period 2005–2015. Please note that the right side of the upper panel additionally includes the emission trajectory of the Cost-effective-1.5 °C-redCDR scenario in light blue, in the same graph as the 1.5 °C scenarios with full CDR availability.

mitigate the impact of delay on transition *speeds* compared to the 'NDC' scenario, they still require higher maximum decadal emissions reduction rates in the energy sector, faster expansion of land for afforestation and bioenergy crops, and higher CO_2 prices increases than the cost-effective scenarios. This finding holds also for the annual increase in renewable power deployment (supplementary material, section S.1.3.2).

A less pronounced picture emerges for the *scale* indicators. While cumulative CCS use is virtually unchanged across the four policy scenarios, land use for bioenergy and afforestation and in particular the cumulative amount of net negative emissions, and thus the degree of temperature overshoot, varies from 'NDC' (highest) to 'Cost effective' (lowest). However, 'Net Zero' performs almost equally well than 'cost-effective' scenarios for likely below 2 °C, only for 1.5 °C does it lead to higher net negative emissions and land use.

The 'Good practice' and 'Net zero' scenarios also mitigate the *price impacts* compared to the NDC scenario, even though maximum food and carbon price increases in a single decade are still higher than in the cost-effective scenario. Notably, the two regulatory policy scenarios have similar or—in the case of 2 °C with full CDR—even higher macro-economic costs than the NDC scenario. This highlights the fact that regulatory policies can lead to lower distributional challenges associated with direct price impacts even though they incur higher macro-economic costs (Bertram *et al* 2015).

These rankings are robust across the three cases of the likely below 2 °C limit with full and restricted CDR availability and the 1.5 °C limit with full CDR availabilty. In general, restricting CDR availability limits—by definition—cumulative CCS and net negative emissions (*scale*), but increases the magnitude of

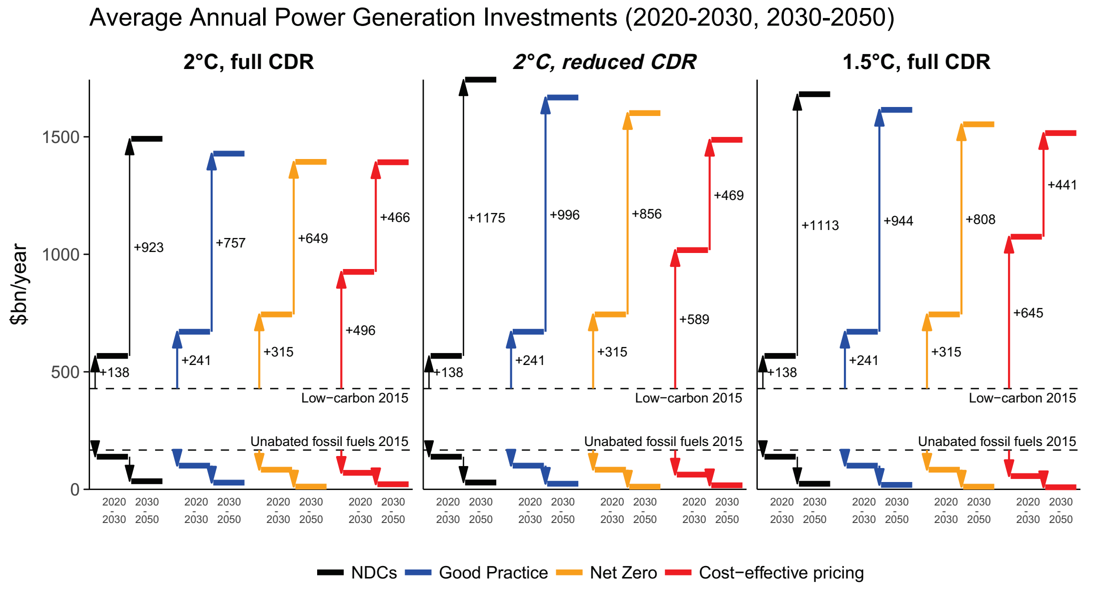

Figure 2. Annual average investments for the periods 2020–2030 and 2030–2050 in low carbon power technologies (upper part; including renewable and nuclear power and fossil fuel power plants with CCS) and unabated fossil fuel power plants (lower part) as well as changes in investment levels between the two periods and between 2015 and 2020–2030.

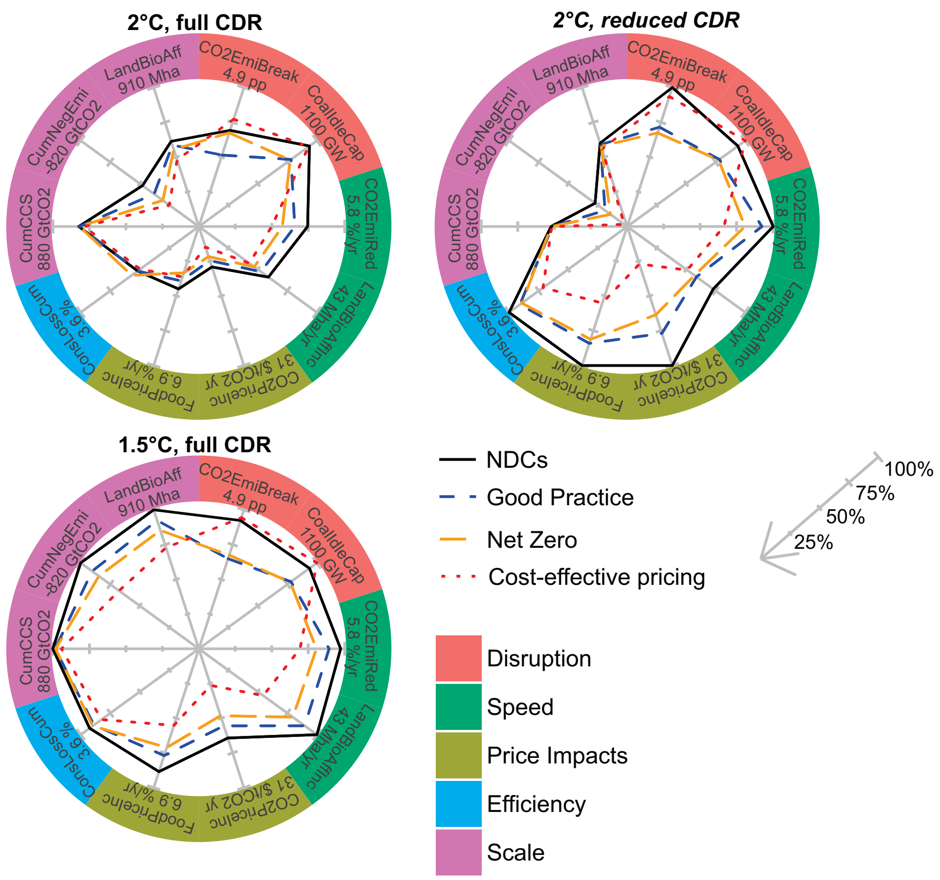

Figure 3. 'Implementability profiles' of the four policy scenarios for likely below 2 °C and full CDR availability (top left), well below 2 °C and reduced CDR (top right) and 1.5 °C and full CDR (bottom left). Each of the axes of the spider diagrams describes one of the implementability indicator (see table 2 for definitions and temporal scope). Axes are scaled from 0 (origin) to the maximum indicator value across all scenarios specified below the indicator name. Axes are grouped according to indicator categories (see colour legend). Please note that the same data is provided in table 2 in terms of absolute values.

the transition *speed* and *disruptiveness* indicators, in the cases of food and carbon prices by more than a factor of two. The food price result is counterintuitive and due to the fact that continued strong demand for biofuels keeps land demand at similar levels as for unrestricted CDR, while higher emissions prices impose an additional penalty on agricultural production (Stevanović *et al* 2017).

Implementation challenges of 1.5 °C pathways are larger than for likely below 2 °C pathways in all dimensions, particularly concerning *scale* (50%–60% more land demand for BECCS and afforestation and 110%–180% more net negative emissions) and *speed* (30%–70% higher maximum increase in land demand per decade for BECCS and afforestation and 30%–40% higher maximum emissions reduction rate). Generally, we find the differences in implementation challenges between 1.5 °C–2 °C to be larger than the effect of different near-term policy stringency. The benefit of strengthening early action with the 'good practice' and 'net zero' policy packages increases for restricted vs. full CDR availability and for 1.5 °C vs. likely below 2 °C particularly with regard to rapid trend breaks in CO_2 emissions (disruptiveness).

Discussion and conclusions

We find that the 'Good practice' and 'Net Zero' policy packages to strengthen the NDCs could provide a bridge towards achieving the ambition of the Paris Agreement. Although economy wide carbon pricing would be the economically most efficient policy to achieve emission reductions, it could be politically difficult to implement in the short term, for instance due to stranded assets and job losses in some sectors resulting from a strong increase of carbon prices. The policy packages consisting of a range of measures and sector targets may be favoured because of less direct visibility of mitigation costs as well as policy makers' experience with or ideological preference for non-market policies (Drews and Bergh 2016). Combinations of different policies and sector targets, such as the packages described above, could hence facilitate the implementation of the Paris Agreement. They would lead to fewer disruptive changes with less distributional implications, slower transition speeds, lower land demand and lower overshoot than following the NDCs until 2030. Without such near term strengthening of the NDCs, the temperature goals of the Paris Agreement may be no longer in reach in 2030. The policy packages might also serve to achieve a broader set of sustainable development objectives that are central for real-world policy-making (Jakob and Steckel 2016, von Stechow *et al* 2016).

However, with increasing ambitions the lower economic efficiency of such policy packages can be expected to aggravate the trade-offs between economic efficiency and political feasibility and become a major obstacle for the implementation of climate policies. This trade-off can be reduced if successful short-term policies result in ambitious long-term carbon pricing schemes. Hence, they should be regarded as entry points and complements to carbon pricing, not as viable alternatives in the long-term.

The study presented here is only a first step in connecting the analysis of mitigation pathways towards the Paris climate goals with an assessment of the implementability of near to medium term (2020–2050) climate action that would be consistent with these pathways. More research will be needed to better describe distributional impacts in mitigation pathways and to consolidate a set of meaningful implementability indicators for evaluating the scope of climate policies to initiate deep emissions reductions. A strengthening of current climate policy plans will be needed to keep the door open for reaching the Paris climate goals. Thus, the identification of climate policy portfolios that can serve as entry points to deep mitigation pathways is critical. Here we have shown that ambitious regulatory policy packages in combination with initially moderate, but increasingly ambitious carbon pricing could be a candidate for such entry points. Much will depend on the extent to which the climate policy portfolios can be tailored to address a broader set of sustainable development goals beyond limiting future climate change.

Acknowledgments

The research leading to these results was supported by the German Federal Ministry of Education and Research under grant agreement 01LS10A (PEP1p5). The authors declare no conflict of interest.

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