Limited impact of COVID-19 recovery packages on near-term CO2 emissions pathways

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Abstract

Part of the economic recovery plans implemented by governments following COVID-19 is directed towards the energy transition. To understand the potential effects of these post-COVID green recovery packages on reductions of greenhouse gases emissions, we investigated three different approaches. Firstly, we analysed simulation results of Integrated Assessment Models (IAMs) to infer the change in CO2 intensity of GDP that could result from post-COVID low-carbon investment plans. Secondly, we investigated the scenarios provided by the International Energy Agency (IEA) based on a bottom-up energy system model. By combining the two approaches, we found that green recovery packages implemented and planned globally can lead to an emission reduction of merely 1%-6% from 2030 baseline levels at most. Thirdly, we looked into the results of the Adaptative Regional Input-Output model, which simulates the dynamic effects of economic crisis and fiscal stimuli through supply chains following labour shortage. The third approach shows that the increase of activity driven by fiscal stimuli leads to a rebound of CO2 emissions even if they do not target carbon-intensive sectors. We conclude that green recovery packages targeting low-carbon technologies have a limited impact on near-term CO2 emissions and that demand-side incentives, as well as other policy efforts to disincentivise the use of fossil fuels, are also important for scaling up climate mitigation.

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Keywords : COVID-19, Green stimulus packages, energy investments, Integrated assessment models, emission pathways

Abstract

Part of the economic recovery plans implemented by governments following COVID-19 is directed towards the energy transition. To understand the potential effects of these post-COVID green recovery packages on reductions of greenhouse gases emissions, we investigated three different approaches. Firstly, we analysed simulation results of Integrated Assessment Models (IAMs) to infer the change in CO_2 intensity of GDP that could result from post-COVID low-carbon investment plans. Secondly, we investigated the scenarios provided by the International Energy Agency (IEA) based on a bottom-up energy system model. By combining the two approaches, we found that green recovery packages implemented and planned globally can lead to an emission reduction of merely 1%-6% from 2030 baseline levels at most. Thirdly, we looked into the results of the Adaptative Regional Input-Output model, which simulates the dynamic effects of economic crisis and fiscal stimuli through supply chains following labour shortage. The third approach shows that the increase of activity driven by fiscal stimuli leads to a rebound of CO_2 emissions even if they do not target carbon-intensive sectors. We conclude that green recovery packages targeting low-carbon technologies have a limited impact on near-term CO_2 emissions and that demand-side incentives, as well as other policy efforts to disincentivise the use of fossil fuels, are also important for scaling up climate mitigation.

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1. Introduction

To foster the economic recovery in the aftermath of the COVID-19 crisis, stimulus plans exceeding 18 trillion USD in March 2022 were adopted by 89 countries with 95% of the funding concerning advanced economies and China (O'Callaghan et al., 2021). These countries have also committed to strongly reducing their greenhouse gas emissions, in line with the Paris Agreement targets that require a rapid phase-out of fossil fuels and enhanced investments in low-carbon sources (Tanaka and O'Neill, 2018). Many scholars have thus advocated for a "green recovery" that would take advantage of this unprecedented amount of public spending to restart the economy on a more sustainable basis (Andrijevic et al., 2020; Hepburn et al., 2020; Li and Li, 2021). The design of recovery measures is critical to reducing CO_2 emissions (Hepburn et al., 2020). At the beginning of the crisis, Hepburn et al. (2020) provided a qualitative assessment of possible recovery measures based on three indicators: the impact on growth, the climate impact, and the speed of implementation. However, they did not provide quantitative insights on them. Andrijevic et al. (2020) (thereafter, A20) advocated for a fraction of the fiscal stimulus to be dedicated to the energy transition, as they estimated that additional low-carbon investments amounting to 300 billion USD/year during the 2020-2024 period were needed to put the world on a pathway to limit the global warming to 1.5°C. Tanaka et al. (2022) analysed this assessment and argued that the required total energy investments can be larger in the near term, that energy investments must be sustained over the long term, and that other measures (in particular, high carbon pricing) are also needed to accompany energy investments. Using two IAMs, Rochedo et al. (2021) showed that recovery investments would reduce emissions only by 3%-7% of the amount required by 2030 to achieve the 1.5°C target. These two studies will be discussed further in Section 4.

The objective of our study is to further assess the impact of stimulus packages on near-term emission pathways by analysing and comparing three different approaches. The first one builds upon A20, focusing on the impacts of low-carbon investments on CO_2 emissions. Correlations between low-carbon investments and the carbon intensity of GDP (the quantity of CO_2 emitted per GDP unit) from IAM results [8] are combined with an analysis of post-COVID recovery investments in low-carbon technologies (O'Callaghan et al., 2021) to infer resulting emissions reductions. The second approach is the World Energy Outlook (WEO) reports of IEA published in October 2020 (IEA, 2020) and 2021 (IEA, 2021), which describe how different policies enforced in the post-COVID era can shape future energy scenarios. The third approach is that of (Shan et al., 2021) (thereafter, S21) who focus on emissions rebounds following fiscal stimuli with a model simulating the propagation of disruptions along supply chains.

2. Methods

2.1 Diagnostics from IAM scenarios

The first approach exploits the relationships between the increase of investments in low-carbon technologies and the associated decrease of the carbon intensity of GDP simulated by six IAMs driven by carbon prices: AIM/CGE, IMAGE, MESSAGEix-GLOBIOM, POLES, REMIND-MAgPIE, and WITCH-GLOBIOM, as provided in McCollum et al. (2018) (thereafter, M18). Four scenarios are considered for each model: a scenario reflecting current policies, a scenario where Nationally Determined Contributions (NDC) are implemented, and two scenarios with global carbon budgets of 1,000 and 400 $GtCO_2$ until 2100, corresponding to 2°C and 1.5°C targets, respectively. The model results are available at the regional level, with the following five aggregated regions: OECD90+EU (OECD as it was in 1990 and EU countries), REF ("Reforming economies" indicating the former Soviet Union), LAM (Latin America), MAF (Middle East and Africa), and Asia (remaining Asian countries, including China).

M18 quantified the investments in the energy system required to achieve these climate goals through carbon pricing while developing energy supply across the 21st century and minimised the total discounted cost of mitigation (intertemporal optimisation) or the step-by-step costs supported by the economy (recursive dynamics). These costs include investments, fuel costs, operation and maintenance costs, and welfare loss due to lower consumption. Satisfying the carbon budget constraint requires high carbon prices, incentivising investments in energy efficiency and low-carbon energy sources, disincentivising carbon-intensive energy production, and reducing energy demand. This in general leads to a decrease in the CO_2 intensity of GDP. Low-carbon investments are thus negatively correlated with the CO_2 intensity of GDP in 2030 across the scenarios, both at the global and regional levels (**Erreur ! Source du renvoi introuvable.**).

To calculate the CO_2 emission reduction in 2030 for given low-carbon investments, we follow two successive steps. First, for each model and region, we linearly regress the carbon intensity of GDP in 2030 (in $kgCO_2$ per USD2020) against the cumulative low-carbon investment over 2021-2030 across all scenarios. Second, for each model, we apply these relationships on a region-by-region basis to calculate the reduction of the carbon intensity of GDP for given low-carbon investments and deduce the emission reduction by using the GDP growth forecast of the International Monetary Fund (IMF). Considering CO_2 intensity per GDP unit enables us to account separately for the effects of i) low-carbon investments on carbon intensity and ii) COVID-19 and fiscal stimuli on economic activity, which are already included in the IMF analysis. Low-carbon investments over 2021-2030 should decrease CO_2 emissions after 2030 as well, but we focus on emission reductions until 2030. The emission reductions before 2030 were linearly interpolated. The method discussed here is useful for our purpose, but one should bear in mind that it carries certain limitations arising from the use of IAM simulations driven by carbon prices, among others (see Section 4).

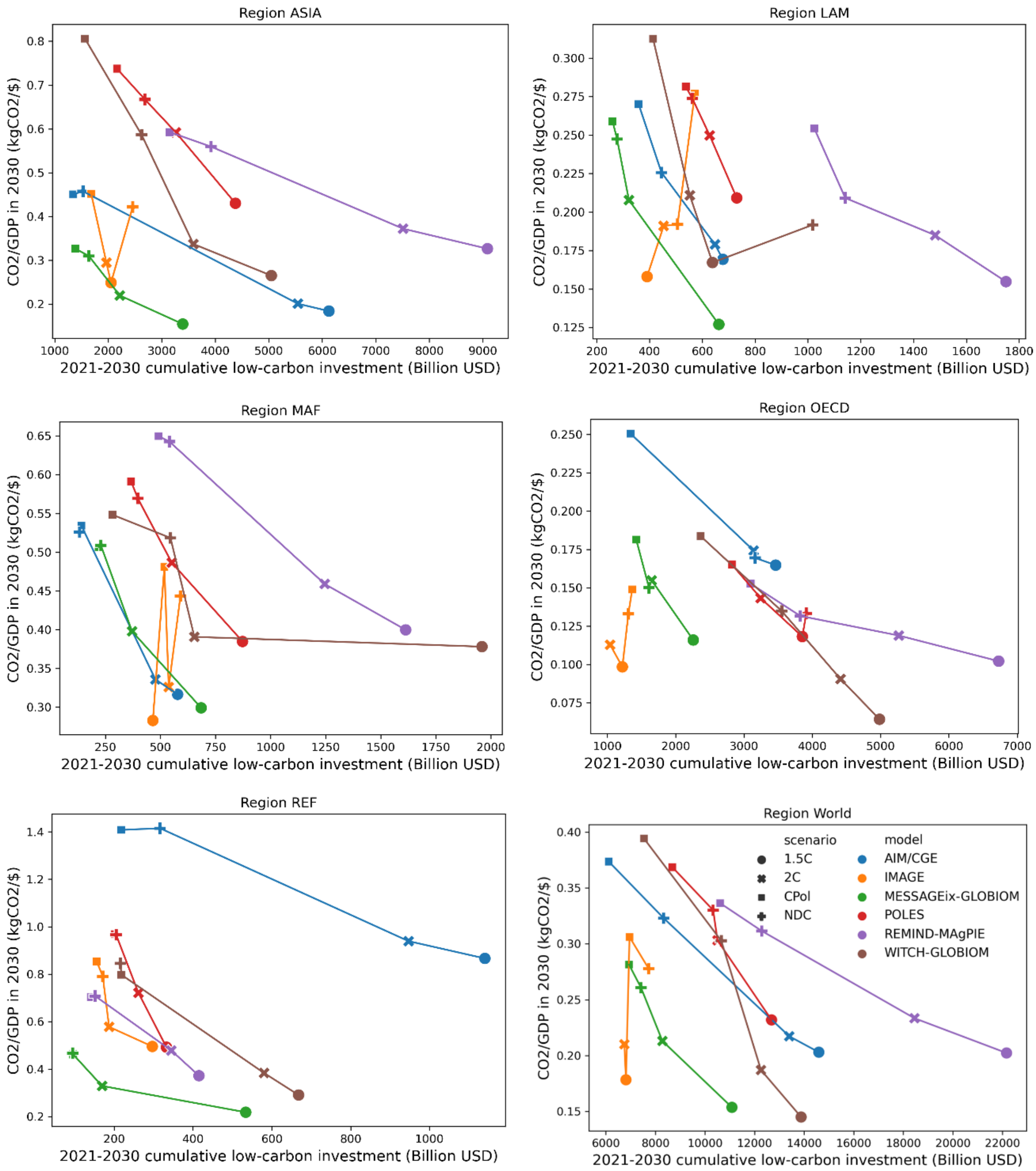

Figure 1: Relationship between the CO_2 intensity of the GDP in 2030 and the 10-year (2021-2030) cumulative low-carbon investment in billion USD obtained from IAMs in M18. The monetary unit is USD2020. Each curve is composed of four points, one for each scenario, each panel is for a different region: Asia, LAM: Latin America, MAF: the Middle East and Africa, OECD: OECD as it was in 1990 and EU countries, REF: former Soviet Union, and the whole world.

More technically, the regression slope $c_{r,m}$ represents the change in CO_2 intensity of GDP in 2030 (in $kgCO_2$/USD) in region *r* estimated from model *m*, accompanied by cumulative low-carbon investments of 1 billion USD between 2021 and 2030. Thus, increasing low-carbon investments by δI_r over this period yields a change in the regional carbon intensity of GDP, $\delta e_{r,m}$.

$$\delta e_{r,m}(2030) = c_{r,m} \cdot \delta I_r$$

As a result, the regional emission changes by $\delta E_{r,m}(2030) = \delta e_{r,m}(2030) \cdot GDP_r(2030)$. Regional GDP values in 2030 are based on IMF growth projections of October 2021 for 2021-2026 (IMF, 2021), extrapolated until 2030. The sum of $\delta E_{r,m}$ across regions gives the change in global emissions.

To estimate the increase in low-carbon investments until 2030, we use the classification of the Oxford Recovery Project (United Nations Environment Programme, 2021). In M18, low-carbon investments cover "investments into renewable electricity and hydrogen production, bioenergy extraction and conversion, uranium mining and nuclear power, fossil energy equipped with CCS, and the portion of electricity T&D and storage investments that can be attributed to low-carbon electricity generation". For consistency with IAMs, we consider investments only in the categories of "clean transport infrastructure, clean energy sector, building upgrades and energy efficiency as low-carbon investments within the recovery packages." The other categories of green public investments are not considered as low-carbon investments: namely, "clean research and development investment and natural infrastructure and green spaces investments", which are not modelled in IAMs analysed by M18. Recovery packages inventoried by the Oxford Recovery Project are just partly dedicated to low-carbon technologies: low-carbon investments amount to 511 billion USD, 20% of total recovery investments (Table 1).

Table 1: Total recovery investments by category. Data were obtained from the Oxford Recovery Project report, which reflected data available in the Oxford Recovery Observatory up to February 2022. In the Oxford Recovery Observatory, the total COVID-related fiscal spendings amount to 14.6 trillion UDS and fall into three categories: recovery spending, rescue spending, and unclear spending. Investments in "recovery spending" (total amount: 2.6 trillion UDS) are shown in Table 1. More details in SM 1

Type	Billion USD	Share
Low-carbon investments:	*511.2*	*19.7%*

Buildings upgrades and energy efficiency infrastructure investment	52.8	2.0%
Clean energy infrastructure investment	153.2	5.9%
Clean transport infrastructure investment	303.2	11.7%
Clean new housing investment	2.0	0.1%
Other investments:	*2080.5*	*80.3%*
Clean research and development investment	59.7	2.3%
General research and development investment	366.1	14.1%
Local (project-based) infrastructure investment	206.9	8.0%
Natural infrastructure and green spaces investment	169.7	6.5%
Other large-scale infrastructure investments	438.4	16.9%
Traditional energy infrastructure investments	40.5	1.6%
Traditional transport infrastructure investments	604.0	23.3%
Disaster preparedness and capacity building	177.0	6.8%
Military investments	18.2	0.7%
Total	*2591.7*	

Table 2: Low-carbon recovery investments by region. Data were obtained from the Oxford Recovery Project report. See the caption of Table 1.

Region	δI_r(Billion USD)
ASIA	46.1
LAM	3.6
MAF	0.7
OECD	460.8
REF	0
Total	*511.2*

The CO_2 emissions pathway is obtained by subtracting the emission reduction from a baseline pathway that does not account for recovery packages. The IEA 'Stated Policies Scenario' from WEO (2020) (thereafter STEPS2020) is used as a baseline because it includes only a small fraction of recovery packages: low-carbon investments packages announced before mid-2020 amounted to 63 billion USD (O'Callaghan et al., 2021) when STEPS2020 was developed.

2.2 WEO scenarios of IEA

The second approach is based on the WEO reports from 2020 and 2021 (IEA, 2021, 2020). We consider the following three scenarios proposed by the IEA: STEPS2020, its update in 2021 (STEPS2021), and the Sustainable Development Scenario (SDS2020). STEPS are scenarios *“which reflects current policy settings based on a sector-by-sector assessment of the specific policies that are in place, as well as those that have been announced by governments around the world*.” STEPS2020 and STEPS2021 incorporate NDCs and recovery measures adopted before mid-2020 and mid-2021, respectively. SDS2020 has the same assumptions as those in STEPS2020 regarding economic growth, except that stringent climate and sustainable development policies are implemented in SDS2020: “*a surge in clean energy policies and investment puts the energy system on track to achieve sustainable energy objectives in full, including the Paris Agreement, energy access and air quality goals*”.

These storylines describe the evolution of the energy system until 2050, from the extraction of fossil fuels to final energy use, energy markets, and investments required to satisfy the energy demand. The storylines are implemented to the World Energy Model (WEM), a technology-rich and data-intensive model. WEM computes how the energy system evolves to meet exogenous energy demand without feedback on the economy. STEPS2020 and SDS2020 have the same GDP growth.

SDS2020 incorporates a plan (sustainable recovery plan) designed to foster economic recovery while mitigating climate change. This plan is a set of various climate policies, from regulatory frameworks to market design and fiscal incentives, modelled with high granularity. For instance, the lifetimes of nuclear plants are extended, stronger standards are applied to domestic appliance energy efficiency, coal-fired powerplants are retired early or retrofitted to capture and store carbon, and motorway speed is reduced. Decarbonisation is not primarily driven by public investment: governments create appropriate policy frameworks including carbon pricing, but 70% of these investments are realised by private companies and are thus assumed to come from private finance.

2.3 Adaptative Regional Input-Output model

The third approach developed by S21 analyses the impact of the pandemic and fiscal stimuli on global emissions. The description of the economic impact of the pandemic focuses on the propagation of shocks through supply chains, including the interdependencies across different sectors and regions. They applied to this case study an Adaptative Regional Input-Output model (ARIO) (Hallegatte, 2008), which is designed to study the economic consequences of disasters.

It describes the economy as a set of households and producers belonging to different sectors and regions. Households create the final demand, and the supply from producers creates an intermediate demand. The production by a sector Δ of a good α requires three production factors: exogenous capital, exogenous labour, and other intermediate goods. Initially, production meets demand. Then comes the pandemic and associated restrictions: a temporary labour shortage in sector ∆ leads the production of good α to decrease. Substitution between factors is assumed to be impossible as actors cannot make the necessary adjustments on time. The demand of ∆ for intermediate goods shrinks (backward propagation), as well as the downstream production that requires α (forward propagation). Firms can overproduce to rebuild their inventories to overcome the disruption, as labour and capital are not fully employed at pre-crisis production levels. Intermediate demand increases and then returns to the pre-crisis level. Furthermore, fiscal stimuli increase final demand: a 1 billion USD fiscal stimulus targeting sector ∆ is modelled as an increase of 1 billion USD of final demand for α. CO_2 emissions are computed as the sum over all sectors of their activities multiplied by their exogenous emissions factor. The global carbon intensity of GDP is therefore susceptible to vary as the weight of different sectors and regions in the global economy changes and as emissions factors evolve exogenously.

S21 analysed several emissions pathways, termed fiscal stimuli (FS) scenarios, which differ by the severity of the pandemic and the fiscal measures taken until 2024 to mitigate economic damages. They differ in three regards: (i) the size of stimuli ("current FS" as of mid-2020 and "FS+" where fiscal stimuli amount to 10% of 2019 GDP in major economies, both distributed until 2024), (ii) the distribution across sectors (either targeting high-technology sectors or heavy industry, or keeping the current distribution), and (iii) the evolution of the emissions factor of each sector, to account for climate policies beyond fiscal stimuli. Furthermore, three cases are considered for emissions factors: in one case, they remain at the current level (Carbon Intensive Scenario (CIS)). The other cases were derived from the WEO of 2019: emissions factors either evolve consistently with the SDS scenario (SDS emissions factors) or the Stated Policy scenario (SPS emissions factors).

The main difference between ARIO and the other model approaches considered here is that ARIO explicitly models dynamic changes in activity levels. This enables a realistic account of the economic decline and rebound following the pandemic, whereas partial or general equilibrium models like the IAMs in M18 might overestimate short-term flexibility and substitution possibility (Hallegatte, 2008). But, contrarily to these IAMs, there is no 'investment' in ARIO that could increase means of low-carbon production because capital is exogenous. Mitigation measures appear only through sectoral carbon intensities.

3. Results

3.1 Linear regressions between low-carbon investments and carbon intensity

While the goodness of fit is very high in a majority of IAMs, IMAGE displays poor correlations (Table 3). The regional regression slopes are highly model-dependent but negative throughout, except those of a few regions in IMAGE. Low-carbon investments are positively related to the carbon intensity of GDP in those regions of IMAGE because energy demands in IMAGE are so sensitive to the carbon price driving the simulations that energy demands shrink in response to high carbon prices, unlike those in most other IAMs (Tanaka et al., 2022). Poor correlations can also be seen in the results of WITCH-GLOBIOM, in which some regions are affected by the same phenomenon. Thus, the relationship between low-carbon investments and the carbon intensity of GDP holds only in a subset of IAM simulations we examine. For the sake of the analysis, we disregard these two models and apply the correlations estimated from other four models in the rest of this study.

Table 3: Estimates of $c_{r,m}$ (in (kgCO_2/USD) / (billion USD) of each model and region. $c_{r,m}$ represents the change in CO_2 intensity of GDP in 2030 (in kgCO_2/USD) associated with an increase of 1 billion USD in low-carbon investments during the period 2021 to 2030.

$c_{r,m}$	Model					
Region	AIM/CGE	IMAGE	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	WITCH-GLOBIOM
ASIA	-5.9×10^{-5}	-1.2×10^{-5}	-8.8×10^{-5}	-1.4×10^{-4}	-4.7×10^{-5}	-1.6×10^{-4}
LAM	-2.9×10^{-4}	6.1×10^{-4}	-3.1×10^{-4}	-3.8×10^{-4}	-1.2×10^{-4}	-1.5×10^{-4}
MAF	-5.1×10^{-4}	1.1×10^{-3}	-4.5×10^{-4}	-4.0×10^{-4}	-2.3×10^{-4}	-8.6×10^{-5}
OECD90+EU	-4.2×10^{-5}	1.1×10^{-4}	-7.1×10^{-5}	-3.5×10^{-5}	-1.3×10^{-5}	-4.6×10-5
REF	-6.4×10^{-4}	-2.2×10^{-3}	-5.2×10^{-4}	-3.7×10^{-3}	-1.2×10^{-3}	-1.2×10^{-3}

Table 4: ${R^2}_{r,m}$, the determination coefficient of the regression of the carbon intensity of GDP in 2030 against the cumulative low-carbon investment over 2021-2030.

${R^2}_{r,m}$	Model					
	AIM/CGE	IMAGE	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	WITCH-GLOBIOM
ASIA	0.995	0.001	0.946	0.999	0.992	0.914
LAM	0.971	0.851	0.944	0.999	0.907	0.387
MAF	0.985	0.339	0.953	0.979	0.992	0.551
OECD	0.994	0.463	0.920	0.851	0.948	0.998
REF	0.985	0.705	0.849	0.995	0.995	0.996

3.2 Emissions pathways

The emission reduction obtained from the first approach using our estimate of green recovery packages (Tables 1 and 2) is 0.5-2.2 $GtCO_2$/year in 2030, which represents merely a 1%-6% emission reduction from the baseline level (Figure 2). This reduction is small: for comparison, the 2030 emissions level in SDS2020 is 8.98 $GtCO_2$/year lower than in STEPS2020. This 2030 emissions reduction in SDS2020 of 25% from 2019 levels is within the range of emission pathways towards the 1.5°C target with high overshoot (IPCC, 2022).

Table 5: Emissions reduction in 2030 (in $GtCO_2$/year) calculated from its correlation with low-carbon investments found in the Oxford Recovery Project database.

Model	Emission reduction in 2030 ($GtCO_2$/year)	As a percentage of baseline emissions level in 2030
AIM/CGE	1.30	3.7%
MESSAGEix-GLOBIOM	2.22	6.2%
POLES	1.26	3.5%
REMIND-MAgPIE	0.46	1.3%

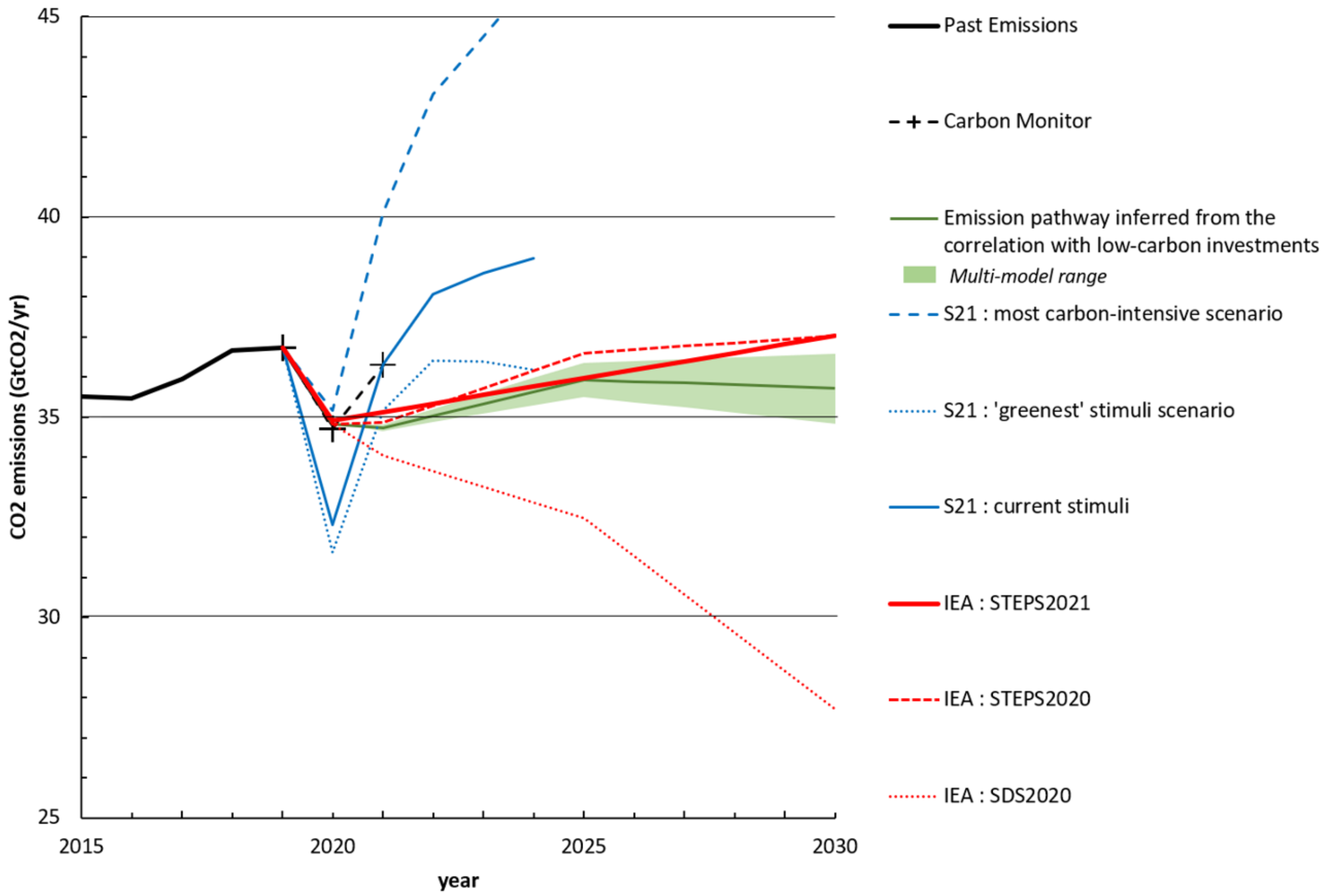

Figure 2: Global total anthropogenic CO_2 emissions pathways (in $GtCO_2$/year) until 2030. The black curve represents historical emissions until 2020 from the Global Carbon Project (GCP)(Friedlingstein et al., 2022). The black cross represents the estimate by the Carbon Monitor (Liu et al., 2020). The red curves are based on IEA WEO scenarios. The green curve represents the multi-model mean of emissions pathways obtained by subtracting the emission reduction based on the correlation with low-carbon investments from the STEPS2020 baseline. The green area represents the multi-model range of such emissions pathways. Blue curves are obtained from S21: The most carbon-intensive scenario has CIS emission factors, FS+ targeting heavy industries. The current stimuli scenario has current FS and SPS emissions factors. The 'greenest' stimuli scenario has current FS targeting high-technology sectors and SDS emission factors. All emissions pathways are adjusted to match the GCP estimates for 2019 (see SM 3 for scenario corrections).

3.3 Low-carbon investments and emission reductions

3.3.1 Investment and emission reductions in IAMs

The slopes of the linear regression (Figure 1, Table 3) can be used to infer the amount of low-carbon investment in each region between 2021 and 2030 required to reduce emissions by 1

tCO_2/year in 2030 [USD/(tCO_2/year)], which is given as $\frac{-1000}{c_{r,m} \times GDP_r(2030)}$ ($where\ GDP_r(2030)$ is in billion USD). At the global scale, low-carbon investments per tCO_2 of emission reduction in 2030 are obtained by dividing the global post-COVID low-carbon investments (Table 2) by the amount of resulting emissions reduction in 2030 (Table 5). This quantity was estimated to have a range from 230 to 1,120 USD/(tCO_2/year) across the IAMs, with a multi-model mean of 540 USD/(tCO_2/year).

The comparison between STEPS2020 and SDS2020 returns similar results: low-carbon investments during the 2021-2030 period in SDS2020 are higher by 570 billion USD/year than in STEPS2020. This corresponds to an additional cumulative investment of 5,690 billion USD. The emissions differ by 8.98 $GtCO_2$ in 2030, resulting in a low-carbon investment per tCO_2 reduction of 633 USD/(tCO_2/year).

By using the same IAM results as in our study (i.e. data from M18), A20 estimated that additional low-carbon investments of 300 billion USD/year until 2024 (hence, 1,500 billion USD until 2024) were required to put the energy system on track to achieve the 1.5°C target. Our corresponding estimate is 410-1,220 billion USD/year (see SM4). The A20 estimate is slightly below our range, which can be explained by the following methodological differences between the two studies. Firstly, when deriving the relationship between low-carbon investments and emission reductions from IAMs, A20 considered only 1.5°C and current policies scenarios till 2024 at global level, whereas our study considered four scenarios (including NDC and 2°C scenarios) till 2030 at regional level. Secondly, while A20 used the results from all available IAMs, our study excluded a subset of IAMs that exhibits energy demand being very sensitive to carbon prices. Thirdly, we incorporated the effect of GDP growth in estimating emission reductions, which was not considered in A20. Fourthly, the scope of low-carbon investments considered in A20 is wider than that in our study (and therefore that in M18).

We further note that, whereas A20 and our study reached similar estimates of required low-carbon investments, the two studies provide different yet complementary perspectives. A20 emphasized how little the required low-carbon investment is, compared to the massive COVID-related fiscal spendings, calling primarily for more green recovery investments. In contrast, our study focuses on the estimate of current green recovery packages and argues that current green recovery packages are inadequate for achieving the 1.5°C target of the Paris Agreement and highlights the need for other measures to support climate mitigation efforts, as discussed in the rest of this paper.

3.3.2 Fiscal stimuli and emissions in ARIO

We have a few remarks regarding the role of fiscal stimuli in S21. In the third approach, the main driver of emission levels is the assumed emissions intensity of each sector. In 2024, the emission levels in scenarios with SDS and CIS sectoral carbon intensities are about 8% lower and 20% higher than in the reference scenario (based on SPS carbon intensities, "current fiscal stimulus size", "current fiscal stimulus structure"). In contrast, the emission levels change by just less than 0.3% across different structures and sizes of fiscal stimulus for a given set of carbon intensities. Hence, varying the size and structure of fiscal stimuli has a minor impact compared to the choice of sectoral carbon intensities.

In the third approach, neither the size nor the structure of fiscal stimuli plays a decisive role: prioritising high-tech industries over heavy industries is insufficient to reduce emissions. This approach provides useful insights into the short-term emission decline and rebound following the pandemic through supply chains across different sectors and regions. However, such an approach is of lesser use to assess the role of fiscal stimuli on emission pathways involving the longer-term decarbonization of energy system because emission levels are essentially the direct outcome of the choice of sectoral carbon intensities, which are not driven by the fiscal stimuli.

4. Discussion and conclusions

This study provides insight into the claim that low-carbon investments included in the recovery packages will not induce a sufficient change in the energy system to achieve the Paris agreement targets (Rochedo et al., 2021; Tanaka et al., 2022; United Nations Environment Programme, 2021). It should however be noted that the use of the investment-emission relationships has three caveats. Firstly, it focuses on low-carbon investments, only a very small fraction of fiscal stimuli, leaving fossil fuel investments that also influence emissions. Secondly, fiscal stimuli in the real world can be only coarsely related to low-carbon investments in IAMs. Thirdly, low-carbon investments are just partially related to CO_2 emissions reductions in the results of IAMs that are driven by carbon prices. These imply that the use of the investment-emission relationships may lead to an overestimation of CO_2 emission reductions per unit investment. Each of the three caveats are discussed below.

Firstly, the investment-emission relationships only reflect a tiny part of the total fiscal stimuli (i.e. 511 billion USD of low-carbon investments for the total fiscal stimulus of more than 18 trillion USD). Although the recovery of economic activity through fiscal stimulus measures is factored into the estimates of GDP levels in 2030, this approach assumes that only low-carbon investments affect the emissions intensity of GDP. Measures supporting carbon-intensive industry within fiscal stimuli are neglected, as well as recovery investments dedicated to carbon-intensive sectors (40 billion USD for traditional energy infrastructure and 600 billion USD for traditional transportation infrastructures), but could increase the carbon intensity of GDP. Hence, the focus on low-carbon investments may lead to an overestimation of subsequent emission reductions.

Secondly, low-carbon investments in recovery packages cannot be related unambiguously to low-carbon investments in IAMs for two reasons: i) investments are not categorised in the same way between the Oxford Recovery Project database and IAMs, and ii) the allocation of investments across sectors and regions is different. Low-carbon investments modelled by IAMs are mainly supply-side investments (70% of low-carbon investments (IEA, 2020)). In contrast, the supply side represents only 30% of current low-carbon recovery packages through clean energy infrastructure investment (Table 1). The current regional allocation of the low-carbon investment package is different from the allocation in cost-effective mitigation pathways in IAMs. 90% of the low-carbon investments from recovery packages are deployed in OECD90+EU countries. 9% are deployed in Asia, less than 2% in Latin America, the Middle East and Africa, and 0% in the former Soviet Union. These mismatches of regional allocations will limit the global efficiency of the investments, as also pointed out in the latest version of the WEO (IEA, 2021) and the associated Sustainable Recovery Tracker updated in February 2022 (IEA, 2022). The use of the suboptimal investment allocation in the optimal IAM results implies that the amount of emission reductions for given low-carbon investments may be overestimated.

Thirdly, in the IAM results we analysed, low-carbon investments do not fully explain CO_2 emissions reductions because these IAMs are driven by carbon pricing that can induce changes in CO_2 emissions also through other pathways. In IAMs, an increase in carbon prices incentivises investments in energy efficiency and low-carbon energy sources, disincentivises carbon-intensive energy production, and reduces energy demand to satisfy the carbon budget constraint (Tanaka et al., 2022). The impact of low-carbon investments alone is limited: Rochedo et al. (2021) used IAMs that directly simulated low-carbon investments (i.e. without driven by carbon pricing) and has shown that, even if the recovery investments represent a significant part (17-35%) of the investments in low-carbon technologies until 2030, they reduce emissions by only a small fraction (3-7%) of what is needed to achieve the 1.5°C target. Low-carbon investment is only one of the levers mobilised in the models to achieve a given climate policy target. This also suggests that the use of the investment-emission relationships may lead to an overestimation of emission reductions.

Our numerical analysis based on the investment-emission relationship suggested that near-term CO_2 emission reductions to be realized through current green recovery packages would be insufficient for climate mitigation toward the 1.5°C target. The final discussion here further suggests that such emission reductions may even be an overestimate due to the methodological limitations. Counterbalancing the rebound of emissions stimulated by fiscal stimuli and ensuring emission reductions on a long-term basis requires broader measures to disincentivize the use of fossil fuels, incentivise demand-side requirements, and make the most of low-carbon investments deployed by governments.

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Conflict of Interest The authors declare no conflict of interest.

Data availability Data supporting the conclusions, Excel files and Python code used to generate the figures in the paper are available on Zenodo with https://doi.org/10.5281/zenodo.6554030

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