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Targeted green recovery measures in a post-COVID-19 world enable the energy transition

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Abstract

Despite the significant volume of fiscal recovery measures announced by countries to deal with the COVID-19 crisis, most recovery plans allocate a low percentage to green recovery. We present scenarios exploring the long-term impact of the COVID-19 crisis and develop a Green Recovery scenario using three global models to analyze the impact of a more ambitious allocation. The results show that a Green Recovery scenario, with 1% of global GDP in fiscal support directed to mitigation measures for three years, could reduce global CO₂ emissions by 10.5–15.5% below pre-COVID projections by 2030. The share of renewables in global electricity generation is projected to reach 45% in 2030, the uptake of electric vehicles would be accelerated, and energy efficiency in the buildings and industry sector would improve. However, such a temporary investment should be reinforced with sustained climate policies after 2023 to lead to socio-economic restructuring towards carbon neutrality by mid-century.

Introduction

The COVID-19 pandemic not only caused a global health and economic crisis but also had a substantial impact on CO₂ emissions. The response measures reduced global CO₂ emission levels in 2020 by about 6-7% compared to 2019¹⁻³ (with a slightly smaller impact on total greenhouse gases)⁴. To recover from the economic crisis, many countries have pledged large sums of money to stimulate the economy. This means that both the pandemic and the recovery measures could affect emissions for years to come. However, the exact impact is highly uncertain given the unpredictable future course of the pandemic and the uncertain implementation of the recovery measures. It is expected that emissions are likely to rebound if the COVID-19 crisis eases^{2,5}. However, the recovery spending could provide a unique opportunity to change this: If recovery packages would focus on accelerating the transition towards low-carbon energy and energy efficiency, it could be a significant boost in implementing the Paris Agreement. In contrast, investment in fossil fuel infrastructure would provide a possible further lock-in. Studies that can guide decisions on this issue are thus critically needed.

Some studies are already available: IEA's Sustainable Recovery report⁶, the analysis of fiscal stimuli and recovery scenarios by Shan et al.⁷, Pollitt et al.⁸ and Emmerling et al.⁹ and the work on single regions by Allan et al.¹⁰ and Lahcen et al.¹¹ However, these studies have by now used older data and used a single model for their analysis. This study aims to go beyond this earlier work by analysing the energy use, economic, and emission impacts of both the COVID-19-pandemic and potential green recovery packages using multiple models. For this purpose, we developed a Green Recovery scenario based on IEA's Sustainable Recovery approach but focusing on investments in measures that directly support sustainability growth. The scenario includes the most recent available data regarding the impacts of COVID-19 and currently adopted and implemented climate-relevant policies on energy use and emissions. We enhance the detail of previous analyses by examining regional and sectoral emissions, selected energy and macro-economic indicators that result from the implementation of our Green Recovery scenario. The use of three well-established global models enables comparing their results and identifying robust insights and policy-relevant recommendations.

Different prospects for green recovery measures

In the analysis, we compare three scenarios in order to assess the possible impact of a Green Recovery: 1) current policies in a pre-COVID situation (Reference), 2) current policies including the impact of COVID (COVID), and 3) the Green Recovery scenario. We implemented the scenarios in two macro-economic models (E3ME and GEM-E3-FIT) and one Integrated Assessment Model (IMAGE). The Reference scenario does not include the impacts of COVID-19. In contrast, in the COVID scenario, the short term (2020-2021) GDP growth rates were made consistent with official projections (including OECD, EC DG ECFIN and World Bank) by adjusting economic activity levels (consumer spending, investment, trade) and introducing sectoral shocks to reflect the observed COVID-19 impacts (Table 1). Both the Reference and COVID scenarios assume current climate policies to be implemented (taken from the public database on climate policies). The Green Recovery scenario, in addition, assumes the implementation of a post-pandemic green recovery strategy in major economies. We assumed that all countries dedicate 1% of their 2019 GDP (approximately 650 billion Euro) each year to green recovery measures between 2021 and 2023. This would mean devoting one-twelfth of the global COVID-19 rescue and recovery budget to green investments. The scenario

includes extended support for low- and zero-emission technologies and infrastructure (e.g., renewable energy, improvements in industrial processes and building efficiency) and surface transport electrification (Table 1). The split between different sectoral stimuli was based on the IEA's Sustainable Recovery report⁶. The selection of sectors and individual policies was decided based on the potential long-term benefits (improving energy system resilience and sustainability) and their current cost-effectiveness for emissions reductions. This means that the selection of policies diverges from the IEA's Sustainable Recovery report, aiming to maximize sustainability benefits and are more suitable for implementations for the models used here. Furthermore, the two macro-economic models allow us to capture the short-term macro-economic and employment impacts arising from the Green Recovery scenario implementation. A full description of the models, scenarios and underlying assumptions can be found in the Methods and Supplementary Data 2 and 3.

Table 1: Main assumptions and measures implemented per sector for the Reference, COVID and Green Recovery scenarios

Results

GDP trends post-COVID

We forced the two macro-economic models to reproduce the data on the 2020 impacts on economic activity: an 8% lower global GDP than pre-COVID forecasts (4.5% below 2019 levels) (Figure 1). The GDP projections further assume a V-shape recovery in growth terms or an L-shaped recovery in level terms after 2021 (based on a strong and effective vaccination programme and no further outbreaks). Consistent with the analysis of other institutes, both models suggest a permanent reduction of global GDP of around 5.5% by 2030 compared to the pre-COVID projection.

Figure 1: Global GDP and CO₂ emission projections. **a**, Global GDP (expressed in MER US\$) between 2015 and 2030 (normalised to 2015 levels), for all scenarios, as projected by the three global models. **b**, Global CO₂ emission projections from energy and industrial processes between 2015 and 2030, for all scenarios. The 2 °C scenario range shows the global CO₂ emissions from energy and industrial processes consistent with a least cost-pathway towards limiting global average temperature increase

below 2 °C by 2100 with about 66% probability¹². All results in the paper have not been adjusted with a harmonization process, and we show the original data. We find that harmonization towards 2019 global CO₂ emissions and GDP would reduce the range of results, as presented in Supplementary Figure 1.

Global and regional emission projections

The COVID scenarios of the three models show a significant impact of the pandemic on projected global CO₂ emissions from energy and industrial processes (Figure 1): a reduction of 5.5% to 7% below 2019 levels in 2020, which is consistent with most recent estimates²⁻⁴. The projected CO₂ emissions for the COVID scenarios of all models reach 2019 levels around 2024-2026. The COVID scenarios' emissions trend roughly follows the Reference trends, with global CO₂ emissions reaching between 5% to 8.5% below Reference levels by 2030. In other words, the Covid-19 pandemic in this scenario has led to a delay in emission growth but no change in the underlying dynamics.

Interestingly, under the Green Recovery scenario, global CO₂ emissions are projected to be reduced by 2.6 to 3.3 GtCO₂ below the COVID levels by 2030. Compared to the Reference scenario, the reduction in emissions is 4.7 to 7 Gt CO₂ by 2030 (about 10.5% to 16%). We discuss the detailed breakdown of the effect of the Green Recovery scenario on regional, sectoral and selected energy indicators later. The results show that the temporarily green stimulus (even if only a small share of overall recovery spending) can have long-lasting environmental benefits. In all models, the emission savings go beyond 2030 as the short-term green stimulus changes the trajectory of technologies (solar, wind, EVs, energy-efficient equipment) by encouraging increased adoption of these technologies and making them more cheaply available through learning effects. However, comparing with scenarios that stay well below 2 °C^{8,13}, it is clear that an investment peak of only three years is not sufficient to change the global emissions trajectory towards such a pathway on its own. A more sustained investment programme would be needed for that. The 2030 emissions gap between our Green Recovery scenario and the mean of the 2 °C scenarios ranges between 17% and 25%. The models also show somewhat different dynamics overtime – depending on the assumption on inertia in the energy system (IMAGE shows a slower response) (Figure 1). For a comparison with the IEA's results, see Supplementary Data 4.

Projected emission reductions in major emitting regions and countries follow the global trend (Figure 2). The Green Recovery scenario achieves an additional reduction of emissions compared to 2015 levels across all regions by 2030. Under the Green Recovery scenario, emissions in the non-OECD countries Brazil, China and India, are projected to increase in the Green Recovery scenario, but less so than the COVID scenario, leading to emissions levels of, on average across the models, 0.5%, 12% and 35% above 2015 levels by 2030, respectively (Compared to 10%, 24% and 50% under the COVID scenario). OECD countries, including the USA and Japan, are also projected to see a further decrease of emissions, 20% and 28% below 2015 levels by 2030, respectively. Our scenario shows that the EU especially, benefits from the increased stimulus package (that amounts to more than 2% of its 2019 GDP). For the EU, the Green Recovery package further reduces emissions relative to 2015 by an additional 5% to 8% compared to the COVID scenario, reaching a mean of 35% below 2015 levels by 2030 (about 50% below 1990 levels).

Figure 2: CO₂ emission projections for major emitting regions. CO₂ emissions from energy and industrial processes, relative to 2015 (%), per major emitting region (panel), for 2025 and 2030 (x-axis), for all scenarios (colour). Symbols indicate individual model results. The bars indicate model mean and were added for reporting reasons.

In terms of sectors, the largest direct impact of the COVID-crisis in 2020 occurred in the transport sector (with a reduction of 8% to 14.5% compared to Reference scenario levels across the three models), as restrictions led to extensive declines in aviation and surface traffic. Also, in terms of absolute emissions, under the COVID scenario, the transport sector was the primary source of emissions reductions in 2020, with a reduction of 0.6 to 1.2 Gt CO₂ compared to the Reference scenario across the three models, followed by the electricity sector (0.05 to 1 Gt CO₂) and industry (0.2 to 0.6 Gt CO₂). The buildings sector was responsible for a 0.02 to 0.2 Gt CO₂ reduction. Its contribution to total emissions was lower than the other sectors, as a decrease in service buildings emissions was compensated by higher residential emissions due to teleworking and forced lockdowns.

The green recovery policy scenario reduces emission in all sectors. The largest relative change between investments and emissions reduction occurs in the industry sector. A four times smaller amount directed to industry compared to the other sectors is projected to result in an additional 1% to 18% emissions reduction by 2030 compared to the COVID scenario. Investments in energy-

intensive sub-sectors within the industry, such as cement and steel production, can cause significant improvements in energy efficiency.

Investments in the electricity, transport and buildings sectors in the Green Recovery scenario can achieve added benefits to the COVID scenario, with emission reductions projected to range from 4.7% for transport to 6.6% for electricity in 2030 (see Supplementary Figure 2). In this scenario, additional capacity for electricity production from renewables is materialised, and better integration of renewable energy systems (solar PV and wind) in the grid is enabled. The number of electric vehicles (EVs) and efficient internal combustion engine vehicles (ICEs) are projected to increase (see the following section). Energy efficiency in buildings is similarly projected to be improved.

Changes in the energy system

Figure 3 shows the impact of the Green Recovery scenario on selected energy system indicators. The share of renewables in total electricity generation is projected to increase globally, accounting for 28% to 45% of global power generation in 2030, surpassing coal as the most prominent electricity-producing technology. In the transport sector, electrification is promoted as the uptake of EVs accelerates, with their share in global stock increasing by 21% to 23% in 2030.

Final energy use in industry is projected to decrease by 4% (mean) in 2030 compared to the COVID scenario, although remaining higher than 2015. The energy intensity of steel and cement production is highlighted because a relatively modest green stimulus amount is projected to reduce final energy use significantly. In the buildings sector, final energy use relative to 2015 levels is projected to be reduced by 2.5% (model average) by 2030. The long lifetime of buildings means that significant changes in both final energy use and emissions reduction cannot be easily attained in the short timeframe that we focus on.

Moreover, the assumed investment of 3 billion euros a year for the three years of the Green Recovery scenario in preventing methane leakages from oil and gas production could have substantial results. Methane leakages are projected to be reduced by 21% in 2030 compared to 2015, with an additional 1.3 Gt CO₂-eq avoided.

Figure 3: Selected global energy indicators. Projected changes in selected global energy indicators, for 2025 and 2030 (x-axis), for all scenarios (colour). **a, b**, Final energy use in the industry and buildings sector respectively, relative to 2015 (%). **c**, Share of renewables in electricity production (% of total). **d**, Share of electric vehicles (% of total). Symbols indicate individual model results. The bars indicate model mean and were added for reporting reasons.

Macro-economic and employment impacts

Our assessment shows that green recovery measures can boost activity growth in all countries triggered by increased investment in low-carbon technological options (including solar PV, onshore and offshore wind, electric vehicles, heat pumps, renovation) that offer a stimulus in global economic output. Global GDP is projected to increase by 1% to 1.5% for the duration of the stimulus until 2023 (triggered mainly through increased investments) and later by 0.2% to 0.5 % in 2025 and by the same percentage in 2030, relative to the COVID scenario (Supplementary Table 2). The green recovery measures bring lasting benefits to the global economy. Investment in new infrastructure, like electricity grids and energy-efficient buildings, would improve productivity while reducing fossil fuel

expenditure and driving down low-carbon technology costs through learning-by-doing effects. Costs of PV systems are decreased by 14% to 17% across models by 2030 compared to the Reference scenario, while wind energy system and EV costs decrease by 4% to 5% and 7% to 8%, respectively. As a result of green recovery and the resulting activity growth, employment is also projected to increase relative to the COVID scenario. Global jobs increase by about 1 to 10 million over 2025-2030.

GDP impacts of green stimulus are limited in the long term at a global level because there are both winners and losers from the transition. Countries that are net importers of fossil fuels and large low-carbon technology producers (e.g., EU, China) see increased GDP, as the reduced fossil fuel imports are replaced by domestic activities related to renewable energy supply and associated green jobs. In contrast, the socio-economic impacts are limited for the US and other energy-exporting countries. The green transition, both domestic and elsewhere, generates less demand for fossil fuels and reduced hydrocarbon export revenues.

What makes our green stimulus different from typical fiscal policy response to a crisis such as reduction in VAT is its long-lasting impacts on the environment. This occurs by speeding up low-carbon technology uptake by making renewable and efficient energy technology cheaper (learning effects). Without further stimulus, impacts on GDP and jobs beyond 2023 are mostly related to this technology transition. However, our results show that the transition will adversely affect groups of labour who are currently employed in the fossil fuel industries; therefore, net impacts on employment from the transition are limited.

While the green recovery measures have clear but limited socio-economic benefits for major emitting economies, they trigger large changes across sectors, pointing towards an economic restructuring away from carbon-intensive and fossil fuel supply. Our analysis shows that most of the new jobs induced by green recovery measures are created in the construction sector triggered by the increased installation of renewable energy technologies and retrofitting buildings. New jobs are also created in the manufacturing of clean energy technologies, particularly electric vehicles, solar PV, wind turbines and batteries. At the same time, other economic sectors (e.g., services, industry and agriculture) also indirectly benefit from cascade effects. In contrast, jobs are projected to decline in fossil fuel supply sectors, as the global consumption (and production) of fossil fuels is negatively impacted by green recovery measures (Figure 4).

Employment effects projected by macro-economic models depend on the extent to which wages adjust to labour demand modifications and the availability of skill formation. Previous analysis shows that the low-carbon transition may require relatively higher labour skills. However, this is not as large as many green occupations require only a minor 'topping up' of existing skills^{13,14}. As the labour market transformation induced by Green Recovery is not significant in magnitude (with maximum changes of about 0.5% of total jobs), the stresses caused to the labour market through skill shortages would be limited.

Figure 4: Changes in global employment. Changes in global employment by sector (in millions) induced by the Green Recovery scenario (based on E3ME results: left and GEM-E3-FIT results: right)

Discussion

The impact of the COVID-19 pandemic has already mobilised governments to announce substantial investments in economic recovery plans. The planned investments could potentially be used as an opportunity to foster a low-carbon transition if efficiently implemented in crucial energy, transport, and industry sectors. Our analysis suggests that under the Green Recovery scenario, emissions are projected to further reduce by 5.5% to 7.5% from the COVID scenario by 2030. Subsidies and technology learning stimulate the implementation of low-carbon technologies (solar, wind, EVs, energy-efficient equipment). This suggests that even a temporary stimulus package (that is only a small part of the total fiscal recovery packages announced globally to this point) can potentially achieve long-lasting environmental benefits. The share of renewables in total electricity generation is projected to increase in the Green Recovery scenario in all major economies. The uptake of electric vehicles accelerates, and final energy savings in industry and building sectors lead to more emission reduction. Our results show the importance of focusing policy on the industrial sector. Increasing the share of industry decarbonisation in stimulus packages would result in significant emission and environmental benefits – in our scenarios, a four times lower stimulus package in industry resulted in almost comparable savings in emissions with the other sectors. Finally, small investments in preventing methane leakages from oil and gas production also result in significant emissions reductions in a sector that was mostly unaffected by the pandemic⁶.

The increase in low-carbon investment provides a strong economic stimulus, thereby promoting GDP growth. Investment in new infrastructure, like electricity grids and efficient buildings, is projected to improve overall productivity. Employment is also positively affected, with roughly 2 to 10 million jobs saved or created by 2030 relative to the COVID scenario, representing an increase of 0.1% to 0.5% across models. Increased GDP growth on its own, however, may lead to a “rebound” effect in global emissions triggered by increased activity and energy consumption if not combined with ambitious climate policies.

Our findings result from three global models. However, the green recovery packages need to be embedded in each country's (development) context to maximise synergies and sustainability and socio-economic benefits. This means that also national model analysis will be needed to support further policymaking. The gap remaining for a trajectory leading to a below 2 °C pathway is still considerable by 2030, to the range of 17% to 25%. Reinforcing Green Recovery scenarios with ambitious climate policies is required to lead to economic restructuring towards net-zero emissions.

Methods

Models

All global model teams followed the same scenario protocol for comparability. The global models were used to analyse the economic, sectoral, and technological implications of the COVID and Green Recovery scenarios. The models are the integrated assessment model IMAGE¹⁵ and two macro-economic models, i.e. E3ME¹⁶ and GEM-E3-FIT^{17,18}. IMAGE was mainly used to look at energy systems behaviour and associated CO₂ emissions. The macro-economic models E3ME and GEM-E3-FIT were used to quantify the macro-economic and employment consequences of climate policy, including the development of clean energy technologies. Macro-economic models are valuable tools to evaluate the impacts of alternative policy options in response to the COVID-19 pandemic by identifying the economic channels through which the outbreak's direct and indirect effects manifest themselves¹¹. The three models are described in detail in Supplementary Data 1.

Scenarios

Table 2 presents the different scenarios. The scenarios build on each other to accurately assess the progressive impact of the COVID pandemic on the current policies trajectory and the benefits a targeted green recovery can achieve. The time horizon for the scenarios is 2030.

Table 2: The Reference, COVID and Green Recovery scenarios

The **Reference** or current policies scenario assumes that the main climate and energy policies in place as of November 2020 (cut-off date) are fully implemented^{19,20}. Quantified policies include legislative decisions, executive orders (e.g., the United States), and their equivalent²¹. We did not quantify the impacts of publicly announced plans or strategies (e.g., Nationally Determined Contributions) unless specific policy instruments support them. We selected the most recent and most important policies considered for emissions projections primarily based on literature research, input by NewClimate Institute based on their Climate Policy Database²², and a country expert review of the aforementioned policies. We used a modeling protocol, updated from Roelfsema et al.²¹, including a detailed

spreadsheet listing policies by country to implement current policies in the IMAGE, GEM-E3-FIT, and E3ME models.

The GEM-E3-FIT and E3ME assumptions for the **COVID** scenario were developed to include short-term impacts of COVID-19, with GDP projections from official sources, including DG ECFIN (Summer 2020)²³, OECD Economic Output (September 2020)²⁴, and World Bank Global Economic Prospect (June 2020)²⁵. The GDP projections were used to calculate other E3ME and GEM-E3 model variables (industry output, consumer spending, investment, employment, CO₂ emissions). We used the same GDP assumptions in the IMAGE model, thus ensuring full consistency of the analysis among models and included activity changes among sectors. The specific implementation of the COVID scenario in the three global models is described below:

- **GEM-E3-FIT's** COVID scenario includes the short-term economic impacts of the COVID crisis, based on official projections, and was modelled with a reduction in aggregate demand to capture the impacts of COVID-19 on specific sectors combined with a disruption in international trade and a decrease in investment and available labour and capital in 2020 to reflect reduced working time due to lockdowns, following Lahcen et al.¹¹. In this process, endogenous model responses and algorithms are used to allocate growth rates to different sectors while retaining consistency at aggregated levels. After 2022, the GEM-E3-FIT socio-economic projections revert to the same growth rates pre-COVID, implying a reduction of GDP, energy consumption, and CO₂ emissions from pre-COVID levels.
- **E3ME's** COVID scenario was updated to include the short-term impacts of COVID-19. These projections were based on official projections (see Table 1) and Cambridge Econometrics earlier analysis of COVID-19⁸. Sectors most affected by the pandemic and subsequent policies introducing lockdown measures are air transport, hotel and catering, and recreation sectors. Additionally, the pandemic causes severe disruption to trade and reduces global demand and planned investment. This leads to a reduction in manufacturing demand. The power sector also experiences a reduction in demand from transport restrictions but somewhat offset by the increase in the residential sector's energy demand. It should be noted that these projections were developed in October 2020 and do not include the latest COVID-19 developments, such as further outbreaks and second lockdown seen in many countries. After 2021, the E3ME COVID projections revert to pre-COVID-19 growth rates based on the assumption that there are no longer-term behaviour changes due to the crisis.
- **IMAGE's** COVID scenario was modelled via (i) the calculated impact of the changes in GDP and other macro-economic indicators and (ii) a reduction in demand to capture the implications of the COVID-19 crisis on specific sectors. More explicitly, aviation and surface traffic changes were introduced, and the reductions in manufacturing demand, especially for the cement and steel sectors, were included. The residential buildings sector witnessed an increase in energy demand as more people spent more time in their homes, contrary to the service and commercial sectors which saw a decrease in energy demand. Impacts on the electricity sector were assumed to be accurately represented via the demand drop in the other sectors. In 2022, the IMAGE demand projections revert to the pre-COVID growth rates, except for aviation traffic which is assumed to return to typical growth rates in 2023^{26,27}. The modelling of the COVID-19 impact is described in Supplementary Data 2.

The **Green Recovery** scenario is based on the same approach as the IEA Sustainable Recovery report⁶. A green stimulus framework is a qualitative approach that contains criteria that policymakers could consider for any green stimulus interventions to address short-term needs with long-term benefits successfully. IEA's Sustainable Recovery report provided an integrated approach to support economic recovery and create jobs while improving the energy system's resiliency and sustainability. We are approaching the issue mainly from a sustainability and emissions perspective, trying to keep the Paris climate goals in reach. Societal benefits such as job creation, economic growth, deaths avoided, etc. are not the main focus of our scenario; however, our work fully captures the potential economic and employment co-benefits of such a green recovery using two well-established macro-economic models (E3ME and GEM-E3-FIT) as a natural consequence of increased investments in low-carbon and energy-efficient technologies and infrastructure, rather than a driver.

Our Green Recovery scenario's basic assumptions are as follows: we assume that all countries dedicate 1% of their 2019 GDP each year to green recovery measures for a total of 3 years (2021–2023), equating to about 650 billion Euro 2010 per year. Our assumption would mean devoting one-twelfth of the global COVID-19 rescue and recovery budget and one-sixth of the developing countries' COVID-19 recovery budget to green investments support. The current fiscal support on COVID-19 rescue and recovery are of the order of 15% of GDP for the group of G20, 6% for middle-income countries and developing countries, and about 12% globally^{28,29}. If countries had already pledged a higher percentage of their GDP in identifiable and genuinely green measures when this work was carried out, that pledge was used instead. Thus, the share of GDP assumed to be directed to green recovery is higher in the EU at 2.1% of its 2019 GDP^{30,31}. Low-income countries (as classified by the World Bank) are excluded from this research.

For the implementation of the green stimulus investments and following IEA's implementation of their Sustainable Recovery, the stimulus package was split into almost identical percentages between the electricity (renewable energy technologies like solar PV and wind coupled with the necessary grid improvements), transport (support for electric vehicle uptake and scrappage schemes for ICEs) and building sectors (building renovation and more efficient equipment). A smaller percentage was allocated to the industry sector (mostly related to efficiency improvements). The three models follow these assumptions as a rule, although there were differentiations in specific allocations of the investments, depending on the capabilities and characteristics of each model. A detailed presentation of the implementation of the green stimulus for each model can be found in Supplementary Data 3.

Data availability

Model results can be found on Github: <https://github.com/hsinghs/Green-recovery>

Code availability

The IMAGE and GEM-E3-FIT models are documented on the common integrated assessment model documentation (https://www.iamcdocumentation.eu/index.php/IAMC_wiki). The IMAGE model is also documented on its website (https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation). The E3ME model is documented in the E3ME Technical Manual found on the Cambridge Econometrics website (<https://www.e3me.com/wp-content/uploads/2019/09/E3ME-Technical-Manual-v6.1-onlineSML.pdf>)

377 The Python codes that was used to generate the figures can be found on GitHub:

378 <https://github.com/hsinghs/Green-recovery>

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Author contributions

I.D. led the study design with the help of H.-H.C., P.F., U.C., M.d.E., and D.v.V., coordinated the analysis and drafted the paper; I.D. and H.-H.C. performed the data analysis of the model results; I.D., M.d.E., H.-H.C., H.v.S., P.F., U.C. and D.v.V. contributed to the analysis, provided feedback and refined the draft paper; H.-H.C. created and refined the figures supported by I.D.; I.D., H.-H.C., H.-S. B., V.D., O.E. and D.v.V. developed and implemented the scenarios for the IMAGE model; P.F., K.F., P.K., and L.P. developed and implemented the scenarios for the GEM-E3-FIT model; U.C. and B. K.-D. developed and implemented the scenarios for the E3ME model.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper.

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Figure legends

Figure 1: Global GDP and CO₂ emission projections. **a**, Global GDP (expressed in MER US\$) between 2015 and 2030 (normalised to 2015 levels), for all scenarios, as projected by the three global models. **b**, Global CO₂ emission projections from energy and industrial processes between 2015 and 2030, for all scenarios. The 2 °C scenario range shows the global CO₂ emissions from energy and industrial processes consistent with a least cost-pathway towards limiting global average temperature increase below 2 °C by 2100 with about 66% probability¹². All results in the paper have not been adjusted with a harmonization process, and we show the original data. We find that harmonization towards 2019 global CO₂ emissions and GDP would reduce the range of results, as presented in Supplementary Figure 1.

Figure 2: CO₂ emission projections for major emitting regions. CO₂ emissions from energy and industrial processes, relative to 2015 (%), per major emitting region (panel), for 2025 and 2030 (x-axis), for all scenarios (colour). Symbols indicate individual model results. The bars indicate model mean and were added for reporting reasons.

Figure 3: Selected global energy indicators. Projected changes in selected global energy indicators, for 2025 and 2030 (x-axis), for all scenarios (colour). **a**, **b**, Final energy use in the industry and buildings sector respectively, relative to 2015 (%). **c**, Share of renewables in electricity production (% of total). **d**, Share of electric vehicles (% of total). Symbols indicate individual model results. The bars indicate model mean and were added for reporting reasons.

Figure 4: Changes in global employment. Changes in global employment by sector (in millions) induced by the Green Recovery scenario (based on E3ME results: left and GEM-E3-FIT results: right)

Tables

Table 1: Main assumptions and measures implemented per sector for the Reference, COVID and Green Recovery scenarios

Reference scenario		
Climate policies, GDP projections & Sectoral activity levels	The Reference scenario assumes all currently adopted and implemented policies are implemented, and no additional measures are undertaken. The Reference scenario excludes COVID impacts.	
COVID scenario		
Climate policies	Same as the Reference scenario	
GDP projections	2020-2021: In the short term (2020-2021), GDP growth rates were made consistent with official projections by adjusting economic activity levels (consumer spending, investment, trade) and introducing sectoral shocks to reflect the observed COVID impacts (e.g., impacts on air transport, and industry). Macro-economic assumptions were taken from the OECD Economic Outlook (for non-EU countries) ²⁴ , the IMF World Economic outlook ³² , the World Bank Global Economic prospects report ²⁵ and the DG ECFIN Autumn Economic Forecast (for EU countries) ²³ . 2022-2030: Macroeconomic projections as calculated by the GEM-E3-FIT and E3ME models. Return to Reference GDP growth rates assumed after 2025.	
Sectoral activity levels		
Transport	Aviation traffic: Activity drop (60% below 2019 levels) in 2020, return to Reference growth rates by 2023	
	Surface traffic: Activity drop (18% below 2019 levels) in 2020, return to Reference growth rates by 2022	
Industry	Steel, cement and other industrial production/demand: Activity drop (10% below 2019 levels) in 2020, return to Reference growth rates by 2022	
Buildings	Residential energy consumption: Activity increase (10% above 2019 levels) in 2020, return to Reference growth rates by 2022	
	Commercial energy consumption: Activity drop (25% below 2019 levels) in 2020, return to Reference growth rates by 2022	
Electricity	No specific assumptions made. Electricity activity levels were assumed to be sufficiently proxied by activity levels in the other sectors	
Green Recovery scenario		
Climate policies & GDP projections	Same as COVID scenario	
Sectoral activity levels	Measure	Percentage of total green stimulus
Transport	Promotion of electric vehicles via consumer subsidies and scrappage scheme	30% - 33% across three models
Industry	Support for energy efficiency measures and methane leakage avoidance	4% - 8% across three models

Buildings	Promotion of energy efficiency measures in buildings (e.g. thermal insulation) via consumer subsidies	30% across three models
Electricity	Support for renewable electricity production via subsidies and grid investments	33% across three models

Table 2: The Reference, COVID and Green Recovery scenarios

Scenario	Description
1. Reference (pre-COVID)	The reference scenario assumes all currently adopted and implemented policies (defined as legislative decisions, executive orders, or equivalent) are realised, and no additional measures are undertaken, in line with Roelfsema et al. ²¹ . The cut-off date for policies is November 2020, and dedicated COVID recovery measures were excluded. The pre-COVID scenario also excludes the COVID impacts (no impacts on the economic projections and sectoral activity); therefore, it can be seen as a “no-COVID” scenario. The scenario further incorporates middle-of-the-road socio-economic conditions throughout the century. The economic scenario is based on the second marker baseline scenario from the Shared Socioeconomic Pathways (SSP2) for IMAGE and GEM-E3 and the IEA Current Policies scenario for E3ME.
2. COVID (post-COVID)	This is a variant of the Reference scenario, but now considering the short-term (2020-2025) economic projections that were updated to include the implications of the COVID-19 pandemic (post-COVID-19), including sectoral activity level changes. More specifically, it contains the new macro-economic assumptions from the OECD Economic Outlook from September 2020 (for non-EU countries, if available) ²⁴ , the IMF World Economic outlook from June 2020 ³² , the World Bank Global Economic prospects report from June 2020 ²⁵ and the Autumn Economic Forecast from November 2020 (for EU countries) ²³ . The pandemic's impact on sectoral activity levels (transport, buildings, industry, and power) was calculated from various relevant sources and is presented in detail in Supplementary Data 2.
3. Green Recovery (post-COVID)	This is a variant of the COVID scenario by assuming the implementation of post-pandemic green recovery measures in major economies that reduce GHG emissions across the board. This includes extended support for low and zero-emission technologies and infrastructure (e.g., renewable energy, improvements in industrial processes and building efficiency) and surface transport electrification. It further accounts for the short-term macro-economic impacts arising from green recovery implementation, as calculated by the macro-economic models.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [TargetedgreenrecoverymeasuresinapostCOVID19worldenabletheenergytransitionSupplementarymaterial.docx](#)