European
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CLIMATE ACTION IN THE POST-COVID-19 WORLD

Insights from EU-funded projects on how to build forward better

Research and Innovation

Climate Action in the Post-COVID-19 world: Insights from EU-funded projects on how to build forward better

European Commission
Directorate-General for Research and Innovation
Directorate B – Healthy Planet
Unit B.3 – Climate and Planetary Boundaries
With the contribution of CINEA.C.C1.1

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Manuscript completed in October 2021.
First edition.

PDF	ISBN 978-92-76-40952-6	doi:10.2777/02755	KI-05-21-243-EN-N

Luxembourg: Publications Office of the European Union, 2021

EUROPEAN COMMISSION

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edited by
Katarzyna Drabicka

2021

Directorate-General for Research and Innovation
Horizon 2020

ACKNOWLEDGEMENTS

The European Commission Directorate-General for Research and Innovation would like to thank, first and foremost, all the projects funded under the “Fighting and adapting to climate change” part of the Horizon 2020 work programme that have made this publication possible: CASCADES, CONSTRAIN, ENGAGE, LOCOMOTION, NAVIGATE, PARIS REINFORCE, RECEIPT and VERIFY. We would also like to thank colleagues from the European Climate, Infrastructure and Environment Executive Agency (CINEA), Unit C1, for their help in identifying relevant projects and their results, as well as their support in coordinating and guiding the projects’ input.

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Mariya Gabriel,
Commissioner for Innovation, Research, Culture, Education and Youth

FOREWORD

The world is in a state of climate emergency and the window of opportunity to take action is rapidly shrinking. The devastating COVID-19 pandemic offers humanity a once in a generation opportunity to change course, to prevent the avoidable and to prepare for the unavoidable.

Recent developments have brutally demonstrated that the climate crisis is no longer a distant danger, a worst-case scenario that we can deal with tomorrow – it has become a daunting reality for all of humankind, here and now. Record droughts, wildfires and floods continue to wreak havoc on communities and destroy livelihoods worldwide. Barely a day passes without tragic news in the media about increasingly severe extreme weather events – from unprecedented floods in Belgium, China, Germany and Turkey and a deadly heatwave in most of western North America this summer, to massive wildfires in California, the Mediterranean and Siberia.

The outlook is even bleaker as the impacts are due to worsen with additional warming; no place on the globe will be unaffected. This, in turn, will exacerbate already existing challenges and fuel conflict, displacement, political unrest and human deprivation. This is the message that cuts through the latest landmark report on the state of the global climate crisis by the United Nations Intergovernmental Panel on Climate Change (IPCC), the most authoritative body on climate science.

But there is also an optimistic message in the IPCC report. While science is clear that climate change is irrefutable and we are approaching the point of no return, it also tells us that it is not too late to turn the tide. It shows that we still have a chance to stay within the 1.5 °C target and prevent the worst impacts if we act swiftly and decisively. This will require fundamental transformations in all aspects of human life – how we power our economies, use land and grow food, transport goods and travel and, last but not least, how we treat nature. And while technology has contributed to climate change, it also holds the key to a paradigm shift. Solutions already exist to curb the lion's share of today's emissions and to boost climate resilience. In many places renewable energy is now the cheapest energy source, and the cost of electric batteries has decreased by some 90 % over the past decade. Where no solutions exist yet, researchers worldwide are putting their heads together to close this gap. Horizon Europe, the EU framework programme for research and innovation and an essential enabler of the European Green Deal, will contribute to these efforts, with at least 35 % of the budget dedicated to climate-related research and innovation. It will nurture opportunities to make Europe climate neutral and to adapt to the impacts of warming, including through the flagship Mission on adaptation to climate change and other relevant EU missions, while continuing to expand the boundaries of climate science.

The COVID-19 health crisis has also made dramatically evident the true value of preparedness and resilience, providing an additional argument for acting on the climate emergency. We must seize the opportunity to build forward better as the world emerges from the pandemic. This means better integrating not only climate but also biodiversity considerations in economic stimulus and recovery programmes, as the two crises are interconnected. In Europe, at least 37 % of the EUR 672.5 billion Recovery and Resilience Facility will be spent on green investments and reforms. As we approach the 26th UN Climate Change Conference of the Parties (COP26), we must ensure that the decisions made this year give us the best chance to not only cope with the huge economic impacts of the pandemic, but also stay within 1.5 °C of warming and avert a climate catastrophe.

This report presents some of the latest findings from EU-funded projects on how to accelerate climate action in the post-pandemic phase and why inaction is not an option. I very much welcome this work and hope it will provide valuable inspiration in a race we cannot afford to lose.

CONSTRAIN: WHAT CLIMATE SCIENTISTS HAVE LEARNED OVER A YEAR OF COVID-19

'A strong green COVID-19 economic recovery could slow down global warming by up to half its current rate, giving us greater opportunity to adjust to climate impacts'

- **Authors:** Debbie Rosen (CONSTRAIN / University of Leeds) and Piers Forster (CONSTRAIN / University of Leeds)

- **Project title and abbreviation:** Constraining uncertainty of multi-decadal climate projections (CONSTRAIN, grant no 820829)

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- **Project website:** https://constrain-eu.org/
- **CORDIS project website:** https://cordis.europa.eu/project/id/820829

Climate change and COVID-19 are both threat multipliers, exacerbating existing problems and hitting the most vulnerable the hardest. Many European countries have now experienced multiple waves of COVID-19, and infections continue to rise in many nations across the world. In addition, 2020 has been declared the joint warmest year on record, but current climate pledges are yet to match the Paris Agreement's ambition of limiting warming to 1.5 °C above pre-industrial levels.

The outlook may seem bleak. But work by the EU Horizon 2020 CONSTRAIN consortium shows how a strong green COVID-19 economic recovery could slow down global warming by up to half its current rate in coming decades, giving us a greater opportunity to adjust to the climate impacts, which would worsen the suffering caused by a future pandemic or other global threat. This approach would also limit the total amount of warming we end up with once we reach climate neutrality. By making choices that tackle the climate and COVID-19 crises together, we can help to ensure that a more resilient world emerges on the other side.

The landmark 2015 Paris Agreement sets out an ambition to limit global warming to 1.5 °C compared with pre-industrial levels. With global temperatures now 1.2 °C above pre-industrial levels, and rising, on average, by more than 0.2 °C each decade, limiting warming to 1.5 °C clearly requires decisive global action. Without it, we look set to exceed 1.5 °C before mid century, risking more frequent and more extreme climate impacts.

This is why nationally determined contributions (NDCs) are so important, setting out national climate policies, actions and targets up to 2030. However, current global ambition is still not enough to get us on the pathway to 1.5 °C, and at the time of writing national pledges and targets from across the globe suggest that warming will reach 2.4 °C by the end of this century[(1)]. The EU, for example, submitted a strengthened NDC in December 2020 with a target of reducing emissions by at least 55 % by 2030. This is a major step in the right direction, but to be Paris compatible a reduction of between 58 % and 70 % is needed according to analysis by the Climate Action Tracker[(2)]. The EU is however not alone, with only two of the 33 countries assessed (Morocco and The Gambia) having climate pledges that are compatible with the Paris Agreement.

We still have opportunities to get this right: a strong green economic recovery could cut the rate of warming by up to half in coming decades, giving us vital time and space to plan for and adjust to whatever climate impacts do come our way, while also setting us on a pathway that limits warming in line with the Paris Agreement.

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1. https://climateactiontracker.org/publications/global-update-climate-summit-momentum/
2. https://climateactiontracker.org/countries/eu/

The Paris Agreement's 1.5 °C ambition

Planning and implementing climate action that limits human-caused warming to 1.5 °C above pre-industrial levels means understanding how temperatures have changed to date.

Between 1850–1900 (the time frame for pre-industrial) and 1986–2005 (the recent reference period), there was around 0.6 °C of warming. This means we will reach the 1.5 °C threshold when temperatures have increased by a further 0.9 °C from 1986–2005 levels, and our best estimate is that around 0.6 °C of this increase has already occurred.

This human-caused warming happens on top of the natural climate variability occurring year to year that tends to dominate the climate on timescales of up to a decade. As a result, establishing how humans have influenced the climate means taking a longer-term perspective, looking at 20- to 30-year averages across the globe (Figure 1).

If the temperature rise reaches or exceeds 1.5 °C in a single year or location, it does not mean that the Paris Agreement's 1.5 °C ambition is thwarted: if long-term average human-caused warming still falls below 1.5 °C, that ambition is still within reach. However, the more global annual temperatures approach, reach or exceed 1.5 °C of warming, the closer the world will be to a long-term average that moves us into dangerous climate territory.

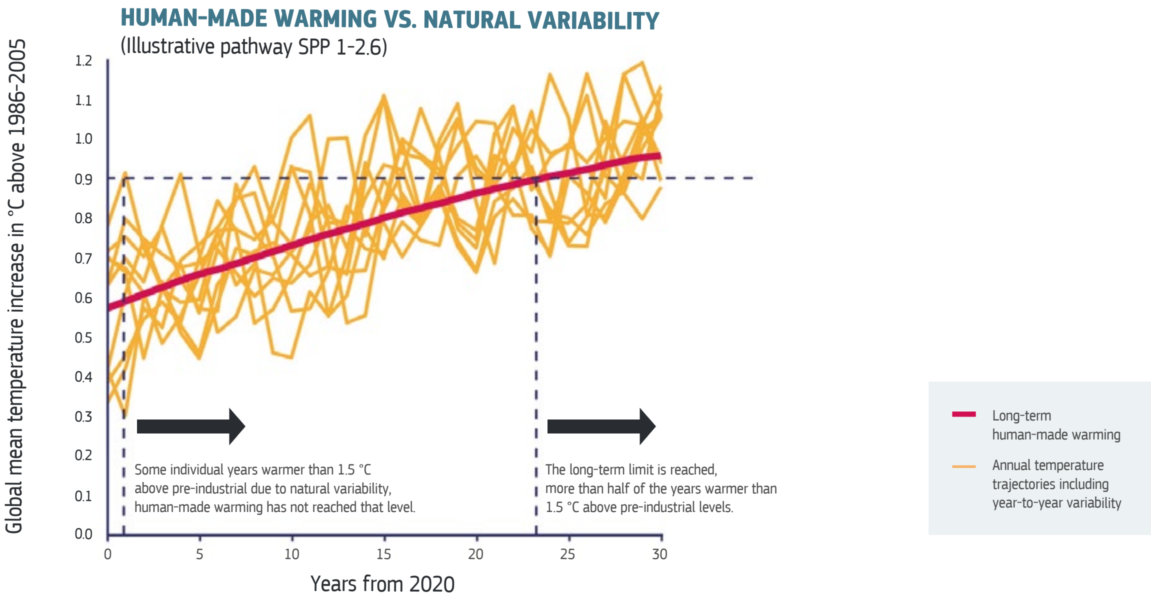

Figure 1: Human-made warming versus natural variability (illustrative pathway SSP 1–2.6). Understanding where we are in terms of the Paris Agreement's 1.5 °C limit, showing warming levels from the 1986–2005 reference period to 2020 (0.6 °C) and beyond. Long-term warming of a further 0.3 °C from 2020 would mean we reach the Paris Agreement's 1.5 °C threshold. The natural variability time series as well as the 30-year average are purely illustrative. SSP, shared socioeconomic pathway. (Source: CONSTRAIN)

COVID-19's climate legacy depends on economic recovery options

At the height of the first global lockdown in 2020, CO2 and other emissions fell dramatically, largely due to the corresponding fall in road transport as people stayed at home (Figure 2). Emissions soon showed signs of recovery as restrictions eased, and a similar pattern was seen at the start of 2021, when emissions fell (although not to the same extent) as infection rates surged but bounced back soon after.

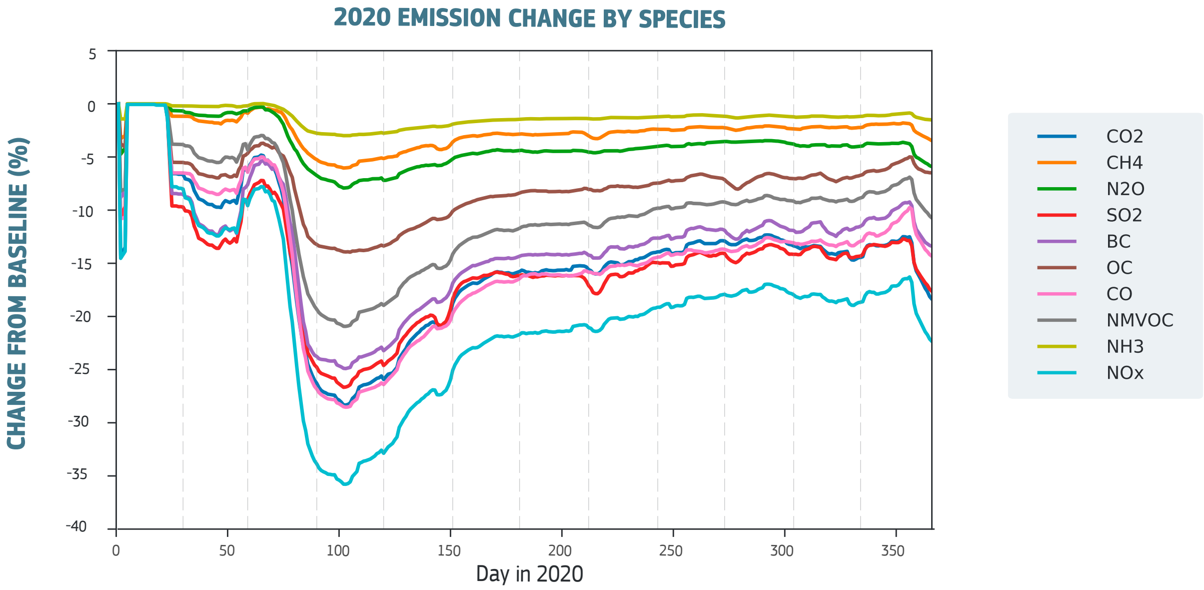

Figure 2: Global lockdown pollution level changes. Apple and Google mobility data, designed to provide policymakers with information on the effectiveness of lockdown measures, used as a proxy for changes in pollution compared with a pre-COVID-19 baseline. Credit: Piers Forster. BC, black carbon; NMVOC, non-methane volatile organic compounds; NOx, nitrogen oxides; OC, organic carbon.

The short-lived nature of these changes means that, despite the huge upheaval, COVID-19 has so far caused only a small 'blip' in our post-industrial emissions trajectory: atmospheric CO2 concentrations continue to rise and, even if some partial lockdown measures stay in place until the end of 2021, global temperatures in 2030 will only be around 0.01 °C lower than expected, based on the NDCs in place in mid 2020.

The lasting effects of the pandemic on climate therefore depend on how green the economic recovery options and associated investments are. And as successive lockdowns have also had negative impacts on the economy and health, disproportionately affecting those already disadvantaged in society, we must make sure that the recovery pathways chosen promote not just climate action but also welfare implications and global equity.

A green COVID-19 recovery could cut warming rates by up to half

Much attention has been paid to the 7 % COVID-19-related drop in global CO2 emissions seen in 2020, but the potential impact of COVID-19 on the long-term rate of global warming has received far less attention.

Slower warming means more time to plan for and adapt to any further temperature rise while we are still on the path to net zero. However, because the climate varies naturally from year to year, so does the speed of global warming.

Until now, this has made it difficult to identify how cutting emissions might make a difference on relatively short timescales, including the critical period for the Paris Agreement's 1.5 °C ambition. CONSTRAIN research has untangled this natural variation from human influence, using thousands of temperature projections from different climate models combined with real-world measurements of natural climate variability.

Using this to look at warming rates in two green COVID-19 economic recovery scenarios shows how the choices we make now can slow down warming rates compared with the current emissions reduction pledges represented by NDCs (Figure 3).

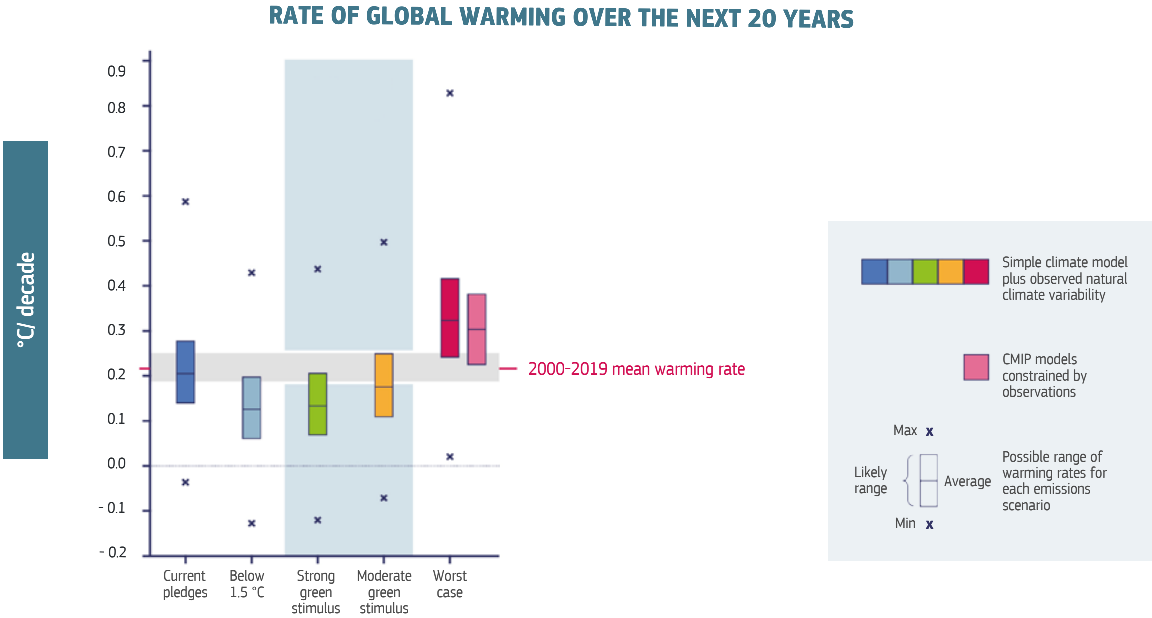

Figure 3: Near-term (20-year) warming trends for pathways exploring two COVID-19 recovery options (moderate and strong green stimulus pathways), as well as current emissions reduction pledges (NDCs), a no-mitigation fossil-fuelled ('worst-case') scenario and a pathway aiming to limit warming to below 1.5 °C by the end of the century. The strong green stimulus pathway (green bar) reflects a 1.2 % increase in investment in low-carbon technologies, and a fall of 0.4 % in fossil fuel investment, leading to a 50 % fall in greenhouse gas emissions by 2030 and global net zero CO_2 emissions by 2050. CMIP6, Coupled Model Intercomparison Project phase 6. (Source: CONSTRAIN)

A strong green economic stimulus package can clearly pay large dividends in the near-term, cutting the current rate of human-induced warming by up to half over the next 20 years, even when fully accounting for natural variability in the climate system.

Implementing a strong green economic recovery from the COVID-19 pandemic that slows down warming in coming decades will give us more chance to build resilience to expected future climate impacts, and also help to avoid the most dangerous climate change. Such a pathway would also halve global emissions by 2030, getting us on the path to net zero by 2050, and giving us a good chance of keeping the temperature rise below 1.5 °C.

What next?

Seeing the benefits of strong climate policy decisions on relatively short timescales, in terms of lower warming rates, is surely an incentive for decisive climate action.

With the United States re-entering the Paris Agreement, countries increasingly setting net zero emissions targets and the concept of net zero becoming increasingly mainstream, things are looking more hopeful. The potential benefits of net zero, both economic and wider, for example in terms of driving innovation, creating new and better jobs, reducing air pollution and lowering energy bills, are meanwhile being recognised more and more.

However, climate targets and action need to be joined up with the vast sums being invested in COVID-19 economic recovery packages, leading to structural economic change that facilitates emissions cuts. Otherwise, recovery-related emissions that rise above levels projected before the pandemic cannot be ruled out. In fact, the International Energy Agency (IEA) is predicting a major surge in CO_2 emissions this year as the world rebounds from the pandemic, largely driven by increased coal use in Asia.

With thoughts turning to the delayed UN Climate Change Conference of the Parties (COP26), scheduled for November 2021, there is a real opportunity to get these messages through on the global stage. We must do all we can to ensure that policy decisions made this year match the rhetoric, supporting and inspiring action that addresses the huge economic impacts of the pandemic, while also averting a full-blown global climate catastrophe.

About CONSTRAIN

The 2020 CONSTRAIN project is a consortium of 14 European partners tasked with developing a better understanding of global and regional climate projections for the next 20–50 years. CONSTRAIN brings together world-leading scientists, including many United Nations Intergovernmental Panel on Climate Change lead authors. Alongside leading European academic institutions, the consortium includes Climate Analytics, which adds expertise in tailoring and disseminating information to policymakers and practitioners.

CONSTRAIN's ZERO IN report series provides information on scientific topics that are crucial to the Paris Agreement, including new developments at the science–policy interface, new insights into the complex processes represented in climate models, and implications for climate projections and impacts over coming decades.

As well as addressing the climate impacts of the COVID-19 economic recovery, the second ZERO IN report (CONSTRAIN, 2020) also provides insights into the latest climate models and the Paris Agreement's 1.5 °C ambition.

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VERIFY: NEAR-REAL-TIME CO2 EMISSIONS MONITORING – RESULTS DURING THE COVID-19 PANDEMIC

'Tracking CO2 emissions in near-real-time reveals that after a short drop, emissions have snapped back to their pre-COVID-19 levels'

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- **CORDIS project website:** https://cordis.europa.eu/project/id/776810/fr

As the ambition and urgency of climate mitigation efforts increase, annual estimates of national CO2 emissions provide only vague and outdated information about changes and progress. In contrast, near-real-time activity data provide novel frequently updated estimates of emissions, allowing the effects of the COVID-19 pandemic and of the subsequent and ongoing economic recovery to be tracked, in particular whether stimulus packages, chiefly from the Recovery and Resilience Facility in Europe, aligned with the Green Deal objectives will effectively accelerate the decarbonisation of economies and translate in the years to come into a faster decrease in emissions for the next stocktakes of the Paris Agreement on climate change. Low latency daily emissions estimates are a powerful tool for identifying the mechanisms that cause emissions to increase, such as during cold waves or heatwaves, and will allow better informed action to be taken to maximise the effectiveness of mitigation actions.

Despite the partial mobility restrictions in European countries and in some US states during the second and third waves of the COVID-19 pandemic, we found that emissions reductions were the largest during the first lockdown period in spring 2020. During the second and third lockdowns the reductions were much smaller, indicating adaptation to the pandemic and the short-term nature of the observed reductions.

The fact that even such substantial worldwide lockdowns led to a one-time decline in global CO2 emissions of only 5.4 % in a single year highlights the significant challenges that we face in terms of climate change mitigation in the post-COVID-19 era. Furthermore, as the experience of 2021 shows, any declines will be quickly reversed by new emissions unless the COVID-19 crisis is used as a break point in our fossil fuel trajectory, notably through policies that make the COVID-19 recovery an opportunity to green national energy and development plans. In the future, as COVID-19-related restrictions end and energy infrastructure evolves, our data and methods will allow policymakers and energy analysts to closely monitor emissions trends and decarbonisation progress and more quickly adjust policies and programmes to fall in line with what is required by the Paris Agreement.

How to build near-real-time emissions estimates

With support from the VERIFY project we compiled near-real-time activity data from numerous sources and produced, for the first time, daily estimates of fossil fuel CO2 emissions from January 2019 onwards for all countries in the Carbon Monitor project, with regional versions for US states, Chinese provinces and the residential sector in the EU.

The near-real-time activity data assembled for the Carbon Monitor project cover power generation (for 29 countries), industry (for 73 countries), road transport (for 406 cities), aviation and maritime transport (for all countries) and residential fuel use (for 206 countries).The daily CO2 emissions from fossil fuel combustion and cement production reflect the seasonality of climate factors affecting heating and cooling, weather conditions, the periodic occurrence of working days and weekends and, of course, the impact of the COVID-19 pandemic.

We then performed a synthesis between the daily variations in emissions from the Carbon Monitor at country scale and spatial maps of emissions from the European Emissions Database for Global Atmospheric Research (EDGAR) and nitrogen oxide observations from space from the Copernicus satellite Sentinel-5P. This resulted in daily 10-km emissions maps, which were regularly updated.

It was suggested from preliminary estimates, which did not cover all of 2020, that the COVID-19 pandemic may have caused a more than 8 % annual decline in global CO2 emissions. However, detailed estimates from data for the whole year showed that the global annual reduction was 5.4 % (– 1 901 MtCO2, ± 7.2 % for the 2 sigma range). This decrease is five times larger than the annual emissions drop at the peak of the 2008 global financial crisis. However, global CO2 emissions gradually recovered towards 2019 levels from late April 2020 with the global partial reopening of the economy and continue to bounce back in 2021. Global CO2 emissions even increased slightly by 0.9 % in December 2020 compared with 2019, indicating the trend for a rebound in global emissions, in particular in China.

Global near-real-time CO2 emissions

The Carbon Monitor uses near-real-time electricity data, ground-based transport congestion indices from TomTom and from US datasets for more than 400 cities, industry output and activity data, individual aircraft position information and residential fuel use activity. The methodology used has been described in Liu et al. (2020a) and data from 1 January 2019 to June 2020 have been published in Liu et al. (2020b). The latest update is from early October 2021 and covers data until 31 August 2021. All the data are freely and publicly available from the project website (https://carbonmonitor.org).

Total global annual CO2 emissions for 2020 were 33.5 GtCO2 (Figure 4), with power accounting for 39 % of emissions, ground transport 17 %, industry 30 %, residential fuel use 11 %, domestic aviation 1 % and international bunkers (international aviation and shipping) 2 %. Of the top five emitters in 2020, China's emissions were 10.5 GtCO2 (power 44 %; ground transport 8 %; industry 40 %; residential fuel use 8 %; domestic aviation 1 %), followed by the United States at 4.6 GtCO2 (power 31 %; ground transport 33 %; industry 21 %; residential fuel use 12 %; domestic aviation 3 %), the EU-27 and the United Kingdom at 2.9 GtCO2 (power 29 %; ground transport 29 %; industry 20 %; residential fuel use 22 %; domestic aviation 0.3 %), India at 2.3 GtCO2 (power 51 %; ground transport 11 %; industry 29 %; residential fuel use 9 %; domestic aviation 0.2 %) and Russia at 1.5 GtCO2 (power 54 %; ground transport 15 %; industry 19 %; residential fuel use 1 %; domestic aviation 11 %).

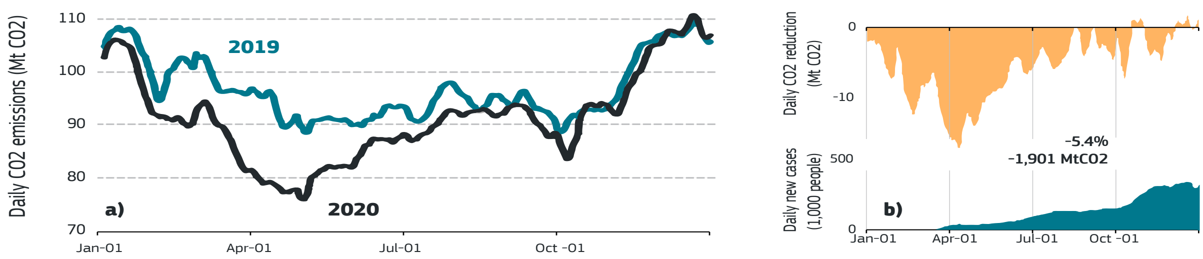

Figure 4: (a) Global daily CO2 emissions in 2019 and 2020. The grey and dark black lines show the 7-day running mean daily CO2 emissions in 2019 and 2020, respectively. (b) Global daily CO2 emissions reductions in 2020 compared with 2019 and global daily new cases of COVID-19 in 2020. (Liu et al., 2020a)

As mentioned earlier, compared with 2019, the global CO2 emissions in 2020 decreased by an estimated 1 901 MtCO2 (± 7.2 % for the 2-sigma range), which represents a relative change of –5.4 % (Figure 4). In comparison, CO2 emissions grew continuously over the past decade (2010–2019), with an average growth rate of 1.6 % per year. The decrease in CO2 emissions in 2020 is the largest ever absolute annual decline in emissions, larger than the emissions decrease of the 2008 financial crisis (– 380 MtCO2) and even the decrease reconstructed for the end of World War II. Specifically, we estimate that emissions fell by 9.8 % in Brazil, 9.4 % in the United States, 8.1 % in India, 7.5 % in the EU and the United Kingdom (Spain 13.1 %, United Kingdom 9.5 %; France 9.0 %; Germany 7.9 %; Italy 7.4 %), 5.0 % in Japan and 2.9 % in Russia. Conversely, China's CO2 emissions in 2020 increased slightly by 0.5 %, because China reopened its economy earlier than most other countries. Data for selected countries for 2019 and 2020 are displayed in Figure 5. The significant decrease in CO2 emissions in 2020 compared with 2019 is linked to the impact of the complex responses to the COVID-19 pandemic, including stay-at-home orders, the closure of factories, the collapse of air traffic and perturbations in supply chains. The largest weekly reduction was found in week 15 of 2020 (6–12 April), a decrease of 18 % compared with the same week in 2019. The decrease in emissions in the ground transport sector contributed more than one third (37 %) of the total global emissions reduction in 2020 compared with 2019.

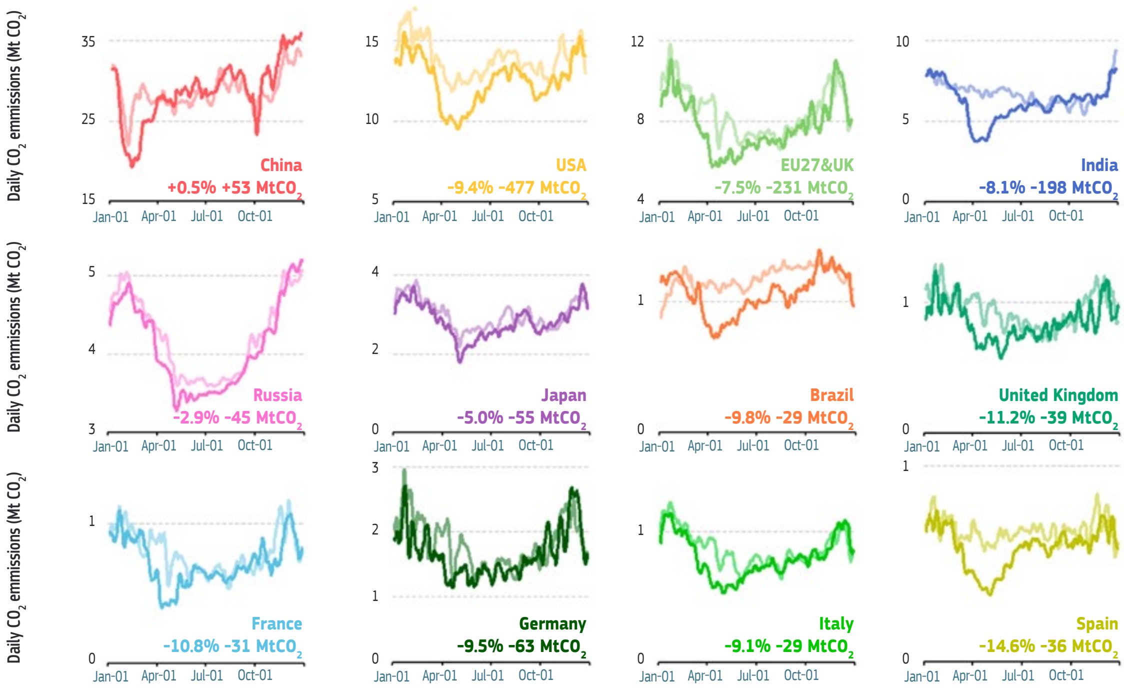

Figure 5: Daily CO2 emissions in 2019 and 2020 for selected countries. The light and dark lines show the 7-day running mean daily CO2 emissions in 2019 and 2020, respectively. The data at the bottom of each graph shows the percentage change between 2020 and 2019 and the magnitude of the reduction; a negative value means less emissions in 2020 compared to 2019.

Le Quéré et al. (2020) published the first estimates of emissions reductions due to the COVID-19 crisis, with a methodology based on lockdown indices and activity data. They established a correlation between reductions in activity and confinement severity, and then used daily confinement severity time series to produce daily emissions. By design, this approach provides an estimate of changes in emissions attributed to the pandemic and ignores other factors such as a higher renewable energy production, lower gas market prices and lower heating demand from warmer cold season temperatures during 2020 relative to 2019. Figure 6 displays the comparison between the updated estimates from Le Quéré et al. (2020) and the Carbon Monitor estimates.

Importantly, although significant declines in CO2 emissions were observed in 2020 that can mainly be attributed to the impact of the pandemic, other effects may have played a role, such as prevailing warmer winter temperatures over most northern industrialised regions during the first months of 2020. In addition, global CO2 emissions gradually recovered from late April with the global partial reopening of the economy. The second and third waves of the pandemic in autumn and early winter 2020 and the corresponding lockdowns reduced CO2 emissions further in western countries, but to a much lesser extent than the reductions in the first wave. Global emissions decreased significantly during the first wave of the pandemic compared with the same month in 2019. However, although many countries were hit by further waves of infections, global CO2 emissions decreased by only 3.1 % in November 2020 and even increased slightly by 0.9 % in December 2020.

Decreases in mobility-related emissions seem to be more persistent than decreases in other sectors: emissions from ground transport were 10.9 % lower in 2020 than in 2019, with the largest monthly decreases occurring in April and May, while monthly reductions were much smaller in November and December. Emissions from the power sector and the industry sector decreased most significantly in April 2020, by 10.0 % and 9.9 %, respectively, but recovered to their 2019 levels from August onwards. However, emissions still decreased cumulatively by 2.5 % and 1.4 % in 2020 compared with 2019 in the power and industry sectors, respectively.

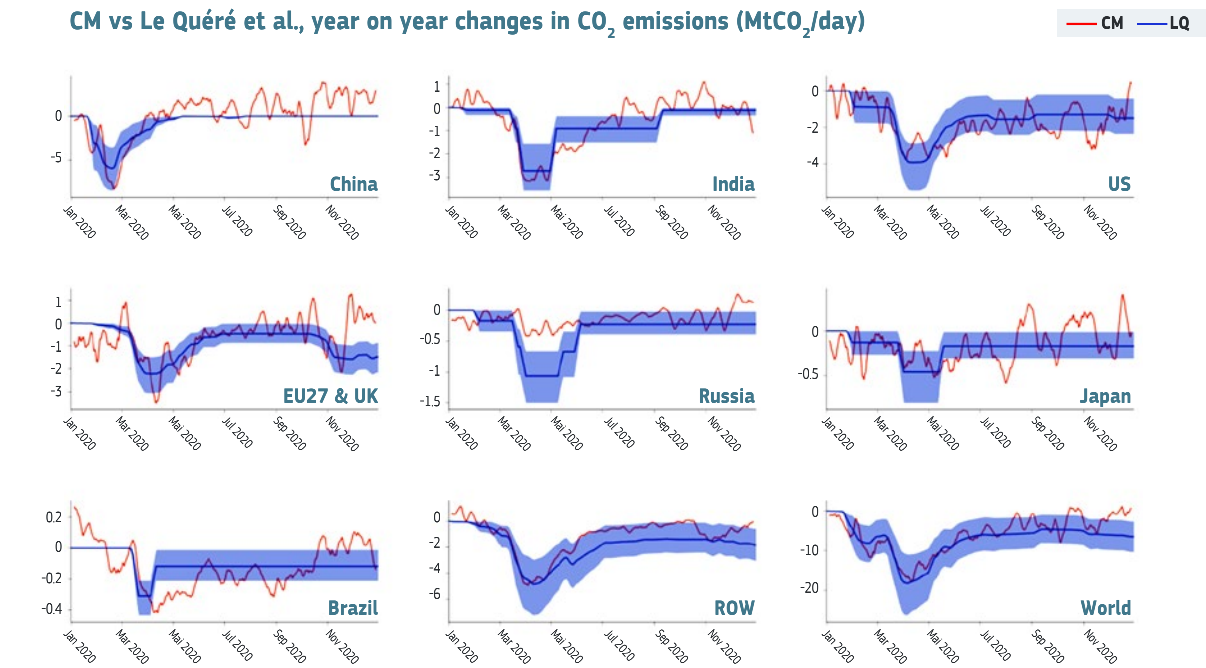

Figure 6: Comparison of year-on-year emissions changes (2020 minus 2019) between the Carbon Monitor (this study; CM) and Le Quéré et al. (2020; LQ) by country (MtCO2/day). A 7-day smoothing filter was applied to the CM daily data. Note that the LQ estimates are only for the effect of COVID-19 on emissions, ignoring other factors. ROW, rest of the world.

US near-real-time CO2 emissions

Regional Carbon Monitor data have been produced for the United States, with near-real-time emissions for 48 states. Using near-real-time activity data compiled from numerous sources, we analysed daily state-level estimates of fossil fuel CO2 emissions from January 2019 to December 2020. Our results quantify the abrupt but temporary decreases in emissions due to the COVID-19 pandemic (particularly related to transport in April and May 2020), but also reveal substantial variations across states according to the stringency of their public health responses. We also find that decreases in commercial demand for natural gas and electricity were partially offset by increases in residential demand in most places. Further, the carbon intensity of US electricity and the share of electricity from coal decreased in many states in the first half of 2020 compared with 2019, but then rebounded in the second half of 2020 when natural gas prices increased.

Near-real-time residential CO2 emissions from natural gas use in EU countries and the United Kingdom

We analysed changes in natural gas use in the industry and built environment sectors from January to June 2020 in Belgium, France, Germany, Italy, the Netherlands, Poland, Spain and the United Kingdom using daily gas flow data from pipeline and storage facilities. We found that reductions in industrial gas use reflect decreases in industrial production across most countries. Surprisingly, natural gas use in buildings also decreased, despite most people being confined to their homes, suggesting that the effect of the warmer weather and deserted commercial buildings did offset the larger use of energy by households. We conclude that climate variations played a larger role than COVID-19-induced stay-home orders in natural gas consumption by the residential sector across Europe.

Global gridded 10 km near-real-time CO2 emissions maps

Here we present for the first time the near-real-time global gridded daily CO2 emission datasets (called GRACED) from fossil fuel and cement production, with a global spatial resolution of 0.1° by 0.1° and a temporal resolution of 1 day. Gridded fossil fuel emissions are computed for different sectors based on the daily national CO2 emissions from near-real-time datasets (Carbon Monitor), the spatial patterns of the point source emissions dataset Global Carbon Grid, EDGAR and spatiotemporal patterns of satellite nitrogen dioxide retrievals. This study on global CO2 emissions is in response to the growing and urgent need for high-quality, fine-grained near-real-time CO2 emissions estimates to support global emissions monitoring across various spatial scales. We show the spatial patterns of emissions changes for the power, industry, residential consumption, ground transport, domestic and international aviation, and international shipping sectors between 2019 and 2020.

Conclusions

The COVID-19 pandemic has fostered a new area of research to obtain near-real-time emissions estimates. The data have produced the first assessment of how the pandemic has disrupted energy systems. As the pandemic fades away, the near future of emissions is still highly uncertain, with opposing forces of an increase in low-carbon energy sources stimulated by economic stimulus packages and a resumption in demand. These data will gain more value over time and enable improvements in the carbon intensity of economies to be tracked. Further, information on emissions at a finer level of granularity, helped by better activity data, is expected to support regional and city-scale emissions reduction efforts by helping to track their trajectories and monitor the effectiveness of various 'climate plans' and associated instruments. Last but not least, as Europe is developing an ambitious CO2 emissions monitoring initiative as part of the Copernicus programme, with a constellation of CO2 imagers, near-real-time emissions maps will become an important part of a future monitoring system to fill the gap in the information provided by satellites.

This effort initiated by researchers should be pursued and amplified. Further work is needed to better attribute the identified emissions changes to the underlying socioeconomic drivers, including changes in human behaviour. A finer granularity, achievable now down to facility level with satellite data, is also highly desirable to quantify emissions from power plants and cement and steel factories and support existing and new European regulations to decarbonise these sectors. Near-real-time estimates of emissions should also be extended to tracking methane leaks and the emissions of pollutants co-emitted with carbon fuels, to improve air quality forecasts in Europe and provide invaluable real-time information on the state of progress towards the goals of the Paris Agreement, now that time is of the essence.

About VERIFY

VERIFY (2019–2022) is a research and innovation project, involving 40 European partners, aimed at developing a system to estimate greenhouse gas (GHG) emissions to support countries' emissions reporting to the United Nations Framework Convention on Climate Change Secretariat. The emissions are estimated based on advanced modelling approaches using atmospheric GHG measurements, tracer transport inversions and various arrays of land and ocean observations, in situ and from space. The system separates their anthropogenic and natural components and their drivers. The project focuses on the three major GHGs responsible for global warming: CO2, methane and nitrous oxide.

VERIFY produces each year a synthesis of GHG fluxes for Europe (EU-27 and the United Kingdom), comparing observation-based estimates with national inventory flux estimates. A comparison is also produced for each country and these are accessible through a user-friendly web interface (http://verify.lsce.ipsl.fr/index.php/products).

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Other publications

A number of other papers are now in review, with preprints available:

- a paper in collaboration with the EU Joint Research Centre's EDGAR team (https://edgar.jrc.ec.europa.eu/) that includes spatially gridded estimates of daily emissions (https://arxiv.org/abs/2107.08586),
- a paper on changes in road transport during successive COVID-19 waves (https://arxiv.org/abs/2101.06450),
- a paper with US state-level estimates and analysis (https://eartharxiv.org/repository/view/2233/),
- a paper on residential emissions in Europe (https://www.essoar.org/doi/10.1002/essoar.10507326.1).

Our data were the basis for two features in the leading scientific journal Nature in 2020:

- Nature (2020), 'How the coronavirus pandemic slashed carbon emissions — in five graphs' (https://www.nature.com/articles/d41586-020-01497-0),
- Nature (2021), How the coronavirus pandemic slashed carbon emissions — in five graphs (https://www.nature.com/articles/d41586-021-00090-3).

NAVIGATE: ASSESSING THE IMPACTS OF THE COVID-19 PANDEMIC ON INEQUALITY, ENERGY DEMAND AND MACROECONOMIC DEVELOPMENT, AND THE RESULTING POLICY IMPLICATIONS

'Green recovery packages can boost employment, especially in the construction and clean energy sectors, while reducing emissions in major economies by about 10–15 % by 2030 compared with pre-COVID scenarios, but they must go hand-in-hand with long-term, ambitious climate policies to have lasting effects'

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- **Project title and abbreviation:** Next generation of AdVanced InteGrated Assessment modelling to support climaTE policymaking (NAVIGATE, grant no 821124)
- **For more information please contact:** navigate@pik-potsdam.de
- **Project website:** https://www.navigate-h2020.eu
- **CORDIS project website:** https://cordis.europa.eu/project/id/821124

The COVID-19 pandemic, lockdown restrictions and other measures that have been put in place have potentially far-reaching implications for inequality within and between countries, for energy demand in different sectors, and for structural change and economic growth. All these factors are also highly relevant for climate action. In response to the COVID-19 crisis, the EU Horizon 2020-funded NAVIGATE project, which aims to improve the capabilities of integrated assessment modelling to support climate policymaking, has undertaken rapid responsive research activities in these three areas.

First, Johannes Emmerling (EIEE) and colleagues looked empirically at past pandemics to estimate the historical socioeconomic and environmental response in the years after them. Based on five pandemics (Middle East respiratory syndrome, severe acute respiratory syndrome, H1N1 influenza, Ebola and Zika) since 2003, they found significant and persistent increases in inequality, unemployment and government debt, and decreases in gross domestic product (GDP). Projecting these trends to the COVID-19 pandemic hints at a deeper and more persistent economic shock than presented in the International Monetary Fund (IMF) World Economic Outlook[3] and a persistent increase in inequality and poverty.

Second, Charlie Wilson (Tyndall Centre for Climate Change Research), Bas van Ruijven (IIASA) and colleagues tracked the impacts of the pandemic on energy demand, particularly in the buildings and transport sectors. The NAVIGATE team will continue to monitor these and potential further impacts to inform future scenario modelling of EU and global climate policies. One thing is certain: the impacts of the pandemic on energy demand – both for better and for worse – have opened up a critical window of opportunity for governments to prevent the backsliding over recent years on efficiency gains and to make progress on the low-carbon transition.

Third, Panagiotis Fragkos (E3Modelling S.A.) and Jean-Francois Mercure and Yeliz Simsek (Global Systems

3. https://www.imf.org/en/Publications/WEO

Institute, Department of Geography, University of Exeter) explored the macroeconomic impacts of the pandemic, and related green recovery packages, including on economic growth, structural change and emissions. They focused on the uptake of renewable energy and electric vehicles and energy efficiency. The results show that green recovery measures can boost employment, especially in the construction sector and clean energy industries, and at the same time lead to a persistent substantial drop in global and EU emissions, but are not enough to ensure the transition to climate neutrality by mid century.

Impacts of the COVID-19 pandemic on inequality

Past pandemics have had substantial impacts on many dimensions of economic and environmental sustainability. Even dating back 2000 years, besides the death toll, researchers have found significant adverse and long-term impacts on poverty in affected countries. Using more recent data on past pandemics in the second half of the 20th century, we estimated that there was an increase in inequality by, on average, about 0.4 points of the Gini index (0–100), several times the average change in the Gini index over a year in normal times, which was persistent even after 5 years. Similar and persistent impacts on GDP, public debt and employment were also found. In terms of the emissions intensity of energy consumption and the energy efficiency of GDP, however, we found only small reductions (cf. Figure 8). This indicates that the change was mostly demand driven by lower GDP and did not reflect systemic improvements in the energy system. Only about one third of the emissions reduction was due to a shift in the demand for oil (mainly transport) towards a demand for electricity (mainly buildings). Applying the empirical results to the COVID-19 pandemic, we estimated that there were an additional 75 million absolute poor at the global level in 2020 (Emmerling et al., 2021). Moreover, by looking at household surveys in several developing countries in 2020, both before and after implementation of the lockdowns, we were able to quantify the actual and momentary impacts on inequality. We found a large increase in monthly income inequality in most countries, by up to 3 points of the Gini index. Moreover, we found strong evidence that income losses were significantly higher for households with female, less educated household heads with lower pre-pandemic incomes (Dasgupta and Emmerling, 2021).

- **Policy implications.** Altogether, without decisive policy interventions, the outlook in terms of overall economic and environmental sustainability after the COVID-19 pandemic is relatively gloomy based on these results. While recovering from the pandemic, policymakers should simultaneously aim to mitigate climate change while ensuring that the most vulnerable are protected. This highlights the need for stimulus packages to not only address imminent economic and social impacts, but also ensure medium- and longer-term improvements in terms of energy efficiency and carbon intensity of energy on the path towards full decarbonisation. Moreover, the evidence on distributive impacts on poorer households implies that the design of climate policies needs to systematically take into account redistributive effects, for example through tax reductions or transfers.

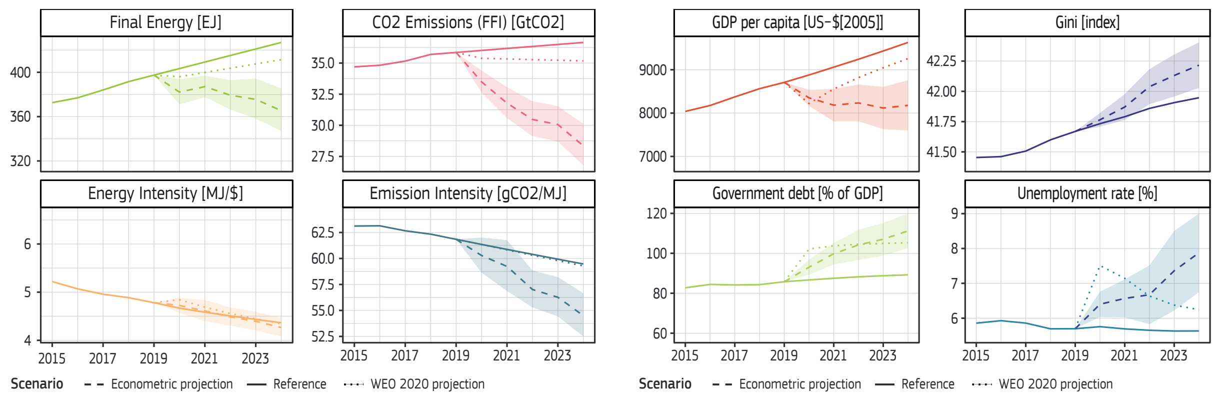

Figure 8: Counterfactual scenarios (solid lines), estimated impact of COVID-19 (dashed lines) and IMF/IEA World Economic Outlook projections (dotted lines).

Long-term impacts of the COVID-19 pandemic on energy demand

The COVID-19 restrictions on travel and the physical distancing interventions clearly impacted transport-related activity as well as the shares and types of activity performed in residential and commercial buildings. Focusing narrowly on energy demand (and related emissions), the overall picture has been mixed. Energy demand for travel decreased, but public and shared transport modes were the worst hit. Energy demand for commercial buildings decreased but this was more than offset by increased residential activity and occupancy rates. Global CO2 emissions in 2020 decreased by around 7 % compared with 2019 levels, with the largest share of the decrease in the transport sector (Le Quéré et al., 2021). Near-term recovery trajectories are uncertain. Looking forward, the principal drivers of change will include fiscal stimulus and infrastructure investments, sectoral employment policies, and increased emphasis on health and well-being in consumer culture.

The IEA published energy demand data for the transport, buildings and industrial sectors in 2020, with an analysis of COVID-19 impacts during and between the 2020 lockdowns (IEA, 2020a). These impacts were particularly profound in the transport sector, with overall sectoral energy consumption projected to be 10 % lower than in 2019. Transport activity in 2020 fell sharply in the aviation sector (down 60 % on 2019 levels) and public transport sector, including rail travel (down 30 %). The remaining air, rail and bus services had lower load factors so their energy intensity per passenger transported increased. Public and shared modes were substituted by private vehicle use and active modes, particularly in cities (IEA, 2020b; ITF, 2020). New car sales were down by 10 %, slowing the transition to electric vehicles.

Impacts on energy demand in buildings and industry have also been clearly evident although less extreme. Energy-intensive industrial output, including basic metals, steel, cement and petrochemicals, fell by 5–15 %, although with regional variations (e.g. cement production in India fell by 85 %) (IEA, 2020a). Specific higher value added sectors like automotive manufacturing fell more sharply in response to the drop off in demand (e.g. by 30–35 % in the EU and United States). Overall, industrial energy demand fell due to lower activity, although fiscal stimulus spending in construction and infrastructure has reversed these declines already partly, alongside the post-pandemic economy recovery (IEA, 2020a). In buildings, overall activity shifted from offices and retail premises to homes. In the first half of 2020, residential electricity use increased by around 20–30 %, which was only partially offset by a 10 % reduction in electricity use in office buildings, which kept running energy-using essential services such as heating and ventilation (IEA, 2020a). Smart gas meter data showed an increase in home heating activity throughout the day, given the higher occupancy levels (Octopus Energy, 2020). From an energy demand perspective at household level, two positive trends observed were (i) an increase in do-it-yourself home renovations, which includes sales of insulation products, and (ii) increases of 20–40 % in online purchases of new appliances such as washing machines, freezers and dishwashers, which tend to be more efficient than the older models they replace (IEA, 2020a).

- **Policy implications**. Whether these impacts of COVID-19 on energy demand will persist is highly uncertain. But as the IEA concludes, ‘in the absence of targeted government policies, a return to pre-pandemic behaviours is likely’ (IEA, 2020a). This has two important implications. First, the persistence of COVID-19 impacts should be monitored and tracked to enable robust long-term analysis of net zero pathways and required policy responses. Just as some 2020 impacts may prove transient, other slower-to-emerge impacts may prove important. As an example, market analysts have argued that consumer culture and expenditure priorities will shift towards digital, health, well-being and basic needs fulfilment (Boumphrey, 2020) and it is important that governments anticipate these changes. More immediately, the post-COVID-19 recovery opens up a critical policy window for proactive policies that limit the adverse effects, driving energy demand up while strengthening the beneficial trends. Some examples of strengthening and counteracting policies for the transport and residential sectors are provided in Tables 1 and 2, respectively.

FIGURE 7: REDUCED ENERGY DEMAND FROM COVID-19 AND STRENGTHENING POLICIES

	COVID-19 impact	Strengthening policies
	Increases in active travel and micromobility within cities	Municipal infrastructure for walking, cycling and low-traffic neighbourhoods; fast-track licensing for micromobility providers
Homes	Increase in purchases of new appliances	Scrappage programme for old information and communications technology and domestic appliances; purchase incentives for A+++-rated equipment
Offices	Decreases in occupancy and appliance use	Planning guidelines enabling conversion to residential use and urban densification

FIGURE 8: INCREASED ENERGY DEMAND FROM COVID-19 AND COUNTERACTING POLICIES

	COVID-19 impact	Counteracting policies
	Slowdown in vehicle fleet turnover and new electric vehicle (EV) sales	EV purchase and road tax incentives; stimulus support for EV manufacturing plants; clear timetable for regulatory phase out of petrol and diesel vehicles; increased taxation of fossil fuels for transport
Homes	Increase in occupancy, thermal comfort levels and appliance usage	Retrofit programmes and roll out of smarter zonal heating technologies to reduce heated floor area
Offices	Continued operation of building heating, ventilation and air conditioning systems despite no/low occupancy	Research, development and demonstration investment in modular building energy system designs; incentives for operational energy savings (e.g. green certification and energy labelling)

Macroeconomic impacts of the COVID-19 pandemic and green recovery packages

The COVID-19 pandemic has led to the worst economic downturn of the past decades, with profound implications for employment, trade, investment and sectoral demand. 'Green' recovery packages could provide an opportunity to curb the economic slowdown while addressing environmental concerns. Using two well-established macroeconomic models (GEM-E3-FIT and E3ME), we assessed the macroeconomic, employment and emission impacts of green recovery options supporting the increased deployment of renewable energy, energy efficiency measures and electric vehicles. Our findings indicate that implementation of green recovery packages boosts economic growth worldwide, triggered by increased low-carbon investment, with global GDP increasing by 1.5 % in 2025 and 1.2 % in 2030 and with long lasting impacts, mostly resulting from the accelerated learning-by-doing of low-carbon technologies, both in electricity production and in clean mobility (Figure 9, left).

Green recovery packages would create about 10 million new jobs globally – and about 1.2 million jobs in the EU – over 2025–2030, mostly in the construction sector (triggered by the increased installation of renewable technologies and retrofitting of buildings) and in the manufacturing of electric vehicles and batteries, while other economic sectors would indirectly benefit from the cascade effects through inter-industrial relations. These packages may also lead to structural changes in the economy through increased participation of clean energy industries and reduced production of fossil fuel supply sectors, which are more vulnerable to crises, as manifested in the COVID-19 pandemic, resulting in improved energy security, especially for energy importers like the EU.

Green recovery packages could effectively reduce emissions in major economies by about 10–15 % in 2030 compared with pre-COVID-19 scenarios (Figure 9, right), but they should be combined with long-term ambitious climate policies to pave the way towards net-zero emissions by mid century. Missing out on this moment to scale up climate action would continue to lock many countries into high-carbon economies, and thus governments should seize this opportunity by integrating a clean energy transition into the core of their policy decisions, while trying to maximise socioeconomic and climate benefits.

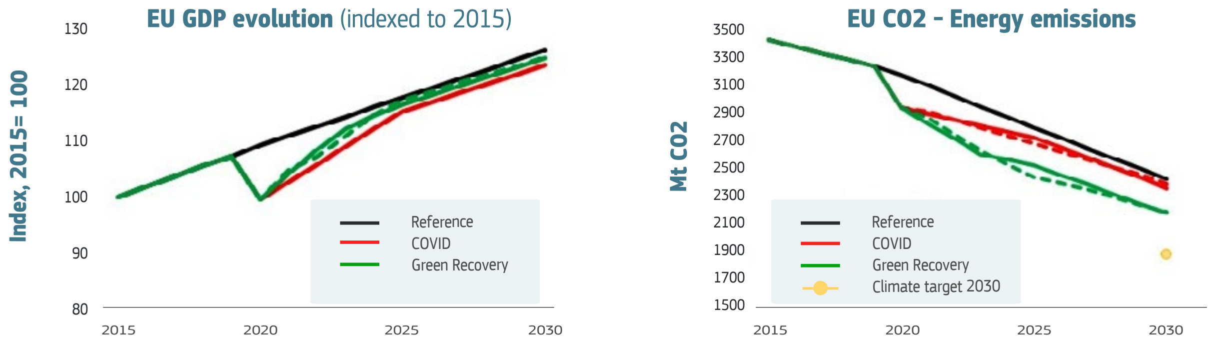

Figure 9: Impacts of green recovery packages on EU GDP (left) and EU energy-related CO2 emissions (right) (solid lines including the reference represent GEM-E3- FIT results; dotted lines represent E3ME results).

- **Policy implications.** The assessment of the economic impacts of COVID-19 and the green recovery packages is subject to deep uncertainty. It is clear though that the pandemic and associated lockdowns have had negative impacts on jobs, incomes, businesses and economic activity. However, green recovery packages can stimulate economic growth through increased investment and productivity (e.g. by phasing out polluting and cost-inefficient activities such as coal mining, while increasing investments in research and innovation, education and skills) and may also lead to structural changes in the economy through increased participation of clean energy industries (e.g. manufacturing and installation of renewable energy systems, production of zero emission vehicles, building retrofits) and reduced production and imports of fossil fuels. Green recovery packages can effectively close the emissions gap in 2030 between current national policies and cost-optimal mitigation pathways to meet the 2 °C target, including the ambitious EU objective of reducing its GHG emissions by 55 % over 1990–2030. The analysis shows that, with green recovery measures, EU CO2 emissions would decline by more than 10 % below reference scenario levels, further reducing the gap with the 2030 European target of a 55 % GHG emissions reduction from 1990 levels. However, these efforts alone cannot deliver the long-term emissions reductions that are compatible with the Paris Agreement goal of climate neutrality, so a significant upscaling of climate policy ambition is required after 2030 to reach net zero emissions in the EU and globally by mid century.

In conclusion, governments worldwide have a unique opportunity today to create new jobs (especially in sectors severely hit by the recent crisis, such as construction), boost sustainable economic growth and reduce GHG emissions by greening their recovery packages, but should also ensure that public spending and support are directed towards competitive firms, sectors and production factors that are compatible with sustainable, environmentally friendly development in the long term. Thus, governments should seize low-cost funding opportunities by integrating climate change and the clean energy transition at the core of their policy decisions. If they fail to do so, they will find themselves locked into a situation with high emissions, low economic growth and excessive debt, coupled with societal tensions resulting from increasing inequalities.

About NAVIGATE

By advancing integrated assessment models in their representation of transformative change and distributional impacts, NAVIGATE provides new insight into how long-term climate goals can translate into short-term policy action, and how countries and sectors can work in concert to implement the Paris Agreement.

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CASCADES/RECEIPT: COVID-19 LESSONS TO RETHINK HOW WE PREPARE FOR THE CLIMATE CHANGE CRISIS

'The COVID-19 pandemic has displayed the multiple interactions between our global networks, revealing unexpected vulnerabilities. To anticipate future similar disruptions from climate change, governments, companies and large organisations must take a systemic perspective on designing risk management policies'

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- **Project title and abbreviation:** Remote climate effects and their impact on European sustainability, policy and trade (RECEIPT, grant no 820712) and Cascading climate risks: towards adaptive and resilient European societies (CASCADES, grant no 821010)

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The COVID-19 pandemic has caused societies around the world to adopt a 'new normal' (Kalantidou, 2021), affecting our lives and almost every socioeconomic sector. This crisis has made clear just how complex and connected our world is. It has also provided lessons to enable us to rethink how we should prepare for global, high-impact cascading disruptions triggered by climate change.

The COVID-19 pandemic and climate change are global crises. They both propagate through interconnected sectors, systems, countries and regions, leading to new, unexpected cascading impacts. A well-known proverb says: 'Make a mistake once and it becomes a lesson. Make the same mistake twice and it becomes a choice'. The COVID-19 pandemic has revealed the vulnerabilities of individuals and communities not only to the direct threat of the disease, but also to the response by public and private entities. Similar factors also govern climate change risks. Learning from the COVID-19 pandemic is important to reduce the underlying vulnerabilities that lead to system failures and to strengthen resilience to climate-related disruptions.

This article provides poignant insights into the cascading effects of the COVID-19 pandemic on trade, supply chains and financial systems. Through the lens of recent publications, we summarise these insights and further reflect on several general lessons learned from the pandemic that support the analysis and responses to complex, systemic and cascading impact chains such as those associated with climate change.

Risks of interrupted trade and food security are amplified by export restrictions and national responses

The EU is the largest economy in the world and the world's largest trading block. Disruptions to supply chains can cause price spikes and potentially even local food shortages. During the first months of the COVID-

19 pandemic, several major agricultural producing nations faced crop yield declines following labour and transport restrictions. Faced with COVID-19-induced market uncertainties, as well as bad harvest prospects, some additional countries implemented export restrictions to secure their domestic food supply. Falkendal et al. (2021) quantified the possible impacts of such export restrictions on global supplies and on the prices of three of the most important food crops: wheat, rice and maize. While local production declines might have only moderate impacts on global prices and supply, trade restrictions and precautionary purchases by only a few key actors could create global food price spikes and severe local food shortages in countries that heavily rely on imports (Figure 10). The resulting supply failures, together with increases in demand due to precautionary stocking by rich import-dependent countries, could lead to food price spikes comparable to those of the last global food crises in 2007/2008 and 2010/2011.

Climate extremes are responsible for a large proportion of food production declines worldwide. Multi-breadbasket failures induced by climatic features such as El Niño and the Southern Oscillation fluctuations affecting multiple production areas simultaneously may lead to shocks that are similar to that experienced during the COVID-19 pandemic. To avoid global food crises, food supply chains and trade should be allowed to operate freely with no far-reaching export restrictions by major producers. In addition, a timely and coordinated international response is needed to minimise food insecurity in times of global crisis.

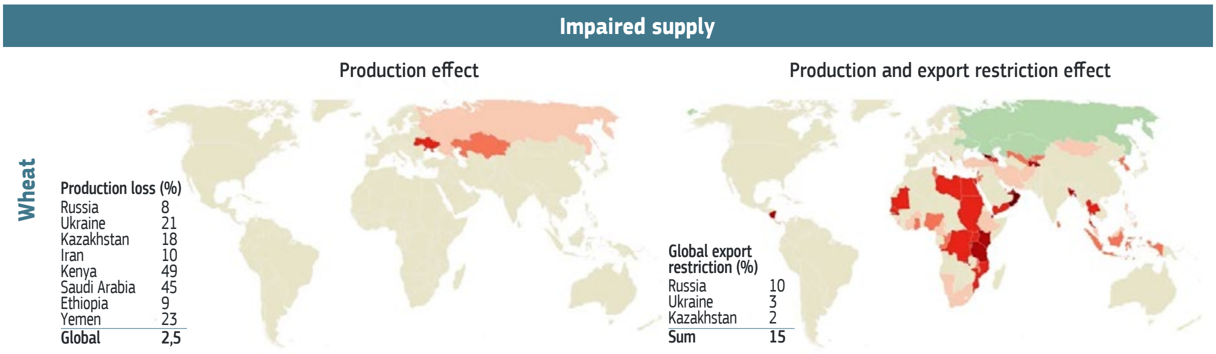

Figure 10: Food security impacts of wheat production failures and unilateral trade policies during the COVID-19 pandemic. The figure shows changes in domestic supply due to potential production declines (left) and export restrictions in addition to production declines (right). The changes in 'impaired supply' (red colours) represent the amount of food a country must cover by tapping into its own grain reserves or increasing imports (Falkendal et al. (2021)).

The finance sector is increasingly aware of climate risks

Insurance, investment and liability agreements lead to exposure of the European financial sector to climate-induced financial risks. In emerging countries, climate risks can quickly compound with pre-existing financial vulnerabilities, leading to cascading economic and financial impacts. To avoid risk underestimation and design effective post-disaster recovery policies, macroeconomic models need to be improved to embed the characteristics of complexity and non-linearity of compound risk (Mahul et al.,2021).

In this context, Dunz et al. (2021) tailored the EIRIN macrofinancial model (Monasterolo et al., 2018) to provide the first assessment of the direct and indirect impacts of the combined COVID-19 and climate hazards on the economy, financial stability and public debt sustainability. The model is stock-flow consistent and endogenises the financial sector and market to assess the conditions for amplification of compound risk in the economy, taking into consideration the fiscal and monetary policy responses. Application of the model to Mexico – which is highly exposed to hurricanes and highly interconnected in the global economy – showed that compounding physical climate risks and COVID-19 risks can amplify losses, with significant implications for the sustainability of private and public debt, which, in turn, could tame the positive effects of government spending. Indeed, the tightening of banks' lending to firms, to keep regulatory capital in the face of deteriorating economic conditions, could prevent firms' access to recovery investments. This, in turn, limits the effectiveness of public investments for economic development on the one hand, and contributes to the increase in public debt on the other hand, thus limiting fiscal space for climate-aligned investments.

Hochrainer-Stigler (2021) compared fiscal stress with disaster risk before and during the COVID-19 pandemic. A dramatic increase in fiscal risk following natural disasters was found for nearly all countries in the world – a trend that is especially alarming for countries that are already very climate vulnerable.

What have we learned from the COVID-19 pandemic?

The examples above illustrate the vulnerability of our global networks to systemic risks. The impacts of the COVID-19 pandemic rippled through interconnected networks around the world. Although governments, civil society and businesses responded quickly, they could not prevent the large-scale cascade of impacts on health, income, well-being, the environment and social equality (Figure 11).

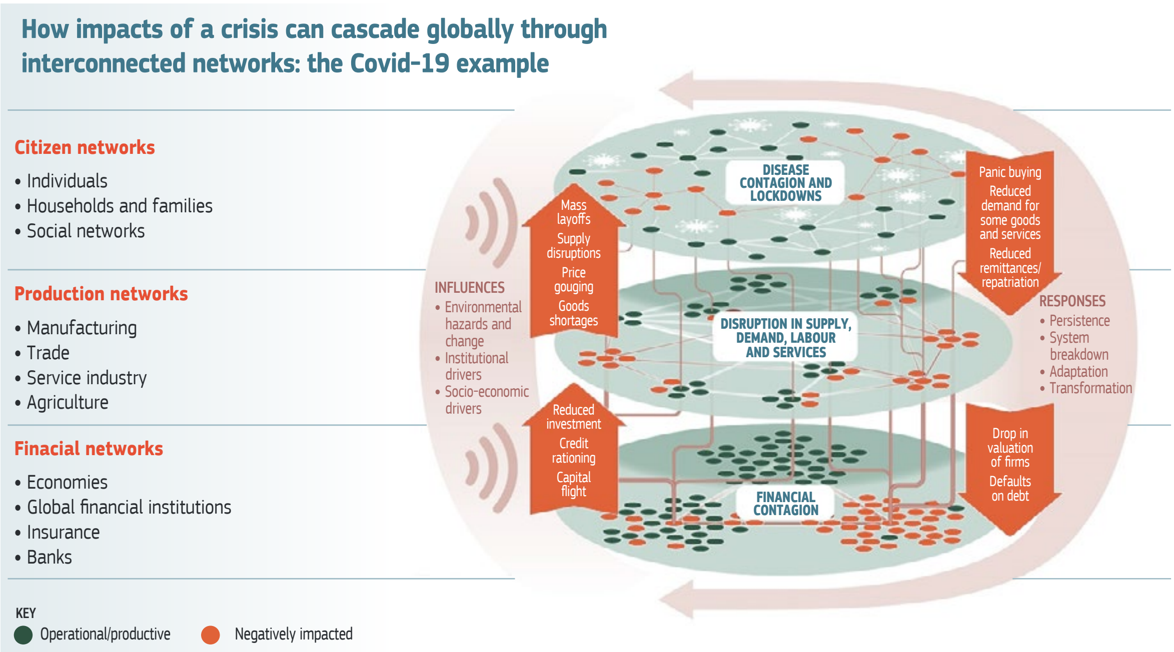

Figure 11: How the impacts of a crisis can cascade globally through interconnected networks: the COVID-19 example (Van den Hurk et al., 2020).

To anticipate future disruptions from climate change, governments, companies and large organisations must take a 'systemic' perspective on designing risk management policies, instead of a strategy in which every actor takes isolated measures. Actions for approaching climate change as a systemic risk include the following:

- apart from mapping direct (local) impacts of climate extremes, explore possible cascading effects across regions and sectors;
- investigate possible event combinations (compound events) that can amplify impacts;
- consider putting systemic risk and resilience strongly centre stage in multilevel decision-making across scales and sectors to inform climate-resilient development pathways.

The multiple interconnections challenge the identification of and response to future climate change impacts. Various science-based tools and concepts are available to identify the pronounced uncertainties and incorporate them in effective policies. Analytical frameworks exist (Carter et al., 2021) that allow transboundary climate change impacts, responses and their propagation to be mapped. Dedicated storylines of high-impact climate events (Shepherd et al., 2019) enable plausible cascading impacts to be explored and improve the insights into the exposure and vulnerability of specific sectors to foreseeable changes in the extent, intensity or frequency of climate extremes in a warmer world. The dynamic adaptive policy pathways approach (Haasnoot et al., 2013) is a proven concept for exploring future policy pathways in response to changing insights and developments that affect the effectiveness of a range of policy strategies. The policy pathways are displayed as a metro map, including policy options, strategic tipping points and (environmental and societal) drivers of policy targets. The COVID-19 pandemic has provided inspiration for climate-proof strategies informed by a portfolio of credible and comprehensive cause–effect chains.

The COVID-19 pandemic has also shown that resilience, understood as the ability to 'bounce back' after a crisis, needs to be reinvented in the face of compounding and systemic risks. A 'building forward' approach to resilience (Surminski et al., 2016) helps design effective disaster risk reduction investments by expanding on the traditional risk reduction considerations and including co-benefits and positive socioeconomic outcomes of risk reduction measures. For this, performance metrics should integrate long-term economic and societal stability considerations, next to social and intergenerational equity. Efforts towards the formulation of coherent policy should include the explicit identification of the entity that carries responsibility for systemic risk management. In addition, national and international solidarity mechanisms can be redesigned in order to encourage multilateral action towards recovery from widespread shocks. The creation of 'knowledge exchange hubs', for example, would allow rapid access to science, technology and guidance to support practical implementation. The development of COVID-19 vaccines is a good example of collaboration between countries that provides effective solutions to external shocks. However, the experience shows that stronger collaboration is also needed further downstream.

An excellent contribution to a broader definition of resilience in the face of changing global challenges is the consultation effort (International Institute for Applied Systems Analysis, n.d.) initiated in 2020 by the IIASA and the International Science Council. These two institutions have brought together experts from all over the world to learn lessons from the COVID-19 crisis for managing other imminent crises, such as climate change. The experts suggested that it would be desirable for the international community to complement risk surveys with an international resilience dialogue that engages policymakers, civil society, the private sector and the scientific community in identifying appropriate governance, prevention and preparedness options for compound and systemic risks, particularly for building the resilience of the most vulnerable (Mechler et al., 2021).

The impacts of the COVID-19 pandemic are still being felt and will be debated for years to come. This also applies to climate change, which is likewise characterised by considerable uncertainty and potential surprises – the notorious 'unknown unknowns'. Science and technology has proven to be a trusted partner in dealing with the COVID-19 crisis. It can play a similar role in understanding and guiding local and global responses to climate change.

About RECEIPT and CASCADES

RECEIPT and CASCADES are two ongoing projects funded under the EU's Horizon 2020 research and innovation framework programme. Both projects assess Europe's vulnerability to climate change impacts that occur outside its borders. It has already been observed that local impacts of tropical cyclones, floods, droughts and excessive heat can spread globally through international collaboration and economic networks. Climate change will affect the intensity, frequency, spatial patterns and co-occurrence of high-impact events in nearly every region of the world, thereby affecting European exposure to climate change. RECEIPT and CASCADES are exploring transboundary climate impact chains for multiple types of climate features, transmission pathways and consequences for Europe.

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ENGAGE: FROM COVID-19 SHOCK TO GREEN RECOVERY

'A low energy demand recovery reduces the costs of meeting Paris Climate Agreement targets, requires a slower system-wide post-recovery decarbonisation rate, and reduces challenges around the electrification of transport and expansion of renewable electricity. Ample opportunities exist for policies to drive the transition in this direction'

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- **Project title and abbreviation:** Exploring national and global actions to reduce greenhouse gas emissions (ENGAGE, grant no 821471)

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- **CORDIS project website:** https://cordis.europa.eu/project/id/821471

The COVID-19 crisis hit during the initial stages of the ENGAGE project and the consortium was able to integrate the potential game-changing nature of this crisis into the assessment of the multidimensional feasibility of climate mitigation pathways and into explorative new emissions pathways. In this article we show that the initial COVID-19 shock reduced coal use in the power sector, that policymakers expect that the pandemic will increase substantially the commitment to policies supporting the transition to low-carbon energy and transport sectors, and that a low energy demand recovery would reduce the costs of meeting the Paris Agreement climate targets.

Immediate impacts of COVID-19: understanding power sector dynamics

As part of the ENGAGE project, Bertram et al. (2021) explored the impacts of the COVID-19 pandemic on the power sector. Global power sector CO2 emissions showed a substantial decline during the lockdowns in 2020, thanks to (i) the COVID-19-induced economic downturn and resulting reduction in electricity demand and (ii) a reduction in the carbon intensity of power generation, as coal generation accounted for the largest decline. These effects illustrate the opportunity for different policies to support a structural and accelerating reduction of power sector emissions.

Even before the COVID-19 pandemic and its impact on the energy system and CO2 emissions, the power sector was undergoing a dynamic transformation process. While fossil fuels (predominantly coal and gas) are used to generate most power in most countries, renewable energies are dominating growth in global power generation. In this context, the moderate reduction in electricity demand stemming from both direct restrictions on industry, commerce and other activities and the overall economic downturn has had a particularly strong impact on power sector emissions. Bertram et al. (2021) analysed real-time data by fuel type up to the end of September 2020 for India, the United States and Europe, which together accounted for 34 % of global CO2 emissions from power generation in 2019. In these three markets, average monthly electricity demand in 2020 declined by up to 20 % compared with 2019, while monthly CO2 emissions from the power sector decreased by up to 50 % (Figure 12). This is because of the 'merit order' effect on the capacity mix of different generation technologies. If demand falls, power plants with the highest variable costs are switched off first. Fossil-fuel-based power plants incur costs from burning fuels to generate electricity whereas the costs of renewable and nuclear power are dominated by the construction cost of the power plants. As a result, these renewable and nuclear technologies are characterised by low variable costs per kilowatt-hour and thus operate even under reduced demand. This merit order mechanism induces an asymmetry against fossil fuels in the electricity generation mix, and therefore CO2 emissions decrease more strongly than electricity demand.

Even within fossil fuel generation, Bertram et al. (2021) found that reductions in power generation were greater for coal than for natural gas, increasing the downwards trend of coal use in Organisation for Economic Co-operation and Development (OECD) countries. This is a counterintuitive finding, as traditionally natural gas power plants are thought to be less favourably placed on the merit order due to higher fuel costs. However, the fast and broad economic downturn during the COVID-19 crisis reduced demand for oil and natural gas in all sectors, leading to lower spot-market prices for gas and favouring gas-powered generation. Coal prices have also fallen, but this has a smaller impact on the variable costs of coal-based power generation. The effect of switching from coal to gas has additionally been supported in Europe by emissions prices[4] in the EU emissions trading system (EU ETS), contributing further to unfavourable economics for coal-based power generation.

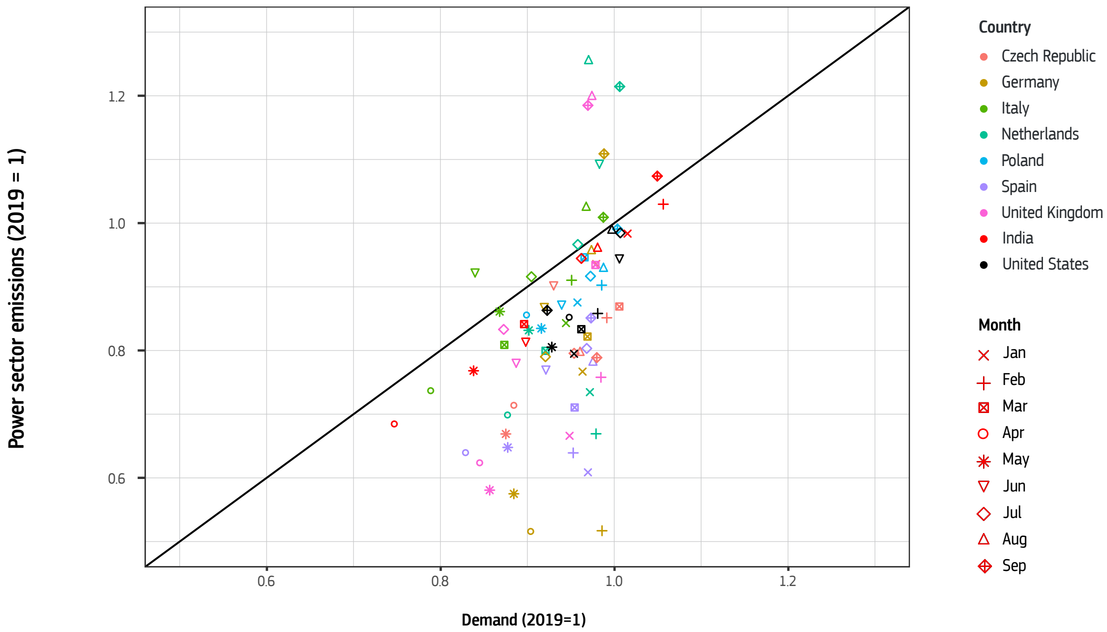

Figure 12: Monthly power demand and emissions in 2020 relative to 2019. Emissions were calculated from fossil generation data by fuel for European countries with the highest power sector emissions from the European Network of Transmission System Operators for Electricity. Indian data are from carbontracker.in. US data are from the Energy Information Administration, calculated from fossil generation data by fuel. February data were adjusted to account for 2020 being a leap year. (Bertram et al. (2021))

Bertram et al. (2021) highlight that the power sector has a crucial role to play in the decarbonisation of the entire energy system and that it was already in the midst of a dynamic transformation process before the COVID-19 pandemic. The economic repercussions of the pandemic have led to a very pronounced reduction of fossil-fuel-based power generation, illustrating the risks of stranded assets in coal power generation for financial actors. While there is considerable uncertainty in near-term projections, it is possible that power sector CO2 emissions will not return to their 2018 levels. In another ENGAGE contribution, Cherp and Jewell (2020) explored the political economic implications for the next few years of the energy transitions induced by the COVID-19 pandemic. They expect that phasing out unabated coal power requires both breaking the lock-in of the established coal regimes and rapidly expanding low-carbon alternatives. In many industrialised

4. While EU ETS prices dropped from EUR 25 per tonnes of CO2 to EUR 15 per tonne of CO2 at the beginning of the COVID-19 crisis, they recovered to EUR 25–30 per tonne of CO2 by the summer of 2020

countries with stagnating electricity demand, it is primarily coal lock-in that is slowing the needed transition. Such countries already have economically viable renewable power sectors that can expand faster than the electricity demand and replace coal power. Several rich and well-governed countries that both produce and use less coal and have older power plants have pledged to phase out coal before 2030, but it is proving more difficult for countries with larger coal sectors, such as India, South Africa and China (Jewell et al., 2019). The story in developing countries is quite different because of their rapidly growing electricity demand, which requires the addition of new power capacity. Very few of these countries have committed to phasing out coal power and many keep expanding their coal power generation capacity (Edenhofer et al., 2018).

Fortunately, the COVID-19 pandemic may ease this boom in coal power plant construction because the economic downturn has dampened electricity demand and may make capital investment harder to come by. Furthermore, construction in countries such as Vietnam relies on international finance and supply chains and may be hit especially hard because cross-border trade and investment has been severely disrupted by the pandemic. The other side of the challenge, expanding the use of low-carbon alternatives to coal, is also different for developing countries. In principle, they could reduce the need for new coal power plants by massively expanding the generation of wind and solar electricity, which has increasingly favourable economics, but in practice their renewable sectors are still not growing fast enough to meet electricity demand growth, let alone replace coal. Cherp and Jewell (2020) expect that the pandemic has slowed the growth of renewables due to lower demand growth, the shortage of investment, and the disruption to supply chains, international technology diffusion and policy exchange due to a decrease in international interaction. The last factors are especially painful, because renewables depend on international technology and policy diffusion much more than coal power.

On balance, Cherp and Jewell (2020) expect the COVID-19 pandemic to have more profound impacts on electricity transitions in developing and emerging economies, where the bulk of electricity use in the 21st century is expected. To support developing countries in choosing low-carbon electricity, it will be essential to quickly re-establish and increase international flows of low-carbon investment, technology, capacity building and policy expertise.

Expected impacts on climate policy: a stakeholder survey

To understand if and how climate policy expectations for the next 5 years in various sectors and regions may have changed as a result of the COVID-19 pandemic, ENGAGE researchers surveyed over 200 policymakers and stakeholders from 55 different countries (Pianta et al., 2021). The study focuses on policies pertaining to the decarbonisation of the energy and transport sectors, which are responsible for over 70 % of CO2 emissions. The study found that, while support for high-emitting sectors is not expected to dissolve completely, commitment to policies supporting the transition to low-carbon energy and transport sectors is expected to increase substantially (Figure 13).

However, survey respondents see the risk that some critical factors may water down the recovery phase's transformative potential. In general, expectations are more optimistic in countries with higher per capita income and higher past climate performance (Figure 14). Significant decarbonisation action taking place only in a subset of highly emitting advanced and developing economies might be sufficient to accelerate global decarbonisation and kick-start the required technological change. On the one hand, commitment to policies supporting decarbonisation is expected to increase in OECD and Asian countries. This represents an opportunity to reduce emissions across various sectors. The power sector will be at the core of this transformation, given the expected surge in green infrastructure and renewable power production investments. Notably, there are positive expectations for several policies with high potential to be economic multipliers and have a positive climate impact, including energy efficiency investments, clean research and development, and investments in clean energy infrastructure (Hepburn et al., 2020). On the other hand, some results are less promising. Latin American respondents tended overall to be more pessimistic. Support for incumbent, high-emitting sectors is also likely to continue in most regions, with more bailouts for airline companies deemed extremely likely. Interestingly, respondents working for governments have more optimistic expectations than respondents from non-governmental organisations and research institutions (Figure 14).

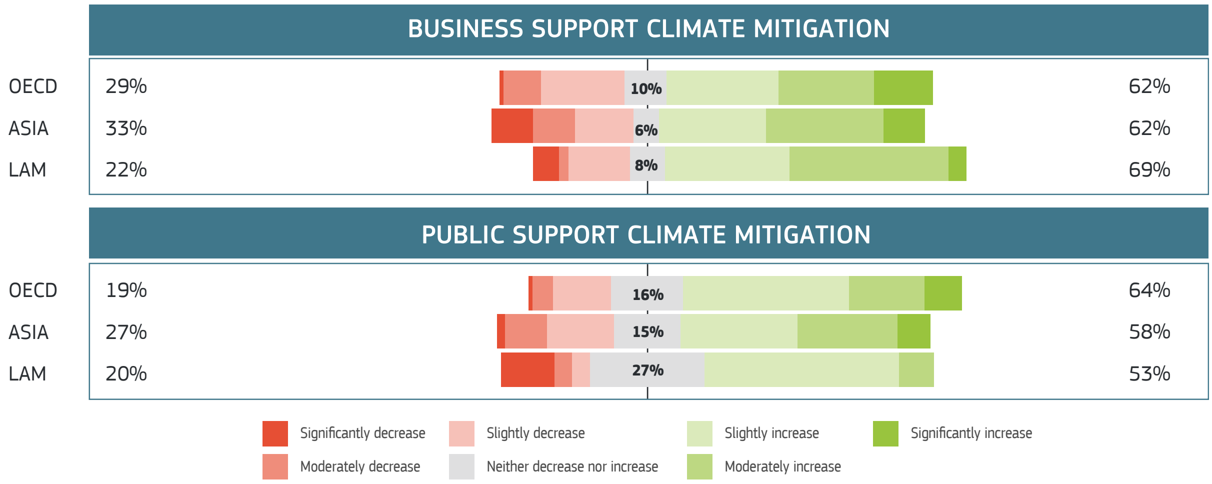

Figure 13: Expected public and business support for mitigation. Likert-scale plot of the answers to the questions on expected trends in business support for climate mitigation and public support for climate mitigation in the next 5 years for OECD, Asian, and Latin American and Caribbean (LAM) countries. Answers are based on a seven-point Likert scale ranging from 'significantly decrease' to 'significantly increase'. (Pianta et al. (2021) (ENGAGE))

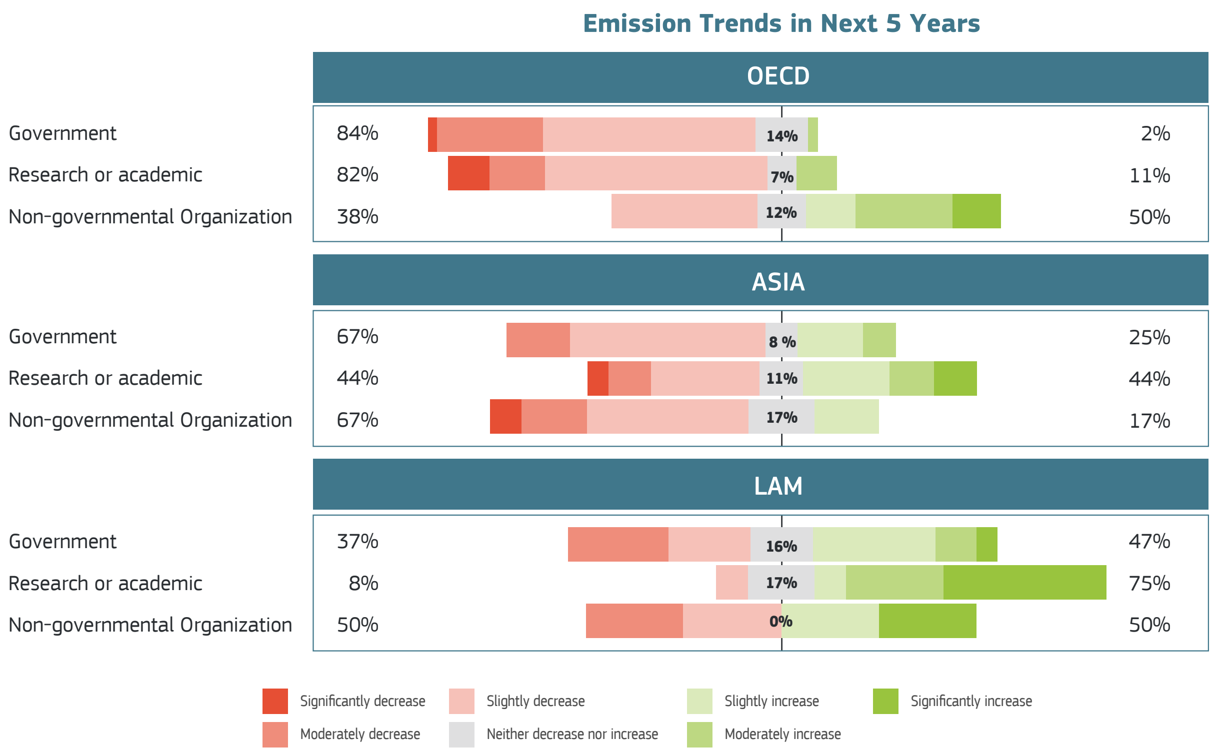

Figure 14: Expectations about emissions trends among respondents working for different organisations. Likert-scale plot of the answers to the question on expected emissions trends in the next 5 years for OECD, Asian, and Latin American and Caribbean (LAM) countries, and for respondents working for governments, research or academic institutions, and non-governmental organisations. Answers are based on a seven-point Likert scale ranging from 'significantly decrease' to 'significantly increase'. (Pianta et al. (2021) (ENGAGE))

Reducing long-term mitigation challenges: a low energy demand recovery

In a final study, ENGAGE researchers assessed the potential effect of COVID-19-induced impacts on energy demand through recovery scenarios that vary the persistence of the changes observed over 2020 (Figure 15). This quantitative global analysis explored how the near-term COVID-19 shock and alternative medium-term recovery pathways of demand-side changes may affect long-term energy demand.

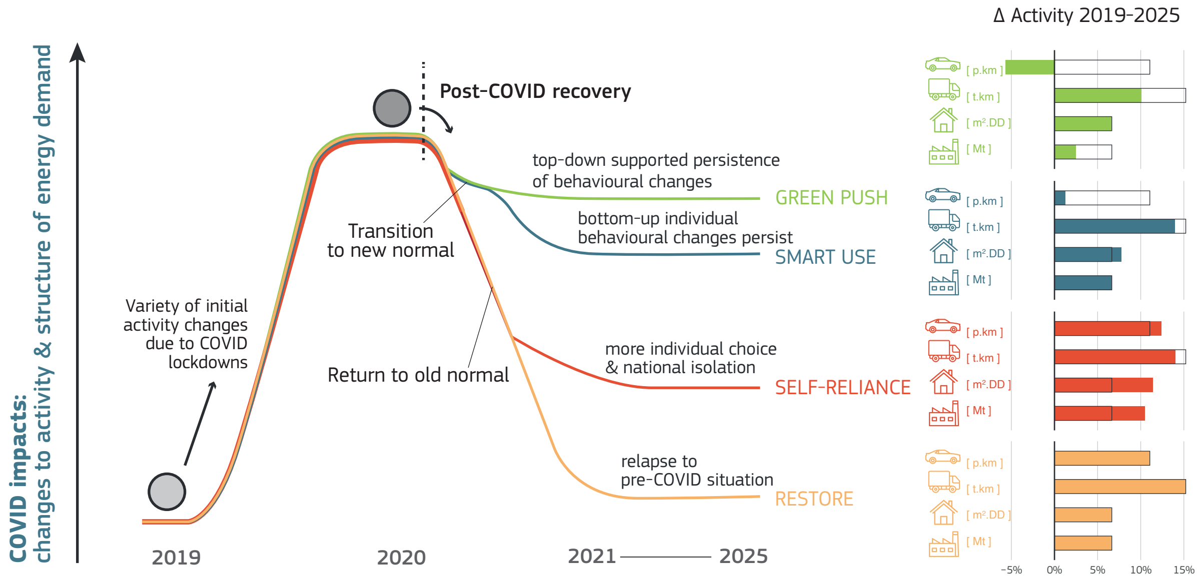

Figure 15: Scenario design along the axis of COVID-19-related impacts. Note that the y-axis denotes disturbance from pre-pandemic 'normality', not increase in demand. Bar charts show relative changes in energy-related activity between 2019 and 2025 in transport (passenger, freight), buildings and industrial sectors for the four recovery pathways. The boxes outlined in black indicate the 2019–2025 change in the restore scenario and serve as a common reference point for the self-reliance, smart use and green push scenarios. Indicators are passenger-kilometres (p.km), tonne-kilometres (t.km), metre squared-degree days (m2.DD) and material production in million tonnes (Mt). (Kikstra et al. (2021))

The study found that enabling a low energy demand recovery can help reduce the costs of meeting Paris Agreement climate targets. The full sectoral contributions to CO2 emissions savings from demand-side changes include both direct end-use emissions and indirect effects on emissions from manufacturing, supply chains and production. After accounting for upstream effects, the CO2 emissions savings related to the pandemic that could persist are predominantly transport related.

While there is no magic bullet for reaching Paris Agreement climate goals, this study shows that guiding the post-pandemic recovery in energy demand-related activities towards less energy-intensive activities is an important part of the arsenal. For example, measures supporting working from home and teleconferencing that reduce flying and commuting can have strong beneficial outcomes for emissions, especially if combined with the rationalisation and reduction of office space and other workspaces and a reduction in administration, entertainment and shopping spaces.

While the effects of the persistence of energy demand changes alone are not sufficient to meet emissions reduction targets, there are important benefits to reducing the transformation challenge. A low energy demand recovery from the pandemic will lessen the required system-wide post-recovery decarbonisation rate. It will also reduce investment needs in energy supply by up to USD 1.8 trillion (9 %) globally until 2030. A low energy demand recovery will also lessen the electrification challenge for transport when passenger mobility recovers from the COVID-19 pandemic, and help reduce the challenges in expanding renewable electricity production.

Summary of policy implications

- When electricity demand decreases, as during the COVID-19 crisis, or grows slower than expected because a low energy demand recovery, higher operational costs for fossil fuels will reduce their use in electricity production. Policies that increase the price of fossil fuels will increase this effect.
- Policymakers expect that support for high-emitting sectors will not dissolve completely during the COVID-19 recovery but are optimistic about the commitment to policies supporting the transition to low-carbon energy and transport sectors.
- Stimulating and maintaining low energy demand practices during the recovery from the pandemic will reduce the transformation challenge in reaching the Paris Agreement climate goals.

About ENGAGE

The ENGAGE project aims to inform and guide strategies to deliver on the objectives of the Paris Agreement by engaging policymakers, industry and civil society leaders in co-producing a new generation of global and national decarbonisation pathways. These new pathways supplement natural science, engineering and economics, traditionally represented in integrated assessment models, with cutting-edge insights from social science to reflect the multidimensional feasibility of decarbonisation and identify opportunities to strengthen climate policies.

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LOCOMOTION: TOWARDS A SUSTAINABLE, GREEN POST-COVID-19 RECOVERY

'The fact that the roads to a just and sustainable energy transition remain tainted with uncertainties underscores the importance of implementing sound energy and economic policies. The major challenge lies in identifying a set of virtuous combinations of supply-side (efficiency and structural change) and demand-side (energy reduction and expansive fiscal policy) measures'

- **Authors:** Jaime Nieto (University of Valladolid), Luis Fernando Lobejón (University of Valladolid) and Luis Javier Miguel (University of Valladolid)

- **Project title and abbreviation:** Low-carbon society: an enhanced modelling tool for the transition to sustainability (LOCOMOTION, grant no 821105)

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- **Project website:** https://www.locomotion-h2020.eu/
- **CORDIS project website:** https://cordis.europa.eu/project/id/821105

LOCOMOTION

The policy response to an unprecedented crisis

The IMF estimates that the COVID-19 pandemic crisis struck the world economy during 2020, with a contraction of 3.5 % in GDP growth rate (IMF, 2021a). Initially, the advanced economies suffered the most (– 4.9 %), especially in the euro area (– 7.2 %) and the EU (– 5 % by October 2020) (IMF, 2020, 2021a). However, the IMF's July 2021 update revised the figures for the advanced economies upwards, specifically mentioning the expectations of the expansive fiscal policy response in the United States and the EU (IMF, 2021b). This shows that further policy action is paramount to overcome the ongoing crisis and future similar situations. If we focus just on the economic consequences of the COVID-19 crisis, it is clear that both the supply side and the demand side have been severely affected, in different ways. On the one hand, general or partial lockdowns curtailed the production capacity of the economy (supply side), with some sectors, such as the transport, tourism and hospitality sectors, more severely affected than others, being directly hit by lockdowns and by the reduction in demand. On the other hand, factors that contributed to the slump in demand were the fall in income and the increase in uncertainty of many businesses, leading to a contraction of capital investment (IMF, 2021a), which will clearly restrain the growth capacity of the EU's economy in the medium term.

As a consequence, public intervention has become necessary to tackle the negative economic impacts of the crisis. In the EU, the economic recovery policies have created an opportunity to increase the ambition of the EU's green transition, tightening the 2030 GHG emissions target from a reduction of 40 % to a reduction of 55 % compared with 1990. The European Green Deal, which entails policies aimed at boosting, for example, renewables, energy efficiency, the circular economy and environmental protection, is going to be reinforced with the NextGenerationEU programme, with 37 % of the EUR 750 billion budget set aside for green investments. In combination with the Just Transition Mechanism, the green transition will be used as leverage to restore income, employment and economic growth in the EU. Therefore, it is paramount to evaluate the effects of this set of policies early on in order to meet both the socioeconomic and the environmental ambitions, as well as explore the potential conflicts and trade-offs and search for more adequate policy pathways.

With this purpose, the LOCOMOTION project analysed four scenarios of green transition / decarbonisation pathways using the integrated assessment model MEDEAS-EU[5] (Nieto et al., 2020), a model nested within the wider MEDEAS-World model (Capellán-Pérez et al., 2020). The scenarios allow the exploration of different policy options for designing a green post-COVID-19 recovery that addresses both social and environmental sustainability, represented by employment and GHG emissions, respectively.

Modelling assumptions and scenarios

MEDEAS-EU is an integrated assessment model based on system dynamics that considers the economy as a subsystem of the social and biophysical system. Thus, unlike most conventional integrated assessment models, the environment conditions the productive capacity of the economy in several ways. For this analysis, the availability of energy resources and labour supply were considered, which effectively restrain the economy's productive capacity. Details of the methodology used are provided in the Supplementary Information in Nieto et al. (2020). As a simulation model, the objective was to explore different pathways that do not assume optimal behaviour or take the targets for granted, that is, the GHG emissions reduction is an objective that might or might not be achieved under different policy assumptions or scenarios. Thus, we defined and simulated four scenarios to explore possible pathways to sustainability in the EU by 2050. These scenarios were linked to energy use reduction targets – broken down in different sources – according to the 2050 energy roadmap (European Commission, 2011) and the EUCO scenarios[6] (E3MLab and IIASA, 2016). The four scenarios were as follows.

- Base. Unrestrained economic growth and energy demand with no policies.
- Business as usual. This scenario simulates a return to pre-pandemic policies and average trends for final economic demand, labour productivity, primary income distribution, the sectoral structure, energy efficiency and the energy mix. It is considered that total primary energy use (TPEU) is that of the EU's 2016 reference scenario (– 10 % by 2050 compared with 2015).
- Green growth. This scenario simulates a narrative that relies on high levels of investment, energy efficiency and a shift to renewables. As a consequence of the additional public and private investments and social expenditure policies, wages increase in the primary income distribution and so does the final economic demand. Investments aimed at obtaining greater efficiency gains improve the productivity of all the skills levels (low, medium and high) of the labour force and lead to greater efficiency in all the economy sectors. The available energy use is considered to follow the path of the more ambitious EUCO+33 scenario: 33 % lower than the 2016 reference scenario by 2030, projected to 2050.
- Post growth. In this scenario, in addition to the green growth supply-side efficiency gains, demand management policies gain momentum, for example promoting collective and public transport and an overall reduction in transport needs, fostering building retrofits and promoting a change in diet. There is a reduction in working time but not at the expense of hourly wages, so labour has a greater weight in the primary income distribution, and there is a shift to less energy-intensive sectors (the primary, light industry, repair and electricity sectors compared with the mining and refinery sectors) and more labour-intensive sectors (education, health, social work, etc.). This structure leads to lower labour productivity growth and final economic demand compared with the green growth scenario, but the change in the energy mix is the same. To meet the EUCO+44 targets (44 % lower than the 2016 reference scenario by 2030), the available energy use (TPEU) is restrained at that level up to 2050.

5. "Modelling the Energy Development under Environmental And Socioeconomic constraints"
6. The EUCO scenarios were produced in the context of the 'Clean energy for all Europeans' package, to help estimate the potential impact of the EU's climate and energy targets for 2030.

The uncertain pathways to sustainability

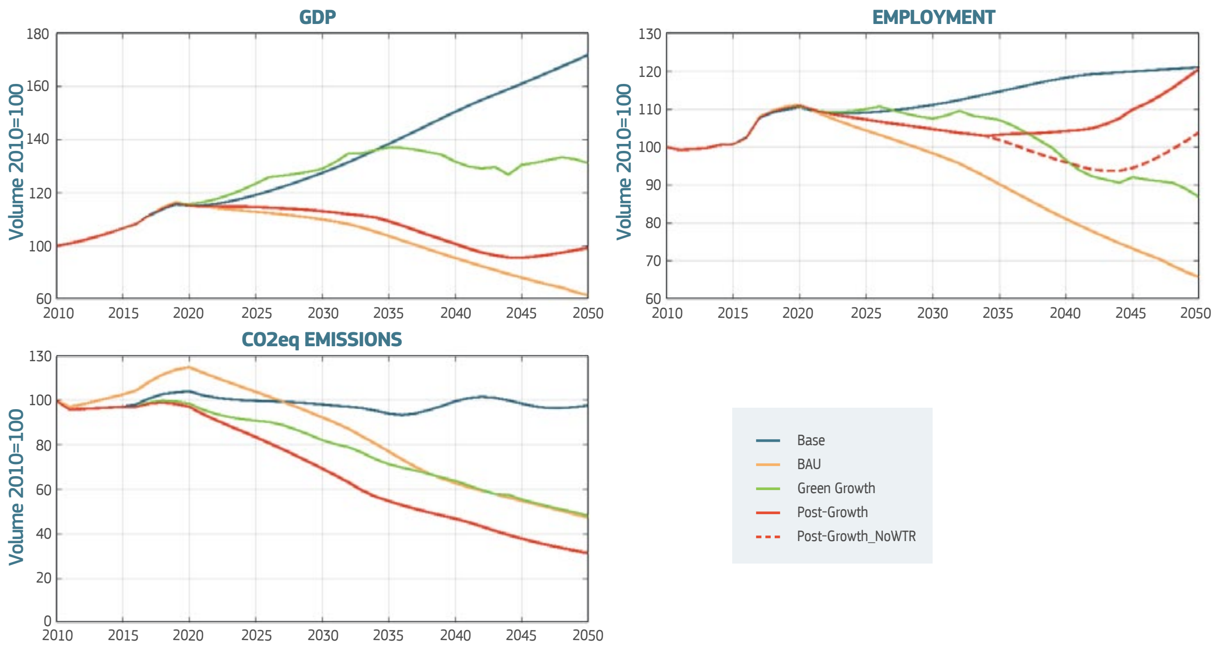

Figure 16: Simulation results for the four scenarios. CO2eq, CO2 equivalent. (Nieto et al., 2020)

The simulations (Figure 16) show that the return to pre-pandemic trends (the business-as-usual scenario) would lead to large declines in GDP and employment: insufficient efforts to reduce the energy demand and phase out fossil fuels would entail an increase in energy dependency, eventually leading to lower economic growth. As a result, GHG emissions would increase at first and would only decline due to the economic downturn. Therefore, there would be huge social costs due to rising unemployment if no energy transition to renewables was undertaken. The EU could always 'free-ride' and increase its energy use while the rest of the world reduces its use, resulting in a failure to meet the EU's climate commitments. Eventually, however, this would negatively impact the EU's economy through climate change damages, which are not accounted for in our simulations. Therefore, the business-as-usual scenario would drive the EU to a dead end either way.

The green growth scenario would lead to a paradox, as a rebound effect on energy use would appear. The investment in green technologies and the shift to renewables would produce virtuous spillover effects on the economy, leading to greater economic growth (even above that in the base scenario). However, the increase in energy demand would mean that the energy efficiency gains are insufficient to meet the EUCO+33 scenario TPEU. Energy efficiency may be restrained by biophysical and economy-wide limits (De Blas, 2019; Paoli and Cullen, 2020), especially given that the energy intensity (energy per unit of GDP) is already low in Europe. Moreover, energy efficiency itself is also subject to rebound effects with regard to demand (Blake, 2005; Duarte et al., 2013; Polimeni and Mayumi, 2015), whereby higher efficiency typically leads to a reduction in prices, followed by an increase in demand that tends to reduce the initial efficiency effect. As a consequence, only a slowdown in economic growth would reduce the energy use in the EUCO+33 scenario –if no alternative policies are applied. Moreover, during the high growth period, the huge labour productivity gains would contain employment creation, which would turn into employment destruction after the economic slowdown. Finally, GHG emissions would not fall enough to meet the climate targets by 2050 due to the rebound in energy demand, as described above.

The constrained demand and huge reduction in energy use in the post-growth scenario would imply a stagnant final demand and GDP growth. Nevertheless, here the employment creation rate is higher than labour productivity growth and, after an initial decrease, labour creation would be restored. This feature is especially relevant when the working time reduction is applied (red solid line in Figure 16). Thus, it emerges as a relevant policy tool, as there is evidence that it reduces GHG emissions by inducing more sustainable consumption patterns, improves health and well-being, reduces inequality and sustains employment (D'Alessandro et al., 2020; King et al., 2017; Wiedenhofer et al., 2018). The difference between the red dotted and solid lines shows the relevance of the working time reduction policy, as the former represents the same scenario excluding this policy. Reduced demand, the increase in share of renewables and the supply- and demand-side efficiency measures lead to the greatest reduction in GHG emissions of all scenarios.

Conclusions: The necessity of multidimensional policies for a green post-COVID-19 recovery

Uncertainty is a natural feature of social and economic systems, and this is especially valid with regard to the COVID-19 pandemic – there will not be a unique pathway to prosperity in the post-pandemic world. Scenario analysis allows a comprehensive assessment of policy. Our research highlights the different trade-offs between the economy (measured in terms of GDP), society (employment) and the environment (GHG emissions). The fact that the road to a just and sustainable energy transition remains tainted with uncertainties makes the implementation of sound energy and economic policies even more necessary. This implies the need to identify virtuous combinations of supply-side (efficiency and structural change) and demand-side (energy reduction and expansive fiscal policy) policy measures.

To summarise, the most important policy implications of the results obtained are as follows (see also Figure 17).

- Policy inaction (base scenario) would drive the EU towards massive climate free-riding (and not meeting the EU's environmental targets), which would have climate change impacts in the future. The business-as-usual scenario, that is, a return to pre-pandemic trends, would imply an economic and social downturn, exacerbating social tensions and threatening political stability in the longer term.

- A shift in the energy mix towards renewable energy would contribute to achieving the climate goals and to a reduction in common respiratory diseases, which cause premature deaths and which have aggravated the effects of the pandemic. This would not only improve well-being and life expectancy, but also increase labour productivity.

- An overall reduction in energy use is required to meet the climate goals, as it will take (a long) time to significantly step up primary renewable energy use, and dedicated measures are needed to avoid any potential rebound effects.

- Given the limited capacity to achieve additional improvements in energy efficiency, an excess of confidence in supply-side energy efficiency gains would likely harm the economy in the medium term and would also not be effective in meeting the climate goals.

- It is not advisable to apply or incentivise austerity measures by governments (expenditure cuts) and firms (wage reductions), as in the 2008 and euro-area crisis responses. The supply-side pandemic effects have already contributed to crippling the economy's productive capacity through lockdowns and other disruptions.

- An expansionist demand-side economic policy such as the NextGenerationEU programme may contribute to accelerating the energy transition, as well as to sustaining and even increasing the level of disposable income. This would be especially applicable to those European regions that have been hit hardest by the crisis, with higher unemployment rates and which are operating below their economy's maximum capacity.

- For these policies to be effective in meeting the climate goals, reducing the EU's energy demand is paramount, which requires structural change.

- Industrial policy should be proactively used as a tool to drift the economy towards sectors with lower material and energy requirements, as well as to promote those sectors that create more and better quality jobs. Sectors meeting these three requirements are those related to social, education and health services, whereas the information technology and renewables sectors provide high-quality jobs and create synergies to reduce the material and energy demands of the economy.

- Working time reduction contributes to adopting more sustainable consumption patterns and, given the challenge in sustaining employment while reducing energy use, it emerges as a powerful policy option.

- Energy demand-side policies should support the following:

  - transport: a shift in freight from heavy trucks to electric rail, accompanied by a general change to light vehicles and a reduction in demand, especially for air transport (de Blas et al., 2020), but also a shift from polluting private transport to low- or zero-carbon collective transport;
  - building (dwellings and offices) retrofitting;
  - behavioural change and a shift in social awareness and towards meat-reduced diets, etc. (Creutzig et al., 2016, 2018; Grubler et al., 2018; Owen et al., 2018);
  - other: a shift to light industry while improving the efficiency of industrial processes.

For these policies to be effective, they should be implemented from a viewpoint of resilience building, considering potential future pandemics and a low-energy regime. Policy inaction and insufficient net energy use reduction are dead ends that lead to free-riding in the short term, but also to an unavoidable economic downturn, energy import dependency and eventually to catastrophic climate change in the medium/long term. Therefore, the policies' starting point should rely on the energy shift to renewables and the net reduction in economy-wide energy use. From the socioeconomic point of view, austerity measures will only aggravate the economic consequences of the COVID-19 pandemic and other possible future pandemics. Considering this, economic expansionist demand policies combined with structural change measures that enable the transition towards less energy- and less resource-intensive sectors/activities should be aligned with a simultaneous set of policies aimed at reducing energy demand. A green post-COVID-19 recovery offers a unique opportunity to drive the transition to sustainable prosperity, with economic, social and environmental benefits for Europe and its citizens.

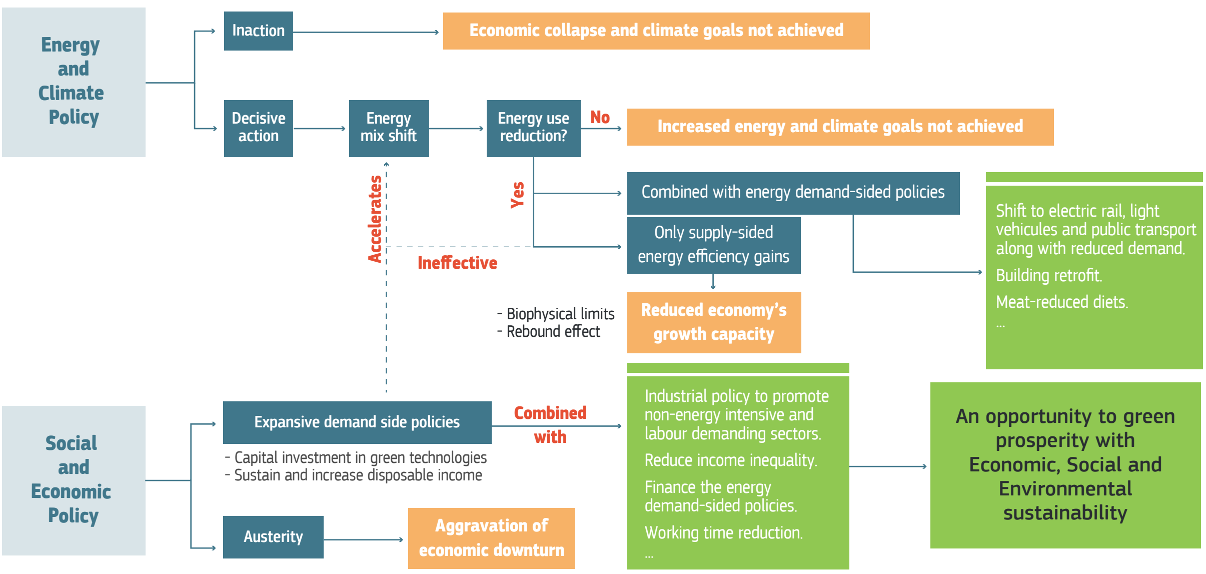

Figure 17: Policy decision-making flow chart presenting recovery options.

About LOCOMOTION and the MEDEAS model

The model is driven by demand, meaning that it is primarily consumption and investment by households, firms, the government and the rest of the world that determines the level of economic activity. Demand depends on economic expectations, population growth and primary income distribution. The economy modelled is broken down into 35 economic sectors, which allows for a more accurate and nuanced analysis of the results. Demand is connected with production (supply) through input–output analysis, which implies that the demand for goods and services from one sector increases not only the production of that sector but also the production of the auxiliary industries that supply the sector (direct and indirect effects). Energy and labour demand depend on the sectoral energy intensity and labour intensity – equal to the inverse of energy efficiency and labour productivity. Once the energy demand by the different final sources is estimated, the energy module of the model and the employment submodule estimate whether there is sufficient energy and labour supply to satisfy the demand. If this is not the case, then the feasible production is lower than expected and, hence, economic growth is curtailed.

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PARIS REINFORCE: INVESTIGATING OPTIMAL ALLOCATIONS FOR GREEN RECOVERY FUNDS

'Channelling COVID-19 recovery funding into clean energy technologies can help drive EU emissions down further, while significantly boosting near- and long-term employment'

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- **Project title and abbreviation:** Delivering on the Paris Agreement: a demand-driven, integrated assessment modelling approach (PARIS REINFORCE, grant no 820846)

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The COVID-19 crisis has had dramatic economic consequences in Europe. Despite significant public interventions, more than 1.8 million jobs were lost in the EU up to September 2020. As fiscal stimulus measures continue to be announced, policymakers have an opportunity to ensure that the short-term stimulus points the economic recovery in a sustainable direction in the long term, considering the trade-off between these goals.

This article investigates this trade-off between short-term economic gains, in the form of employment, and longer-term CO2 emissions reductions from fiscal stimulus packages. Analysis was performed to identify the optimal energy investment mix of proposed fiscal programmes in terms of new energy sector jobs and CO2 emissions cuts compared with a current policy baseline (Nikas et al., 2021).

We focused primarily on the EU-27 plus the United Kingdom but also analysed five other major emitting regions: Canada, China, India, Japan and the United States. For each region, the total recovery budget analysed is described in the 'recovery budget selection' box below. Seven technologies were considered: advanced biofuels, biomass, solar photovoltaics (PV), concentrated solar power, onshore and offshore wind, and nuclear. The analysis compared portfolios with different investment weights for each of these technologies.

We found that green recovery funds can help the EU create up to 1.4 and 0.4 million new job-years by 2025 and 2030, respectively, and further cut emissions by 300–800 MtCO2. Despite heterogeneous implications for each region, both the EU and the five major emitting countries will benefit from greener agendas, on their way to recovering from the COVID-19 pandemic.

RECOVERY BUDGET SELECTION

For the **EU**, the Recovery and Resilience Facility (RRF) is the largest component of the NextGenerationEU programme, the bloc's landmark recovery instrument. The RRF is intended to provide up to EUR 312.5 billion and EUR 360 billion in grants and loans, respectively. Based on (i) the EUR 75 billion of the RRF's green pillar, which is expected to be channelled into clean energy projects on the selected technologies, excluding related infrastructure investments (e.g. storage) (EY, 2020), and (ii) EUR 5 billion from the UK fiscal plan (HM Government, 2020), a maximum budget of EUR 80 billion (**USD 96 billion**) was selected.

China announced a significant recovery package of around USD 740 billion, one third of which is in the form of quotas for special bonds issued by local governments for infrastructure. Currently, the lack of central government guidelines on the types of projects that should be prioritised for investment may lead to the budget flowing towards conventional energy projects. Here, we assumed that about 30 % of the budget can be used for projects related to the technologies of interest in our study, and assessed what would be the best allocation if a budget of **USD 60 billion** was used for green investments.

In the **United States**, of the three fiscal plans for recovery, only the second package accommodates a dedicated budget (**USD 26 billion**) for investments related to the technologies analysed here (The New York Times, 2020), and this is the budget used in this research. This, however, does not include recent pledges by the Biden Administration, which (despite holding a lot of promise) are still under formulation and are thus omitted from the analysis.

In **India**, of the nearly USD 400 billion package announced, only **USD 10 billion** are allocated towards energy (Observer Research Foundation, 2021), with most of this heading to the coal sector. As with China, we used this budget to carry out a what-if analysis, exploring how to optimally allocate it to support green energy.

Finally, **Canada** and **Japan** have pledged that **USD 17.6 billion** (Government of Canada, 2021) and **USD 19.2 billion** (International Institute for Sustainable Development, 2020) from their respective COVID-19 recovery packages will be dedicated to support the green transition. Because of the vague nature of the pledges, these amounts were used without further assumptions.

The EU: optimal allocation of green recovery funds for clean energy

In the EU, Member States were invited to submit national recovery and resilience plans describing reforms and public investment projects they plan to implement with RRF support by 30 April 2021. The EU is among the frontrunners in the ‘swift green recovery’, considering that other countries focus most of their climate efforts in the context of their NDCs and longer-term strategies, thereby opting to allocate small amounts from COVID-19-dedicated fiscal plans to mitigation efforts; in some cases, recovery finance flows towards conventional fossil fuel infrastructure projects.

When looking at near-term employment opportunities, we calculated a potential for 1.1–1.4 million new job-years[7] by 2025 and a capacity for cumulative emissions cuts of 550–800 MtCO2 up to 2030 compared with a policy baseline accounting for all policies as of early 2021 (i.e. excluding those aimed at delivering the updated 55 % target for 2030). However, portfolios performing well in relation to employment were suboptimal in terms of emissions cuts, and vice versa. The former tended to rely heavily on onshore and offshore wind (USD 74 billion and USD 21 billion, respectively) while, when shifting priorities towards emissions cuts, investments shifted from offshore wind to biofuels (USD 19 billion) (Figure 18a).

A key question is whether employment gains can be sustained in the longer run. We calculated that technology subsidisation portfolios creating the most jobs in 2025 (1.4 million job-years) quickly lose momentum, leading to negligible job gains over the entire decade (with less than 20 000 new job-years by 2030). This signals that subsidising technologies that are already on track for further diffusion in the decade, pushed by current policies regardless of the RRF expenditure support, will only speed up investments (and thus the creation of energy jobs) in the near term, without longer-term gains. We also observed that RRF expenditures aimed at emissions cuts appear less sensitive to underlying uncertainties (with onshore wind and biofuels clearly standing out) than those focused on near-term employment opportunities. This implies high competition among technologies if maximising short-term employment gains is the main objective.

We therefore further investigated green RRF expenditure in terms of emissions reductions and new employment in the energy sector, both by the end of 2030. In this case, considering that early stages of project development (i.e. extraction/manufacturing and installation) feature more jobs than later stages

7. Years of work for one person, used here to aggregate different types of jobs triggered by an investment (operation and maintenance, construction, etc.).

(operation and maintenance), we found that the potential for new energy jobs is limited to 0.4 million job-years by 2030, which is still much higher than the end-of-decade impact of shorter-term planning. However, opting for this longer-term sustainability of energy employment opportunities does not undermine emissions cuts (300–800 $MtCO_2$ in 2030). Compared with shorter-term planning, boosting employment at the end of the decade requires heavy investments in offshore wind (USD 63 billion), biomass (USD 24 billion) and biofuels (USD 6.5 billion). Setting a goal to drive emissions down further, compared with a scenario that attempts to maximise jobs, is not as robust and results in half the budget being spent on onshore wind and the other half on biofuels (USD 29 billion), offshore wind (USD 12.3 billion) and nuclear power (USD 10 billion). Contrary to a short-term planning strategy, portfolios maximising job gains until 2030 are more robust to uncertainty, mostly driven by poor employment gains of those prioritising emissions cuts (Figure 18b).

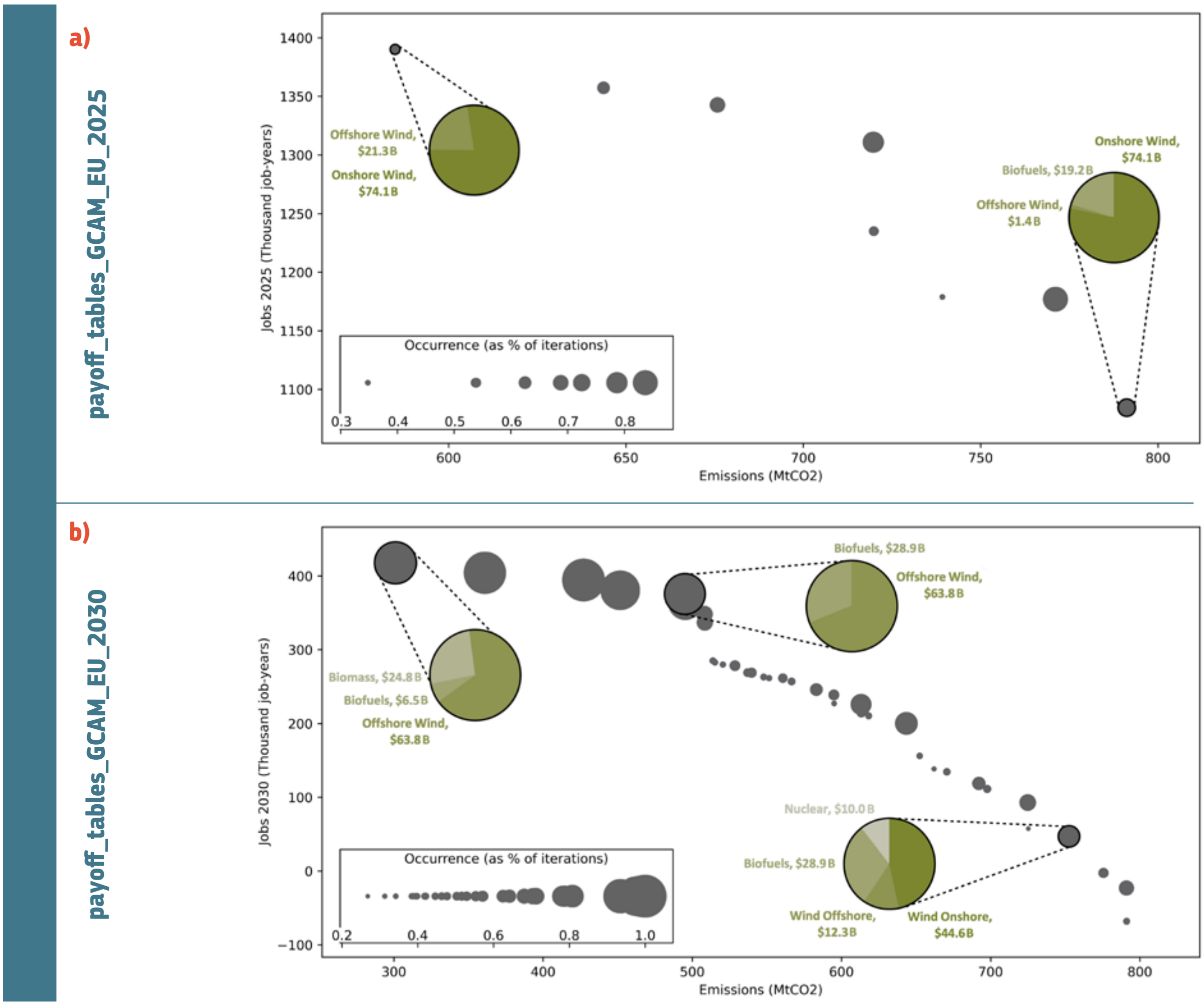

Figure 18: Optimal green RRF subsidy portfolios in terms of further emissions cuts (x-axis) and new employment opportunities in the energy sector (y-axis) (a) Short-term planning, emphasising employment by 2025 and (b) Long-term planning, emphasising sustainable new energy jobs by the end of 2030 (bubble size indicates robustness against uncertainty pertubations).

Given these dynamics, we explored if the technological mix can be diversified towards a better balance between near- and longer-term employment gains, by aiming to optimise emissions cuts, employment by 2025 and employment by 2030 simultaneously. We observed that near-optimal budget allocations tend to favour mostly wind and biofuels, complemented by small shares of biomass, nuclear power and solar PV. After accounting for uncertainty over emissions and employment gains, we indicatively isolated a balanced, robust portfolio comprising offshore wind, biofuels, onshore wind and biomass (USD 63.8 billion, USD 11.8 billion, USD 16.1 billion, and USD 3.2 billion, respectively), achieving about 0.5 $GtCO_2$ of emissions cuts by 2030 and an additional 0.85 and 0.35 million job-years by 2025 and 2030, respectively. This trade-off with new energy sector jobs in the short term is necessary to offset the potential reduction in job gains by the end of the decade, without jeopardising the potential for emissions cuts (Figure 19).

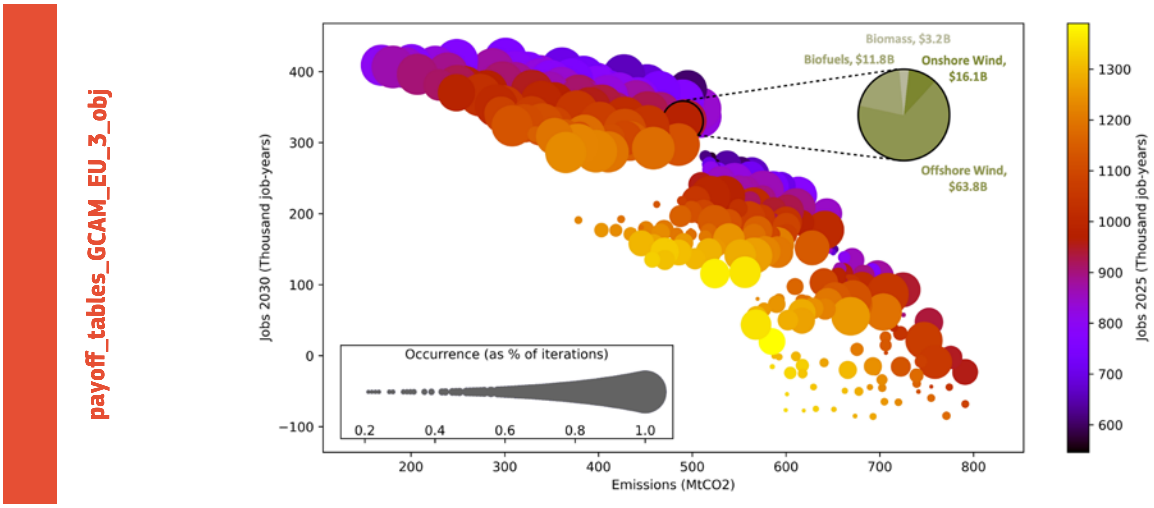

Figure 19: Optimal green RRF subsidy portfolios in terms of further emissions cuts (x-axis) and long-term (left-hand y-axis) and near-term (right-hand y-axis) employment gains in the EU (bubble size indicates robustness against uncertainty perturbations).

Implications of green expenditures from COVID-19 relief packages in other regions

We then extended the analysis to five other major emitters: Canada, China, India, Japan and the United States (Figure 20). We used a similar baseline, developed in the PARIS REINFORCE project, to capture the implications of current policies in these regions (Giarola et al., 2021; Sognnaes et al., 2021).

In the United States, employment prioritisation displays limited diversification, with heavy investments in solar PV, but also more robust performance compared with boosting emissions cuts, which in turn shifts funding towards biofuels, followed by onshore and offshore wind. We also observed a consistent tendency, regardless of the optimisation's time horizon: considering all three priorities (emissions reduction, job-years created by 2025 and job-years created by 2030), a balanced portfolio comprises solar PV, biofuels, onshore wind and nuclear power (USD 18.5 billion, USD 4.7 billion, USD 1.4 billion and USD 1.2 billion, respectively), with a potential for 165 MtCO2 of further cuts by the end of the decade and about 0.56 and 0.25 million new job-years created by 2025 and 2030, respectively.

Canada's case is very similar, although job creation is more evenly split between solar PV and onshore wind. Prioritising emissions cuts also showcases a shift away from solar power to biomass (instead of biofuels), as well as onshore wind and nuclear power. Employment-wise, seeking a viable investment mix in the longer run benefits more from biomass than from wind technologies.

In China, however, analysis highlights challenges in maintaining long-term positive net jobs until 2030: investing in solar PV can accelerate new employment in the energy sector, yet with negative employment impacts over the entire decade. This traces back to the negative effect on employment of subsidies for renewable technologies over the entire decade, due to significant employment losses in the labour-intensive coal mining sector. A more balanced investment mix, mainly subsidising offshore wind (about USD 40 billion), with few investments in solar PV (USD 17.6 billion) and onshore wind (USD 2.4 billion), could yield about a million new job-years by 2025 and 0.25 GtCO2 of emissions cuts up to 2030, while still having a positive employment effect up to 2030 (100 thousand job-years).

In India, the observed diversity in optimal energy investment mixes reflects the current need for a clearer policy direction. Heavy biomass investments could yield longer-term employment effects, as opposed to PV subsidies, which could drive near-term gains but have negative impacts by the end of the decade. Finally, although featuring few employment benefits, wind investments have the potential to deliver bolder emissions cuts (mostly offshore wind).

Finally, Japan shows a completely different story: a strategy overemphasising creating new energy jobs in the near term could significantly hamper employment gains and emissions cuts in the country by the end of the decade. Maximising shorter-term climate and job gains would require further penetration of solar PV and onshore wind; a diversified investment mix of solar PV, onshore wind, offshore wind, nuclear power, biomass and biofuels (USD 12.6 billion, USD 1.3 billion, USD 0.3 billion, USD 4.1 billion, USD 0.2 billion and USD 0.6 billion, respectively) could yield more sustainable results in both horizons (352 000 job-years in 2025, as well as 165 000 job-years and 123 MtCO2 emissions reductions by 2030), hinting that the utility-based solar market is not yet mature in the country.

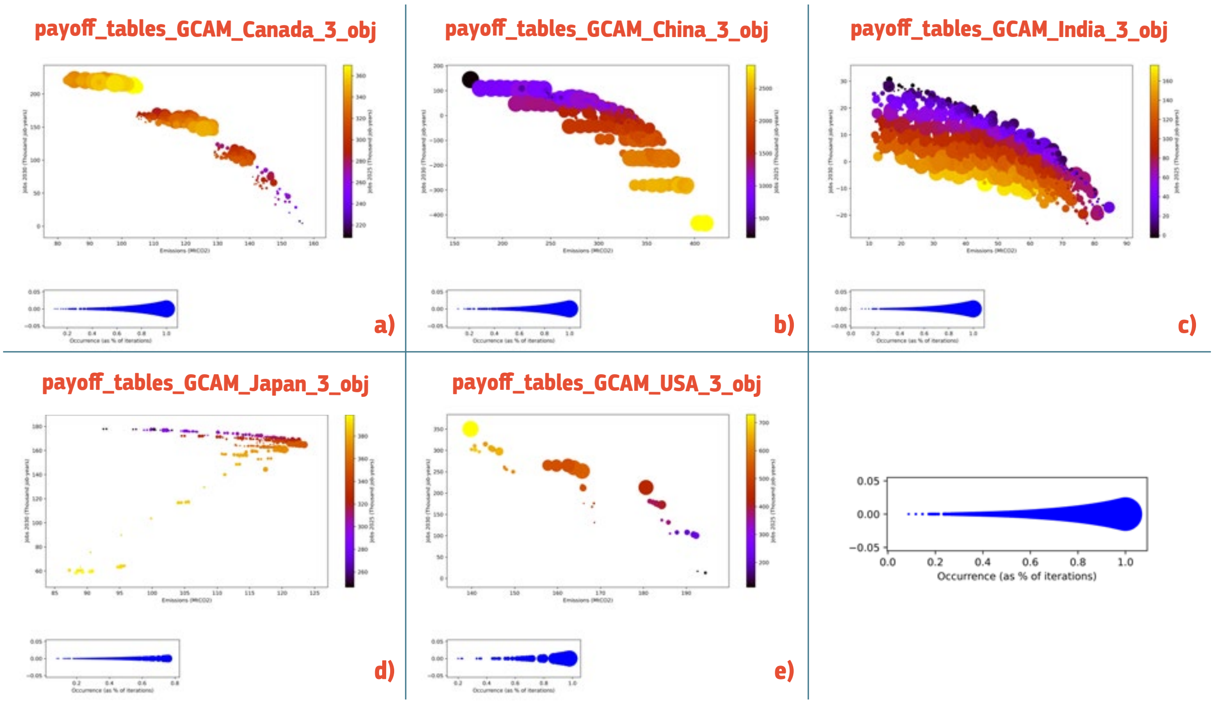

Figure 20: Optimal green use of COVID-19 relief packages in energy technologies in terms of further emissions cuts (x-axis) and long-term (left-hand y-axis) and near-term (right-hand y-axis) employment gains in (a) Canada, (b) China, (c) India, (d) Japan and (e) the United States (bubble size indicates robustness against uncertainty perturbations).

POLICY RECOMMENDATIONS

- There is a clear trade-off between subsidy portfolios performing well in terms of employment and those performing well in terms of emissions reductions. Onshore and offshore wind investments significantly boost energy sector employment, while investments into biofuels are found to perform relatively better for further emissions mitigation (caution is, however, needed regarding their sustainability and availability, especially with regard to advanced biofuels).
- Investment portfolios favouring already cost-competitive technologies (such as onshore wind and solar PV) may create the most jobs by 2025 but will quickly lose momentum, leading to negligible jobs gains over the entire decade. This is because certain investments only pull forward employment opportunities that would have been created anyway before the end of the decade under the current policy framework.
- On the other hand, prioritising currently less cost-competitive technologies (such as offshore wind and concentrated solar power) may alter the trajectory expected under current policies, allowing for diversification of technological capacity with an ongoing positive effect in the future and the creation of longer-lasting job opportunities.

About PARIS REINFORCE

PARIS REINFRORCE is a Horizon 2020 research and innovation project that aims to underpin climate policymaking with authoritative scientific evidence and to enhance the science–policy interface. It has developed a demand-driven integrated assessment framework to effectively support the design and assessment of Paris-compliant climate policies, building on exhaustive facilitative dialogue, a large ensemble of integrated assessment models, robustness analysis and transparent data exchange. In this article, the global change analysis model (GCAM) is combined with a portfolio analysis framework (Forouli et al., 2020) to investigate different technology subsidisation portfolios for the selected budgets for each country. We provide an analysis on maximising employment gains until 2025, as well as employment gains until 2030 and CO2 emissions reductions until 2030. This is an ex post analysis drawing from the observed, well-recorded employment implications of energy projects (Rutovitz et al., 2015) (including work in collaboration with colleagues from the Horizon 2020 projects ENGAGE and NAVIGATE (Pai et al., 2021)) and the latest available insights into the possible synthesis of green recovery-related funds and projects[8]. We also examine the impact of uncertainty over employment and CO2 emissions effects of subsidies using Monte Carlo analysis, to add robustness to the policy recommendations. Throughout the study, we define robustness as a metric to calculate exposure to uncertainties related to the performance of a single investment in terms of jobs created and emissions cuts achieved (we assume a ± 5 % range in the GCAM outputs for each subsidy).

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The recent report of the Intergovernmental Panel on Climate Change could not have been clearer about the urgent need to act on the climate crisis if we want to save the planet and ourselves. Although the COVID-19 pandemic has been a stark reminder that our well-being depends on the health of the planet, the recovery strategies offer a once-in-a-century opportunity for a genuine paradigm shift towards a society that respects planetary boundaries.
What advice can the research community give to policymakers at this critical moment, against the backdrop of the decisive UN Climate Change Conference (COP26), to help them shape a greener, more equitable and prosperous future for all? EU-funded Horizon 2020 projects have some ideas.

Studies and reports

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