DOES COVID-19 HELP OR HARM THE CLIMATE? MODELLING LONG-RUN EMISSIONS UNDER CLIMATE AND STIMULUS POLICIES

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Does COVID-19 Help or Harm the Climate?

Modelling Long-run Emissions under Climate and Stimulus Policies

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Abstract

We propose a model of global energy competition, GLO-COV, to shed light on long-run effects of COVID-19. It accounts for the joint impact of lockdown, economic stimulus programs and climate policy on CO_2 emissions. The model also captures the role of peak oil. It incorporates evolutionary self-reinforcing dynamics which allows addressing path-dependence and lock-in. The model is empirically calibrated on historical energy demand, economic growth, emission intensity, and factors specific to COVID-19. The resulting long-term assessment complements previous studies that focus on short-term effects of the pandemic. We find that without countervailing climate policy, COVID-19 increases long-run emissions. With a carbon tax already in place, COVID-19 leads to lower emissions than scenarios without the pandemic or without policy. On their own, climate and stimulus policies increase variability of, and thus uncertainty about, emissions, while their combination reduces variability. A further advantage of combining stimulus and carbon taxation is that it creates strong synergy, resulting in maximal reduction of long-term emissions.

Keywords: climate change, economic crisis, energy, lock-in, path-dependence, tipping points

JEL classification: C63, Q42, Q54

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1. Introduction

There has been much speculation about how the COVID-19 pandemic will affect climate change and policy. Lockdown has been used as an emergency measure restricting individuals to leave their house or area in an attempt to slow down transmission of the disease. In some countries and periods this has included local, regional, or even national curfews. The direct economic effects of these measures include a decline in shopping, less use of restaurant and hotel services, and even interruptions in supply chains. In addition, telework has become more common, in turn reducing mobility and altering demand for electricity and heating (Bateman, 2020; Jackson et al., 2020). Higher expenditures on health care and sickness leave or even mortality of productive people have added to the negative economic consequences of COVID-19. In this paper we model the effect of such negative shocks of COVID-19 on the market dynamics of energy sources and on associated CO_2 emission patterns.

Few studies have investigated the long-term effects of COVID-19 and associated lockdown measures on energy use and global warming. Such effects can take two routes: economic consequences of lockdown that translate in less steep paths of energy use and emissions; and political consequences due to society becoming more open to stringent climate policies which in turn reduce emissions considerably. Many studies have speculated about the latter (Howarth et al., 2020; Markard and Rosenbloom 2020) and a few have even tested for it (Gosens and Jotzo 2020; Engler et al., 2021; Drews et al., 2022; Savin et al., 2022). We focus here on the first issue, which has received much less attention by accounting for the interaction with public policies in terms of mitigating greenhouse gas emissions and stimulating a recovery from the economic crisis induced by COVID-19. Smith et al. (2021) undertake a rare statistical study to test for short-term effects and consider what happens under carbon tax by simulating a higher coal price – as arguably that price will be most affected by carbon pricing. This is however a very crude way to examine carbon-tax impacts. In addition, they do not account for economic stimulus programs or behavioural factors, as we do. Stimulus packages have been observed in all countries, taking the form of market subsidization of various kinds – energy, products or labour (IMF, 2021). Behavioural factors are relevant to consider as they may play a large role in long-term impacts of economic crises.

In our study we consider the competition between fossil fuels and renewables, with the aim of obtaining a more complete picture of long-term effects of COVID-19 on the economy, energy use and emissions. In addition, we study how these effects interact with the ongoing dynamics of energy use and competition, notably peak oil/gas effects[1], and with carbon tax affecting differentially coal, gas/oil and renewables as these have distinct carbon intensities. Moreover, we will test for the potential positive synergies of economic stimulus policies and carbon taxation as suggested by several authors (Engström et al., 2020; Galbraith and van den Bergh, 2020; Mukanjari and Sterner, 2020).

To this end, we develop a variant of an earlier evolutionary model of global competitive dynamics of energy sources (Zeppini and van den Bergh, 2020) which builds on the theoretical framework of lock-in and path-dependence in the style of Arthur et al. (1987) and Arthur (1989). This can be seen as part of research on "evolutionary environmental economics" (van den Bergh, 2007). This model, which we call hereafter GLO (standing for "GLObal competition dynamics

[1] Peak oil/gas denotes a situation where oil and gas become very scarce, in turn causing their prices to sharply rise. This can be caused by exhaustion in the long run or by supply chain disruptions (e.g., resulting from political conflicts as in the Russia-Ukraine crisis). One might think that the concept of peak oil/gas is not relevant in the context of climate policy as the latter will restrain the use of fossil fuels. However, the current situation is that the world is not on a schedule to meet the Paris goals of 1.5 or even 2 degrees Celsius (UNEP, 2021). In line with this, fossil fuel use is expected to still increase for some time (IEA, 2021).

of energy sources"), describes the future patterns of coal, oil/gas, solar and wind. A detailed description is provided in Appendix A.

The classification of energy sources in the GLO model was adopted to capture differences in emission intensities, profitability, and innovation potential. Aggregating oil and gas into one variable was done for two reasons: (1) oil and gas are more similar and both rather distinct from coal in terms of carbon intensity and price dynamics – as attested by the pattern of oil and gas prices following Russian's invasion in Ukraine; (2) this allows the model to describe both two distinct fossil fuels (coal and oil/gas) and two distinct renewables (solar and wind – which differ in terms of starting cost and learning curve).

The model simulates the global energy demand by production and consumption sectors in the economy as well as the composition of energy supply in terms of fossil fuels and renewable energy. Combining the two allows one to assess the consequences for carbon emissions. The model accounts for the impact of learning curves and climate policies on energy use and emissions. Our earlier study found, among others, that peak oil will induce a transition to coal, in turn augmenting emissions. The model further could identify policies that solve the climate problem, i.e. do not surpass the critical carbon budget, and that are robust in terms of final market shares of energy sources.

The GLO model is part of a line of research employing a behavioural approach to improve our understanding of economic and innovation dynamics. It describes aggregate economic phenomena as the emergent outcome of coordination of decisions by individuals within a population (Bao et al., 2012). In particular, the GLO model accounts for the effect of increasing returns to scale and learning curves in prospective sustainability transitions (Mathews, 2020), which makes it suitable to deal with issues known as reinforcing effects, positive feedback, threshold effects or tipping points, which underly economic crises and instability phenomena in all kinds of systems (Antal and van den Bergh, 2013). Traditional macroeconomic models lack such features, and for this reason have been criticized as inadequate to accurately warn for crises or predict their consequences (Akerlof, 2002; Caballero, 2010).

The extension of the GLO model proposed in this paper, called GLO-COV, accounts for the consequences of COVID-19, including of lockdown measures, on energy sources and associated CO_2 emissions. The latter discouraged commuting, shopping, leisure and holiday trips, and associated travel by car and plane. To model relevant mechanisms in this respect, we can build upon recent empirical studies about the past impact of COVID-19 on global fossil fuel consumption (Smith et al., 2021), and about investment during the pandemic in clean energy versus fossil fuel firms (Wan et al., 2021). Our analysis goes beyond these studies in that it adopts a longer time perspective and considers potential future impacts under scenarios of climate and economic stimulus policies or combinations thereof. Stimulus policies have been implemented by many countries already, with Germany, Italy, Japan and USA having stimulus outlays ranging from about 25% to over 50% of annual GDP.[2] The relevance of studying the combination of climate and stimulus policies is illustrated by the EU stimulus package which amounts to €806.9 billion, to a large extent devoted to encouraging low-carbon solutions, such as renewable energy support.[3]

The GLO model was empirically calibrated on historical energy demand, economic growth and emission intensity (see Section 3 in Zeppini and van den Bergh, 2020). The GLO-COV model builds upon the GLO model and extends the calibration to include factors and impacts specifically related to COVID-19 (for details see Appendix C). It has been speculated that the pandemic might change habits of certain consumers, in terms of telework, commuting, holidays, etc. A review of the literature is offered by Jiang et al. (2021). Among others, they suggest that in terms of commuting a sharp fall in the use of private cars during lockdown may be followed by a

[2] https://www.statista.com/statistics/1107572/covid-19-value-g20-stimulus-packages-share-gdp/
[3] https://ec.europa.eu/info/strategy/recovery-plan-europe_en

sharp increase. According to Sui et al. (2020), 56,3% of previous bus users might shift to other transport means to avoid risky contact with strangers, especially during rush hours. They also note that the peak time for electricity demand by firms and households changes due to COVID-19 lockdown, which may affect requirements for stable supply of energy (see also Zhang et al., 2020). Moreover, they refer to more utopian writings that use concepts like new lifestyles in cities with lower energy usage: e.g., "15 min city" and "20-minute neighbourhoods" to reduce travel, congestion, and local air pollution, or "self-sufficient lifestyles" to reduce dependency on complex production chains. We will devote attention to behavioural change by undertaking sensitivity analysis of rationality and social-influence dimensions of behaviour.

The remainder of this article is organized as follows. Section 2 gives a background to the model approach and defines the policy scenarios that will be studied with it. Section 3 presents model simulation results, with section 3.1 detailing results per scenario, section 3.2 examining variability and synergy of outcomes for policy instruments, and section 3.3 comparing scenario outcomes. Section 4 undertakes sensitivity analysis, focused on the time structure of events and the behavioural assumptions. Section 5 concludes.

2. Model background and definition of scenarios

COVID-19 has spread to all countries, making the pandemic a truly global phenomenon. The global focus of the GLO model is consistent with this. The model describes the dynamics of the four energy sources coal, oil/gas, solar and wind resulting from the aggregation of sequential adoption decisions, accounting for three main factors: intrinsic profitability, increasing returns to scale and learning. In this setting, the model calculated the impact of various climate policies, namely a carbon tax and market subsidies and R&D subsidies for renewables (Zeppini and van den Bergh, 2020). Of these policies, we only consider the carbon tax in the present study. To address the long-term impacts of COVID-19, we make the following adaptations in the model, resulting in the GLO-COV model variant: we introduce a period during which society suffers the direct health effects of the pandemic and is subject to lockdown policies to contain the pandemic. In turn, these cause direct economic and indirect economic effects. The timeframe of COVID-19, shown in Figure 1, is set as having an outbreak after 5 years (i.e. in 2020) and lasting for 3 years.

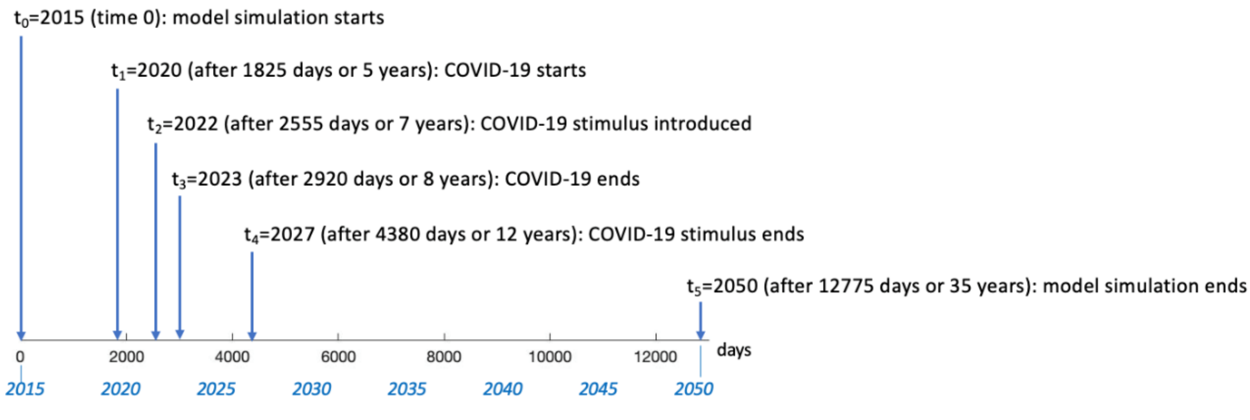


Figure 1. Timeline of events in model simulations (time indicated in both days – the time unit of model simulations – and years, in blue)

Since there is uncertainty about when the pandemic will end – given slow vaccination rates in many developing countries and the emergence and spread of new variants of the virus – we will perform sensitivity analysis of the impact on emissions of the value of the duration of the pandemic and the time of implementation of the stimulus package. As COVID-19 is a classic example of an exogenous shock, we use the calibration results of the GLO model for the prepandemic world in the GLO-COV variant, including the energy supply and shares of energy sources in 2015 (See Zeppini and van den Bergh, 2020). Appendix A provides details about the model structure and variables, appendix B discusses policy settings, and Appendix C the empirical calibration of the parameters. Figure 1 provides a timeline of the events analysed with the GLO-COV model starting with the COVID-19 shock followed by the introduction of the stimulus program, the ending of the severe phase of COVID-19, and subsequently the ending of the stimulus program.

We use the GLO-COV model to study the following six scenarios:

(i) NO-COVID: reference scenario to evaluate the consequence of other scenarios in terms of changes in fossil and renewable energy use as well as CO_2 emissions. Here peak oil is an important element which is assumed to occur after approximately 15 years, around 2030. This scenario is consistent with the basic BAU scenario in Zeppini and van den Bergh (2020), where a full interpretation is offered.

(ii) NO-COVID WITH CARBON TAX: reference scenario to evaluate other scenarios with COVID-19 and carbon taxation. We use a carbon tax equal to 42 $/tCO2 which was assessed in Zeppini and van den Bergh (2020) to be a critical value for continuing versus phasing out coal.

(iii) COVID: this scenario implements an exogenous shock at the beginning of 2020 with a 4% reduction of global energy demand (with respect to the pre-COVID consumption pattern); this shock lasts for the duration of the pandemic (three years), with energy demand growth set to zero for this period. In addition, the shock entails a specific negative effect on oil/gas through an extra cost that limits its attractiveness. This captures the impact of lockdown on transport and travel, which represent oil-intensive sectors of the economy.

(iv) COVID WITH CARBON TAX: this scenario incudes a COVID-19 shock of scenario (iii) and the carbon tax of scenario (ii).

(v) COVID WITH STIMULUS: the planned solution worldwide to recover from, or avert further, economic crises induced by COVID-19, notably lockdown measures. The rational for this scenario is the evidence from many countries where the economic stimulus focuses on encouraging a low-carbon recovery. We model this with a stimulus package consisting of market subsidies for renewable energy (solar and wind) that are operative during five years, starting 2 years after the COVID-19 outbreak.

(vi) COVID WITH STIMULUS & CARBON TAX: this examines what a pre-existing price on high-carbon energy adds to the COVID stimulus package of subsidizing low-carbon energy.

For more details on the policy settings see Appendix B.

3. Simulation results

We simulate energy patterns from 2015 until 2050, generating 100 simulations for each scenario to assess the distribution of outcomes. This allows us to graphically show what are dominant patterns and the range of potential, including less likely, outcomes. In our simulations we show the global energy supply of each energy source in terms of TJoule per day, together with the aggregate measures of average emission intensity and cumulative emissions. Results for the initial period should not be taken as realistic since they are strongly dependent on the initial conditions.

Hence, interpretations should start best around period 1000 (about 3 years later, i.e. starting 2018) when the system has settled in a state that is not directly determined and dominated by these conditions.

3.1 Results for each scenario

(i) NO-COVID

Figure 2 depicts the long-term developments in the absence of COVID-19. This reference scenario serves as a benchmark for judging the policy scenarios – i.e., it should not be confused with a business-as-usual scenario as that would entail various policies of some kind. The pattern shown in the figure reflects the logistic probability distribution of individual choices in combination with increasing returns, which may give rise to dominance of one or a few energy sources in the very long run. In this reference scenario we see that fossil fuels dominate, consistent with reality. One can further note that the supply of coal increases, which makes economic sense as it is still relatively cheap. While in the last decade political support for it has declined, recent months witness renewed support for coal as a source of electricity to compensate for high prices of gas triggered by the Ukraine crisis. Note further that the IEA (2021) states that "Global coal demand in 2021 is set to exceed 2019 levels and approach its 2014 peak". Furthermore, the renewed appeal of coal is testified by recent projects worldwide, such as in the UK, where a new coal mine was approved in 2022 – the first in decades. All in all, this reference scenario meaningfully depicts a hypothetical situation without any climate or stimulus policy.

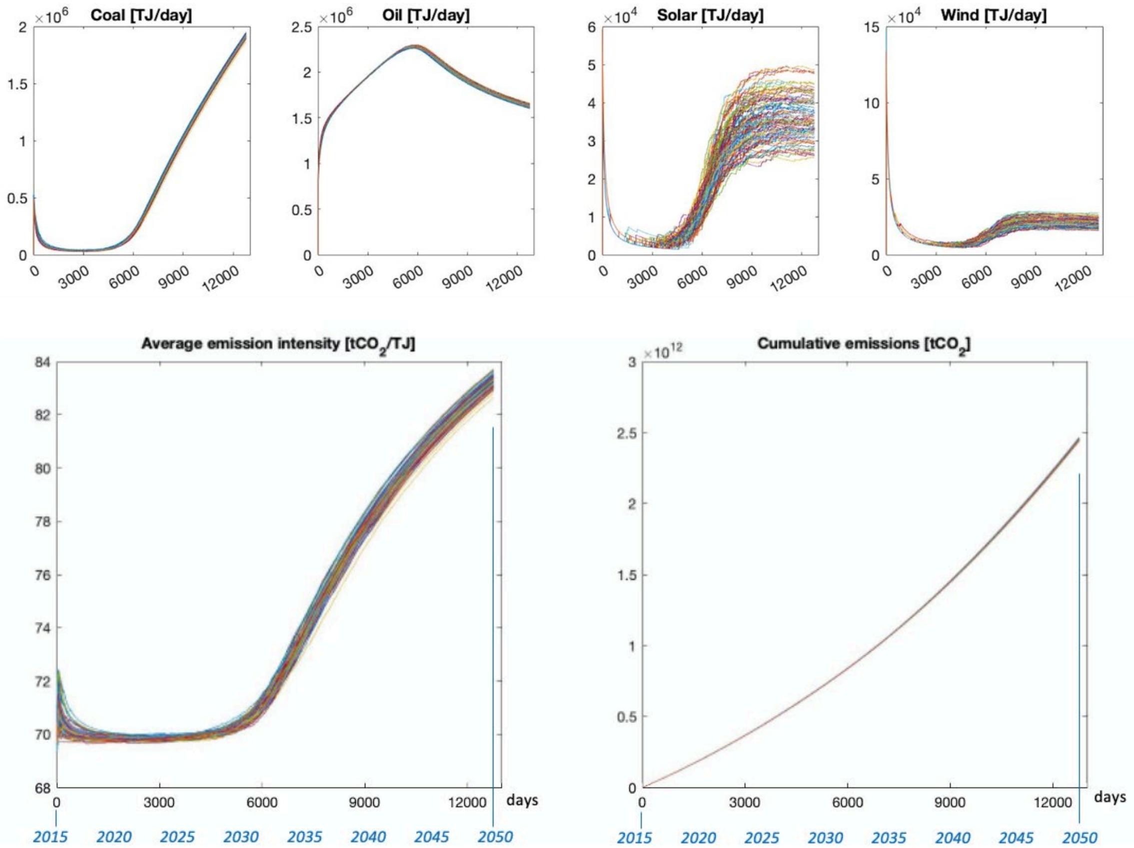


Figure 2. Long-term developments of energy supply (top panels) and CO_2 emissions (bottom panels) under scenario NO-COVID. Each graph shows 100 simulation runs in different colours.

(ii) NO-COVID WITH CARBON TAX

Another scenario of reference for the study of the effects of COVID-19 is the one where a carbon tax is in place. In line with Zeppini and van den Bergh (2019) we use a price of carbon equal to 42$/tCO2. The simulations of energy supply and emissions are shown in Figure 3.

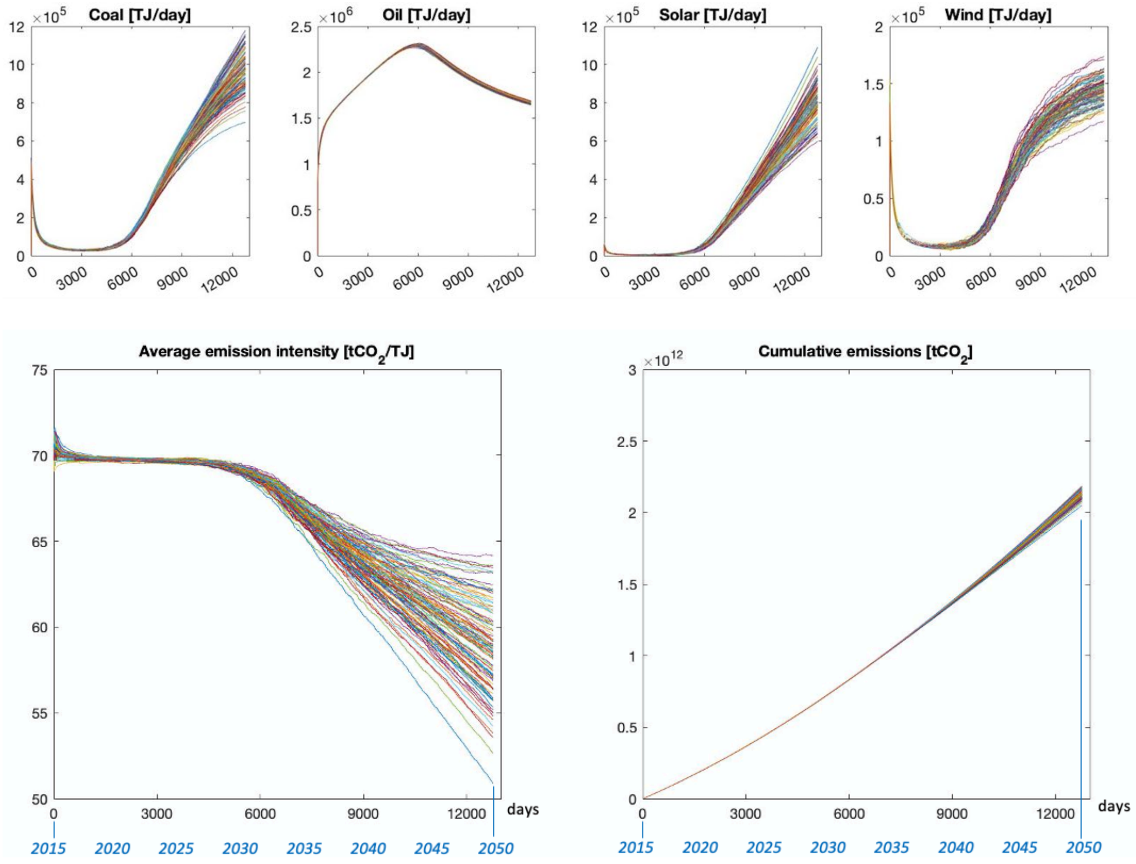
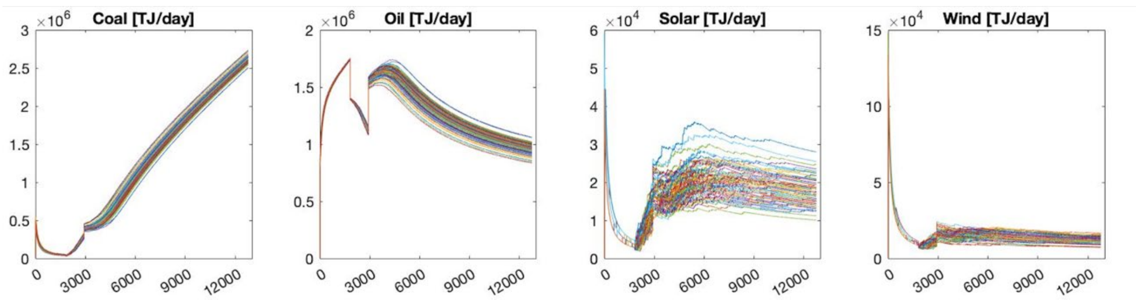


Figure 3. Long-term developments of energy supply (top panels) and CO_2 emissions (bottom panels) under scenario NO-COVID WITH CARBON TAX. Each graph shows 100 simulation runs in different colours.

(iii) COVID

Figure 4 depicts the scenario when COVID-19 strikes, but no economic or climate policy response follows. The impact of COVID consists of a slump in global energy demand (4%) and an additional negative effect (modelled with an added relative cost) on the oil market. These negative shocks come mainly from lockdown introduced to combatting the pandemic, but also from a reduced labour force due to illness.



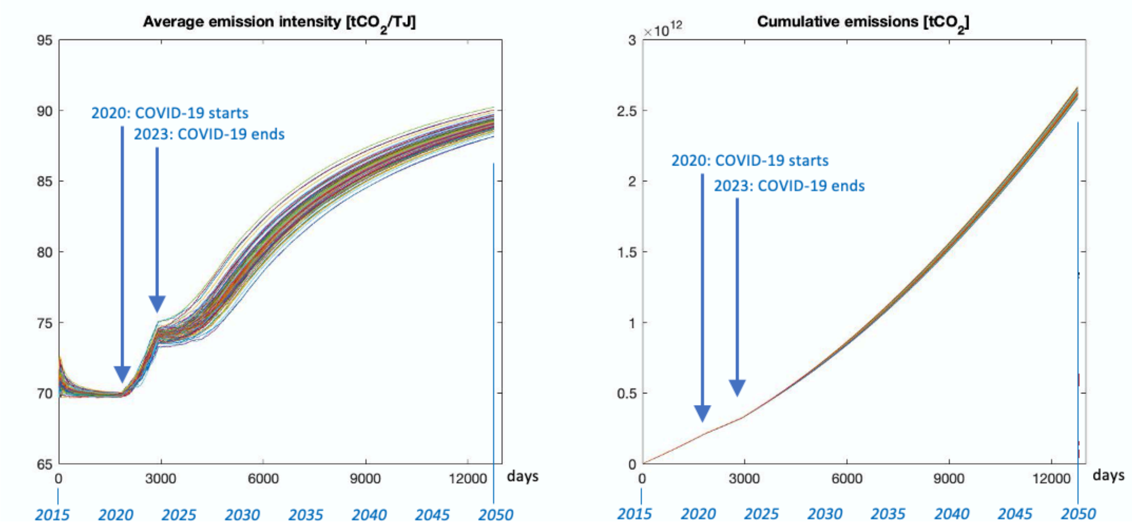
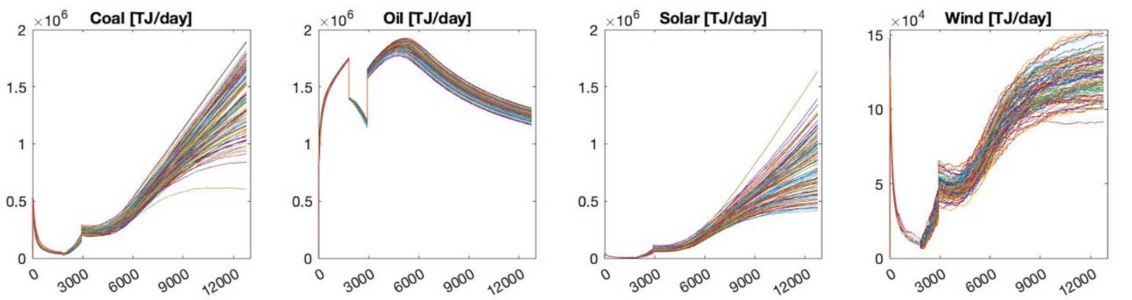


Figure 4. Long-term developments of energy supply (top panels) and CO_2 emissions (bottom panels) under scenario COVID. Each graph shows 100 simulation runs in different colours.

We can appreciate the effect of COVID by comparing outcomes with those under the NO-COVID scenario (Figure 2). The short-term effect of COVID is mostly evident in the energy supply time series of oil/gas, because this is still the dominant energy source in this period of time. After the pandemic ends, we clearly see oil reaching a peak around 2028-2029, that is about five to six years after COVID-19 is assumed to end (2023), and descending rapidly afterwards, to the advantage of coal, mainly. Comparing with the NO-COVID scenario above, the main message here is that the COVID scenario expedites peak oil by about three years. Why? Because the negative impact on oil translates into stronger market externalities for competitor energy sources. Being in a relatively advantageous position, coal is the energy source that gains most from the reduced supply of oil. Solar energy develops marginally, and less than in the NO-COVID scenario. Bear in mind that such extreme results are not found in reality as they are driven by a hypothetical scenario that lacks any serious climate policy and recovery stimulus. It merely serves as a reference for comparing the effects of policies in other scenarios. However, the resurgence of coal is a fact, as recent disruptions in oil supply have induced new projects for the establishment of coal-fired power generation, such as in the UK.

(iv) COVID WITH CARBON TAX

Here we consider the case of COVID-19 arriving in an economy that is already characterised by a carbon tax (with a price level of 42 \$/tCO2). Figure 5 shows the results.



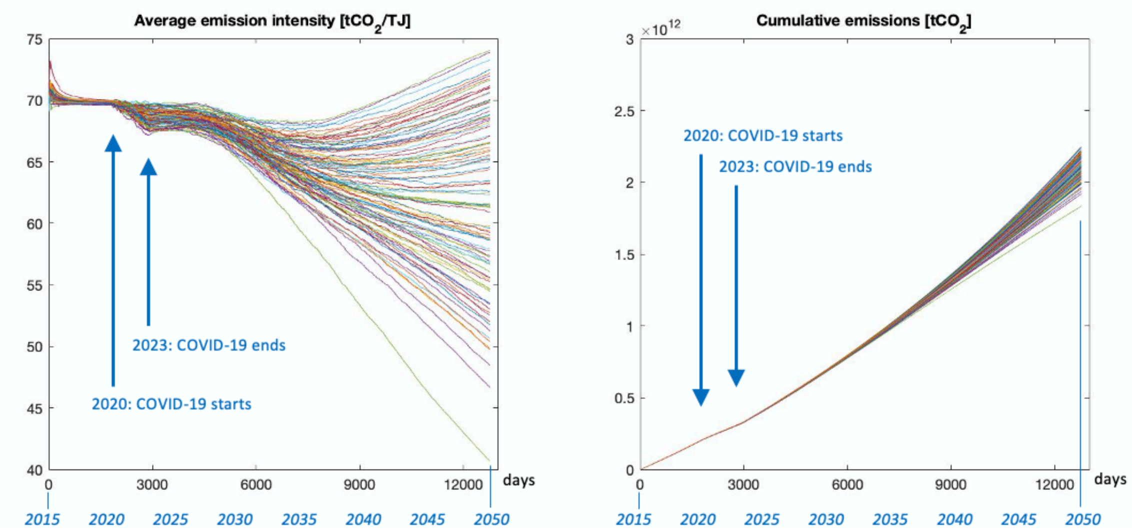


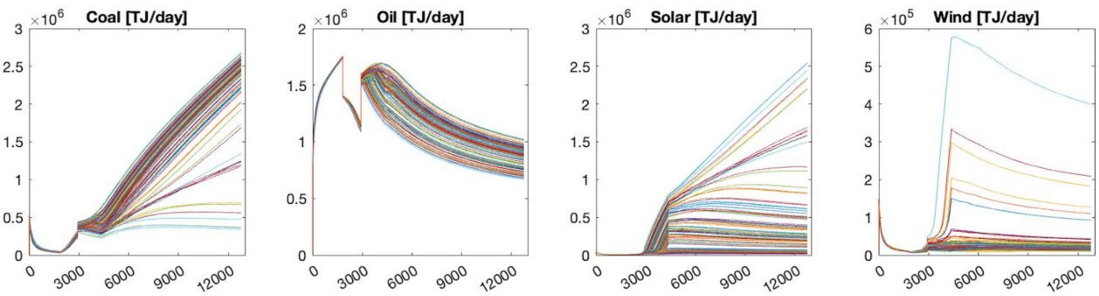
Figure 5. Long-term developments of energy supply (top panels) and CO_2 emissions (bottom panels) under scenario COVID WITH CARBON TAX. Each graph shows 100 simulation runs in different colours.

Apart from the patterns specific to the time window of the pandemic, this outcome is similar to the NO-COVID WITH CARBON TAX. The results show that COVID combined with a carbon tax generates a huge variability of outcomes in terms of energy market shares and emission intensity but less so in cumulative CO_2 emissions. After the peak of oil, solar and coal are the two major competitors in the energy market. When solar wins, we have the lower part of the spectrum of emission intensity, while its upper part is obtained for simulations where coal is the winning energy source.

(v) COVID WITH STIMULUS

Next, we consider how a stimulus package focusing on subsidies for adoption of renewable energy, in response to an economic crisis induced by COVID-19, affects emissions. The basic setting assumes that stimulus starts two years after the onset of COVID-19 and lasts five years (to account for limited budgets of stimulus packages). This time frame is justified by recent developments in developed countries around the world, as despite contractionary monetary policies initiated in 2022, several subsidy schemes are still in place.

The results in Figure 6 indicate there is uncertainty about whether coal dominates completely in the end, or whether solar and especially wind can reach high shares (and emissions stay very low). The chances favour coal, but the stimulus package also allows for outcomes dominated by renewables, notably wind, and low overall emissions. Of course, the latter will involve huge subsidy costs. However, this is consistent with the stimulus packages of both the EU and the USA.



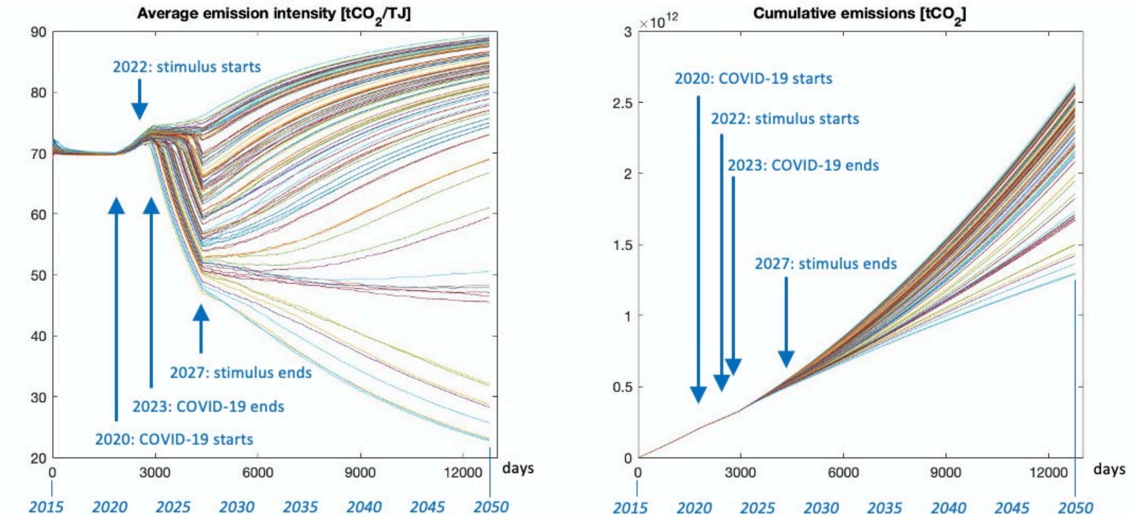


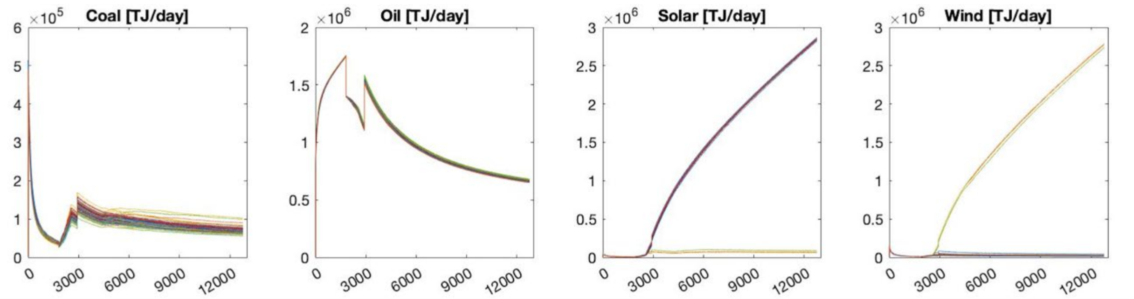
Figure 6. Long-term developments of energy supply (top panels) and CO_2 emissions (bottom panels) under scenario COVID WITH STIMULUS. Each graph shows 100 simulation runs in different colours.

The stimulus package does not deliver its benefits immediately, when introduced in 2022, but one year later, when COVID-19 ends. This results in a transition to solar energy with a relatively high probability, which counters the initial shift to coal. After the stimulus terminates the rate of increase of solar share slows down, but solar remains a large player in the market, which causes emissions to remain lower compared with the NO-COVID scenario.

(vi) COVID WITH STIMULUS & CARBON TAX

Next, we consider how the combination of COVID-19, a stimulus package and carbon tax work out on emissions. We examine a value for the carbon tax of 42 $/t$CO_2$ which we in a previous study assessed to be a critical value for maintaining versus phasing out coal (Zeppini and van den Bergh, 2020). Our intention is to test whether COVID-19 shifts the balance in one or another direction. Note that this critical carbon price is considerably lower than the EU-ETS price during most of 2022 but much higher than carbon prices in most other parts of the world (Finch and van den Bergh, 2022).

As shown in Figure 7, the carbon price resolves much of the uncertainty about the future. Coal is phased out, oil/gas steadily goes down, and solar and/or wind gain over time. The result is that global emissions are much reduced in comparison with the other scenarios.



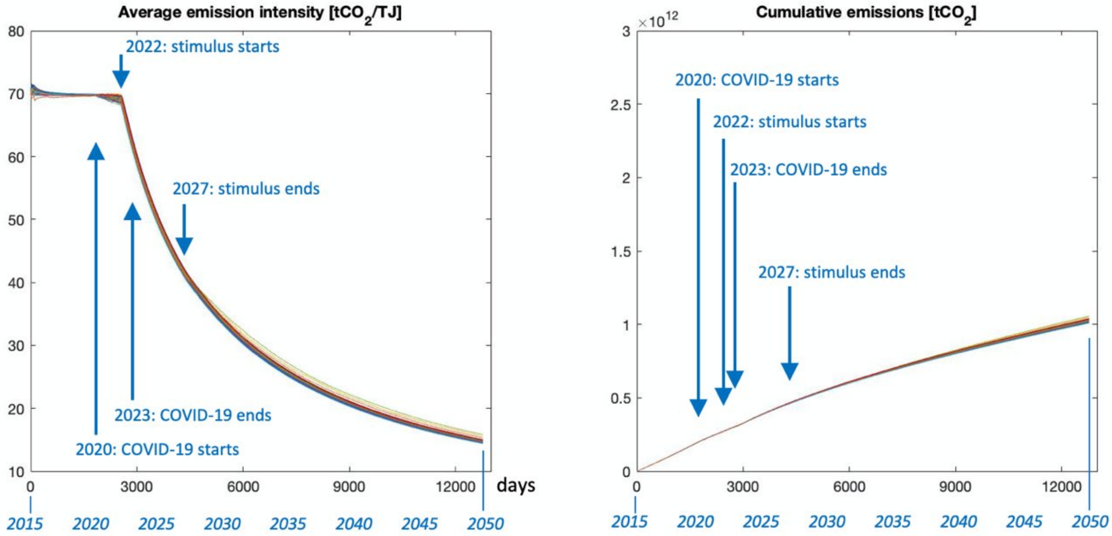


Figure 7. Long-term developments of energy supply (top panels) and CO_2 emissions (bottom panels) under scenario COVID WITH STIMULUS & CARBON TAX. Each graph shows 100 simulation runs in different colours.

3.2 Variability and synergy of outcomes under policy instruments

Figure 8 reports the distribution of final values of simulations (end of 2050) for both the emission intensity and the cumulative emissions. The distribution has been obtained with one hundred equally spaced bins. Bars in the histograms represent the number of times a final value falls within a given bin range, with each histogram comprising one hundred bins. In the case of the emission intensity one bin has a range of 1 ton of CO_2/TJoule, while for the cumulative emissions the range of one bin is $4x10^{10}$ tons of CO_2.

The results show that COVID-19 causes clear emissions increase, with very little uncertainty. With regard to policies responding to COVID-19, when comparing the panels in Figure 8, single instrument increase variability of, and thus uncertainty about, emissions. The carbon tax shows a slightly stronger average emissions reduction effect and shows less variability of outcomes than the stimulus. Instead, the combination of instruments reduces the variability of outcomes considerably, even below that of the COVID scenario without policy.

We further find evidence for positive synergy between stimulus package and carbon pricing. To this end, we compare the panels in Figure 8, to see whether the combination of the instruments reduces final cumulative emissions more or less than the sum of the emission-reduction impacts of single instruments. We find, using average values, that the combination of instruments reduces emissions by approximately 2.6–1=1.6 Tton CO_2, which is considerably higher than the sum of the pure effects of stimulus and tax, i.e. (2.6–2.3) + (2.6–2.1)=0.3+0.5=0.8. In other words, the two instruments show positive synergy to the extent of doubling emissions reduction.

Hence for two reasons, certainty (minimal variability) of outcomes and synergy of policy impacts, the combination of instruments is to be preferred.

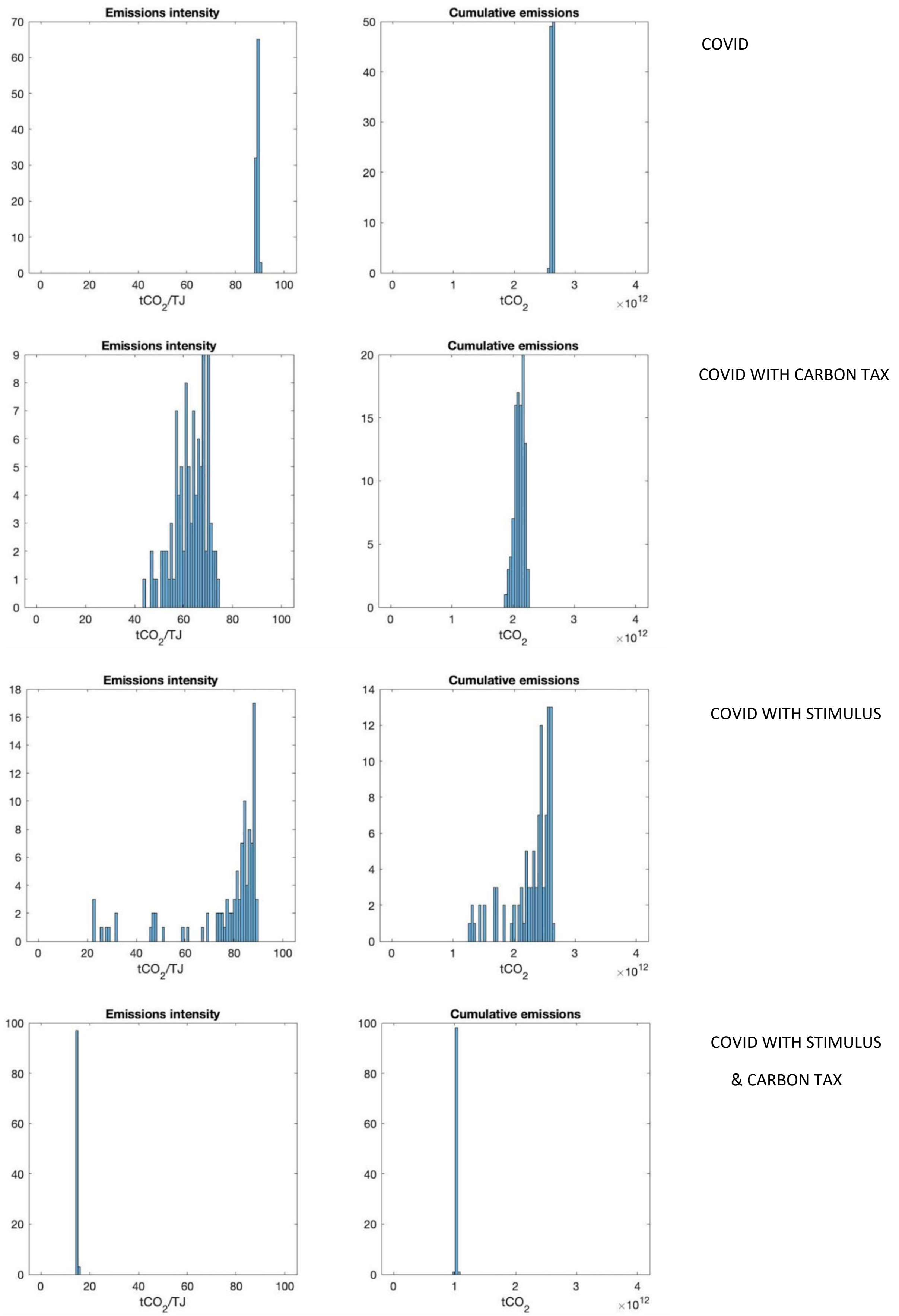


Figure 8. Distribution of emission intensity (left) and cumulative emissions (right) at the end of the simulation period (2050). Each panel row refers to a specific scenario indicated to right.

3.3 Comparing scenarios

Table 1 gives a synopsis of the outcomes. Without countervailing policy, the pandemic increases long-run emissions; with a carbon tax already in place, it leads to lower emissions than both scenarios without COVID-19 but with carbon tax, and COVID-19 without any policy; the pandemic combined with a stimulus package causes cumulative emissions to be below the scenario without COVID-19; finally, combining stimulus and carbon taxation results in the lowest cumulative emissions, producing even a positive synergy effect.

Table 1. Comparison of long-run emissions under the various scenarios

Reference \ Scenario	COVID	COVID WITH CARBON TAX	COVID WITH STIMULUS	COVID WITH STIMULUS & CARBON TAX
NO-COVID	More emissions		Small decline of emissions	
NO-COVID WITH CARBON TAX		Very small decline of emissions		Very large decline of emissions
COVID			Large decline of emissions	
COVID WITH CARBON TAX				Very large decline of emissions

Legend: red (green) means more (less) emissions; darker green indicates stronger emissions reduction.

To better understand the impact of COVID-19 in the different scenarios, we further study the for all scenarios the difference in emission intensity and cumulative emissions with respect to the NO-COVID scenario. In each scenario we evaluate the average emission intensity and cumulative emissions across the 100 simulation runs and construct the time series of the difference between the average emissions in a given scenario and in the NO-COVID scenario. The following results show how much higher or lower emissions are due to the impact of COVID-19, under different policy conditions, and compared to relevant reference scenarios.

(1) Impact of COVID vs NO-COVID

First we compare emissions under COVID with those under the NO-COVID scenario. Figure 9 depicts the results.

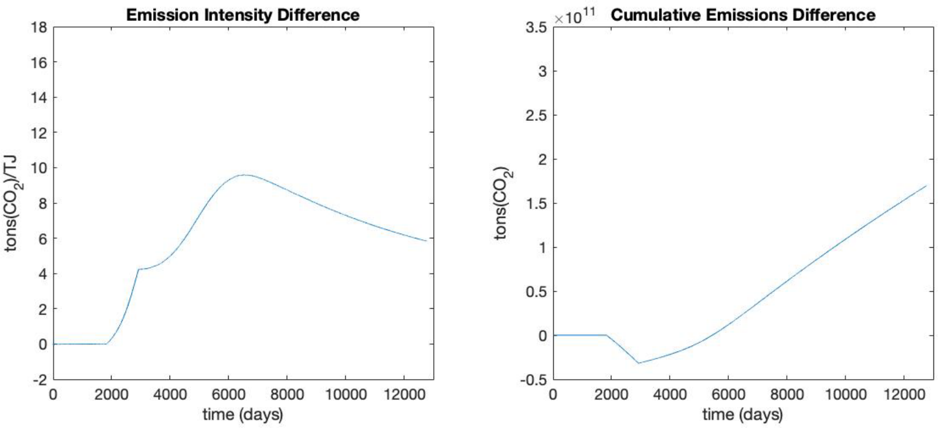


Figure 9. Impacts of COVID versus NO-COVID. Graphs show the difference between averages over 100 simulations runs for the two scenarios.

The simulated patterns of differences clearly show that COVID-19 brings more emissions of CO_2. In terms of cumulative emissions, there is initially a decline during COVID, due to the reduced demand of fossil fuels of a lower economic activity, but an increase in emission intensity, due to the large switch to coal. After COVID ends (in 2023) and lockdowns are relieved, demand resumes, and emissions take off and rise fast, more than they would have done without COVID. Why this? Because COVID-19 advances peak oil, to the advantage of the relatively more polluting Coal. It is interesting to notice how the earlier advent of peak oil induced by COVID-19 translates into a non-monotonic pattern of the difference in the emission intensity. The message is that the COVID scenario induces stronger emissions especially in the early years after it ends, and then its effect vanishes slowly, so that the difference with the NO-COVID scenario becomes less pronounced over the years.

(2) Impact of COVID WITH CARBON TAX versus NO-COVID WITH CARBON TAX

Now we assume that a carbon tax is in place, with a price of carbon equal to 42$/t$CO_2$, and evaluate the difference in average simulated emissions between the scenario with COVID-19 and the scenario without. Figure 10 plots the outcomes.

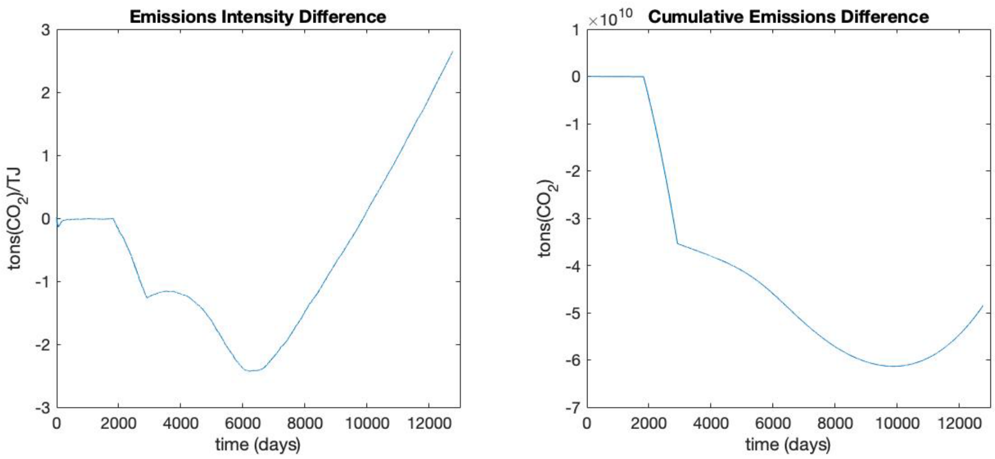


Figure 10. Impacts of COVID WITH CARBON TAX versus NO-COVID WITH CARBON TAX. Graphs show the difference between averages over 100 simulations runs for the two scenarios.

With a carbon tax already in place, the effect of COVID-19 is a drastic reduction of emissions, not only during the pandemic but also afterwards. The emission intensity starts to increase marginally when lockdowns are lifted, only to quickly reverse pattern and decrease again until a minimum is reached around the beginning of 2031. The peak of oil is delayed by COVID-19 to after 2030, which contributes to an increase in emission intensity. This inversion translates to cumulative emission with some delay: cumulative emissions are always lower under COVID than under NO-COVID scenarios (both with carbon tax), but the difference becomes larger (i.e. more negative) until around 2042, and then starts to get smaller (less negative).

It should be noted that this case is difficult to analyse, because the scenario COVID WITH CARBON TAX is characterised by a huge variability of trajectories (see emission intensity in Figure 5), due to the uncertainty about coal or solar becoming the dominant technology. It is remarkable, for instance, that such complicated non-monotonic patterns arise, including an inversion twenty years after COVID-19 ends.

(3) Impact of COVID WITH STIMULUS versus NO-COVID

Here we study the effect of a stimulus package in response to COVID-19. The results are shown in Figure 11.

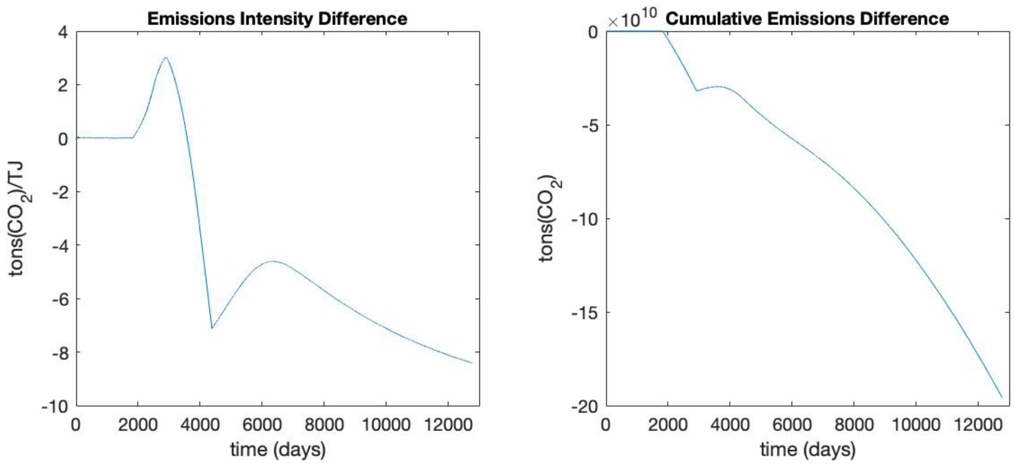


Figure 11, Impact of COVID WITH STIMULUS versus NO-COVID. Graphs show the difference between averages over 100 simulations runs for the two scenarios.

Initially there is an immediate jump of emission intensity, due to the large switch to coal under COVID-19, which is not undone by the stimulus package. This pattern is reversed with a dramatic decline starting in 2023, when COVID-19 ends, and lockdowns are relieved. Two aspect are noteworthy: first, the reversal does not occur when the stimulus is introduced, in 2022, but one year later, when COVID-19 ends; second, without the stimulus the end of COVID-19 only slows down the increase of emission intensity but does not reverse it (Figure 6 above). The downward path of emission intensity continues until the stimulus ends, in 2027. Afterwards, emissions begin to increase again, but only for a limited time span, until after 2032. This is due to the delayed peak of oil, which was also observed to occur without the stimulus package. The result of this pattern of emission intensity translates onto a markedly decreasing pattern of cumulative emissions, with respect to the NO-COVID scenario.

(4) Impact of COVID with versus without stimulus package

In order to appreciate better the role of the stimulus package in emissions reduction, we compare it with COVID-19 without any stimulus. Results are shown in Figure 12.

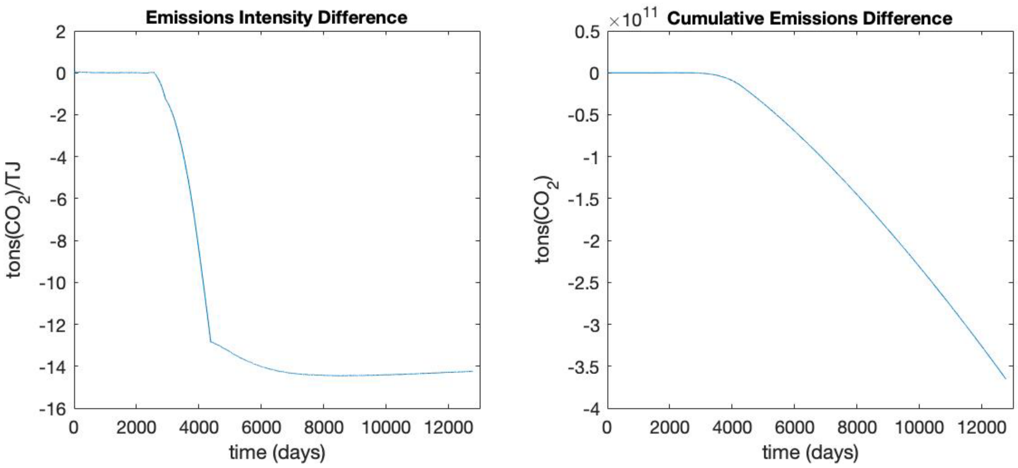


Figure 12. Impact of COVID WITH STIMULUS versus COVID. Graphs show the difference between averages over 100 simulations runs for the two scenarios.

The stimulus packages is found to reduce emissions considerably. The difference is larger than compared with the NO-COVID scenario, due to COVID-19 causing an increase of emissions through the earlier discussed shift to coal.

(5) Impact of COVID WITH STIMULUS & CARBON TAX versus NO-COVID

We repeat the analysis of the role of a stimulus package for COVID-19 by considering the scenario of a carbon tax already in place when the pandemic starts. Figure 13 reports the difference in average emissions between the scenario with COVID-19 and a stimulus package and the scenario without COVID, but with a carbon tax.

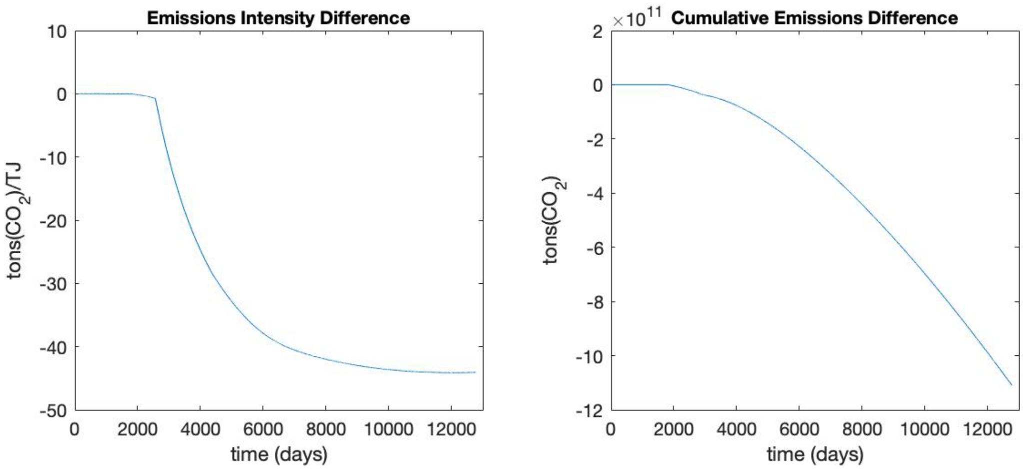


Figure 13. Impact of COVID WITH STIMULUS & CARBON TAX versus NO-COVID. Graphs show the difference between averages over 100 simulations runs for the two scenarios.

The combination of a stimulus package and a carbon tax delivers the strongest reductions of emission intensity and cumulative emissions. While the emission intensity is rather stable initially, it declines sharply once the stimulus package is introduced in 2022.

(6) Impact of COVID with versus without stimulus, in the presence of a carbon tax

Figure 14 presents differences in emissions between scenarios of COVID-19 with and without stimulus, given a pre-existing carbon tax.

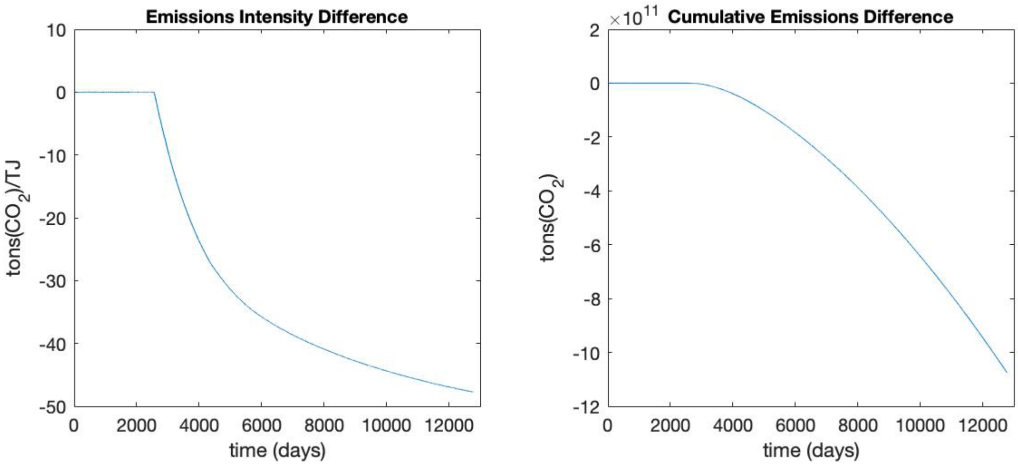


Figure 14. Impact of COVID WITH STIMULUS & CARBON TAX versus COVID WITH CARBON TAX. Graphs show the difference between averages over 100 simulations runs for the two scenarios.

The results are very similar to those in Figure 13. This is because the effect of COVID-19 on emissions is contained by a carbon tax and limited to the time window of duration of the pandemic. As a result, a carbon tax weakens the long-term effect of COVID-19 on emissions.

4. Sensitivity analysis

4.1 Sensitivity to timing of events

We study the sensitivity of our model to different choices regarding the timing of events, namely the time when the financial stimulus is introduced and the time when COVID-19 ends (see Appendix D for more details). To this end, we examine the performance of the scenario COVID WITH STIMULUS under following alternative settings:

(a) baseline: stimulus 2 years after COVID-19 begins, COVID-19 lasts for 3 years (Figure 15a);
(b) stimulus 1 year after COVID-19 begins, COVID-19 lasts for 2 years (Figures 15b);
(c) stimulus 1 year after COVID-19 begins, COVID-19 lasts for 4 years (Figures 15c);
(d) stimulus 3 year after COVID-19 begins, COVID-19 lasts for 4 years (Figure 15d).

Comparing the outcomes for each alternative setting (b-d) with the default setting (a), shows that the baseline findings are robust. The distribution of outcomes remains roughly the same, while the concentration of emission patterns, and hence the average pattern, shift slightly upward.

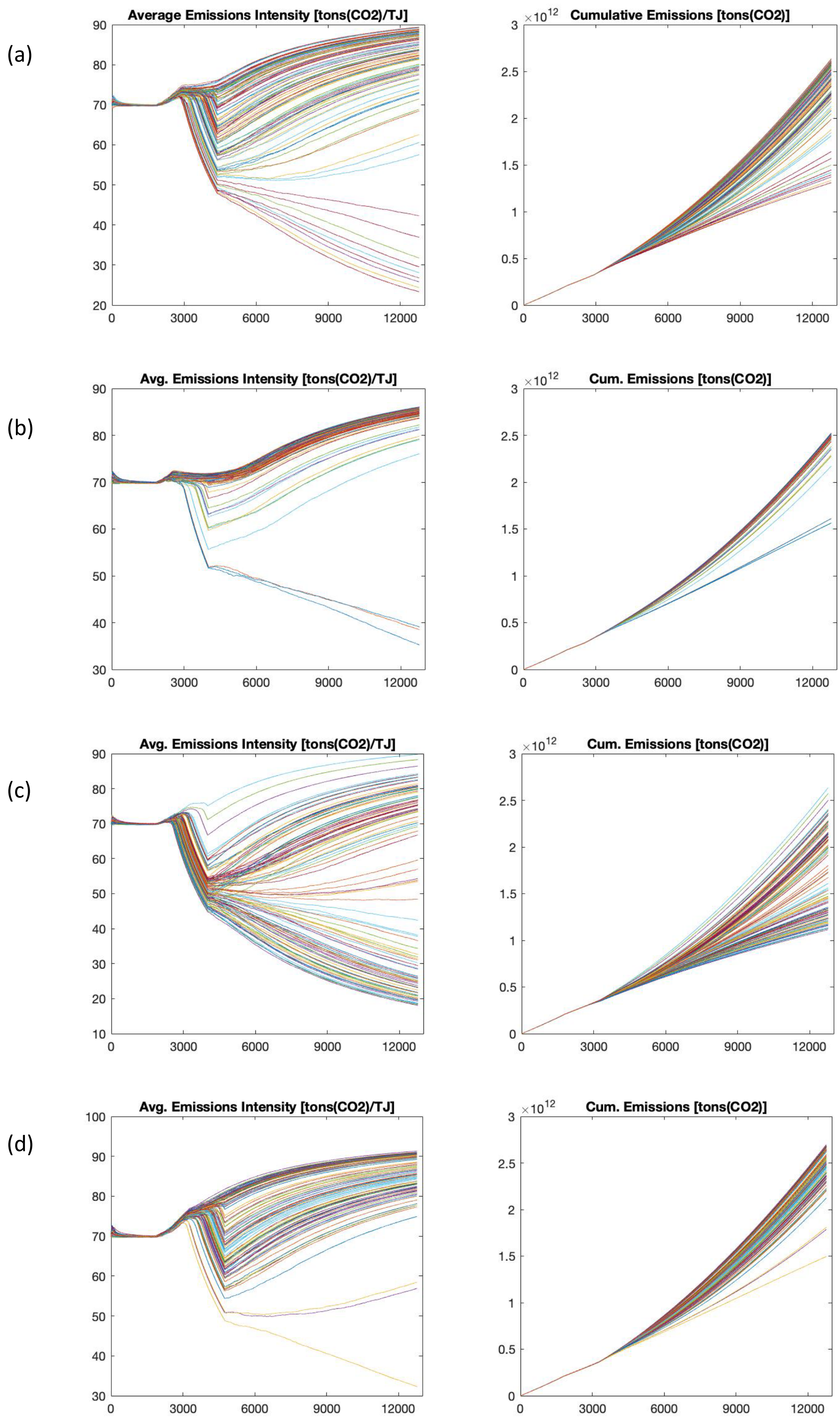


Figure 15. Sensitivity of outcomes of scenario COVID WITH STIMULUS to timing assumptions (meaning of panels (a) to (d) is explained in the text).

4.2 Sensitivity to behavioural assumptions

We also look at what happens if we include behavioural changes in the analysis, notably the degree of rationality as captured by parameter β and the extent of social influence as captured by the positive externality parameter ρ (see Appendix A) Such changes have been speculated about in relation to the pandemic, namely that people become more or less aware of costs and benefits of their choices, resulting in more or less rational behaviour. In addition, it has been suggested that people's habits or social norms change (Botzen et al., 2020; Bouman et al., 2021). Since the direction of these changes is not obvious, we study here what happens when awareness of costs/benefits increases or decreases, and when social influence becomes stronger or weaker. To this end, we examine the performance of the scenario COVID (without countervailing policies) under all possible behavioural-change combinations:

(a) baseline: default settings for behaviour (Figure 16a);
(b) rationality (parameter β) goes up (doubles), social influence (parameter ρ) goes down (halves) (Figure 16b);
(c) rationality goes down (halves), social influence goes down (halves) (Figure 16c);
(d) rationality goes up (doubles), social influence goes up (doubles) (Figure 16d);
(e) rationality goes down (halves), social influence goes up (doubles) (Figure 16e).

The results in the figure show that, compared to the baseline in (a), final cumulative emissions are higher under (b), lower under (c), and about the same under (d) and (e). This means that a higher (lower) degree of rationality translates in slightly higher (lower) emissions, while the results are robust with respect to the intensity of social influence. In addition, it can be noted that emission intensity is stable during a longer time period for assumptions (d) and (e), while under (a)-(c) sharper changes are observed. This suggests that stronger social influence contributes to more stability and smoother change.

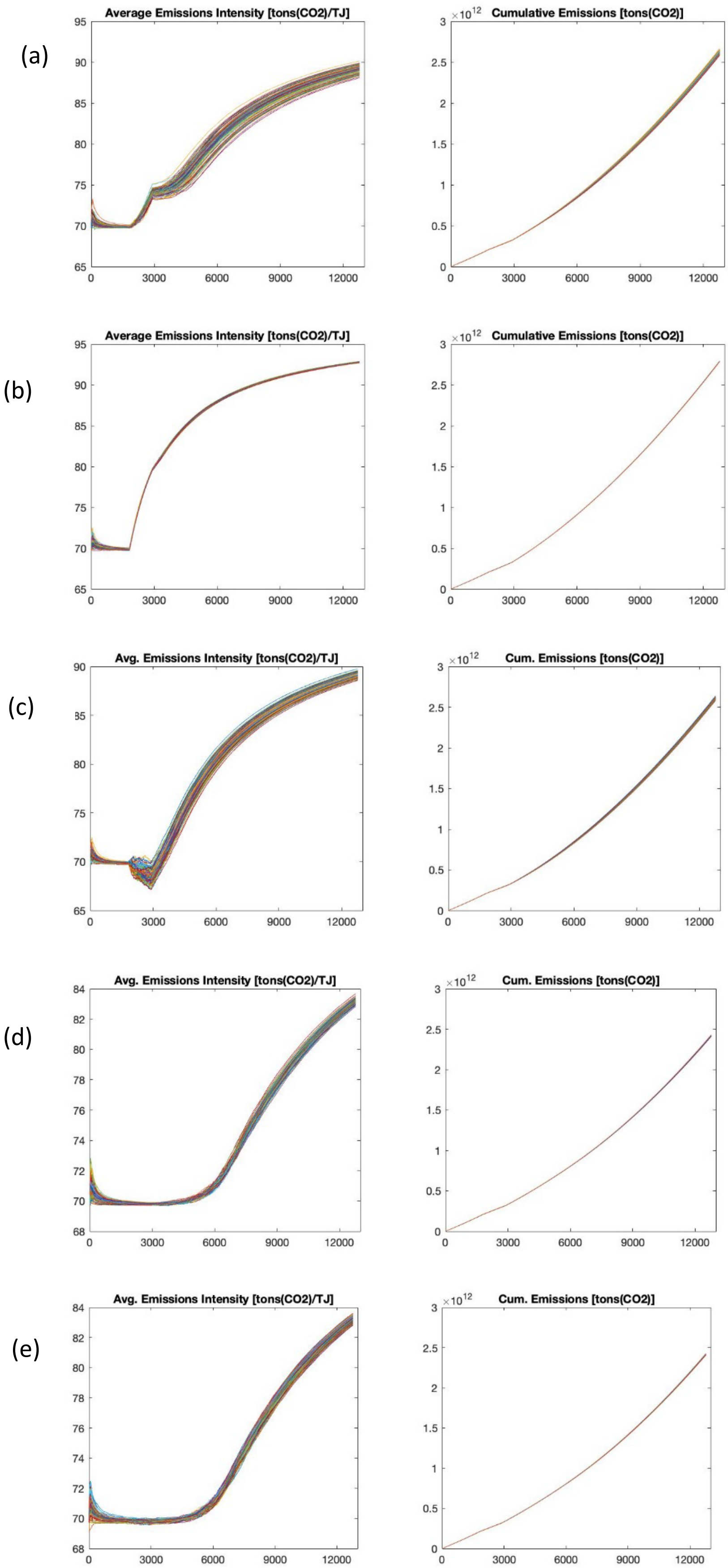


Figure 16. Sensitivity of outcomes of scenario COVID to behavioural assumptions (meaning of panels (a) to (e) is explained in the text).

5. Conclusion and policy implications

While several studies have analysed the immediate effects of COVID-19, we have used GLO-COV, a variant of the GLO model, to study the long-term impact of the pandemic on global fossil-fuel and renewable energy use, the resulting carbon-intensity of the economy, and the pattern of CO_2 emissions. The main findings of our study can be summarized as follows:

1. COVID-19 without countervailing policy increases long-run emissions compared to the absence of the pandemic. The reason is that it stimulates a shift to coal as a dominant energy source, since oil is losing market share and renewables are still too small to compete with established sources.
2. With a carbon tax already in place before the onset of the pandemic, outcomes are different. In this case, COVID-19 leads to lower emissions than absence of the pandemic. The carbon tax also assures that final cumulative emissions are lower than with COVID-19 without policy.
3. If the pandemic leads to the implementation of an economic stimulus package, this reverses the finding under point 1, namely cumulative emissions fall over time versus COVID-19 without policy. In addition, emission come out even lower than in the absence of the pandemic.
4. Policies on their own increase variability of, and thus uncertainty about, emission patterns, whereas their combination reduces variability, even below that of the scenario with COVID-19 in the absence of policy.
5. If policy combines stimulus and carbon taxation, then emissions reach the lowest level of all scenarios. We even find a strong positive synergistic effect, that is, the sum of the separate policy effects on emissions reduction is smaller than their joint effect (van den Bergh et al., 2021). Hence, it is advisable to use both instruments in concert.

Although our model was carefully calibrated on empirical data, it is evident that – like any model – it cannot capture all relevant factors determining energy consumption and CO_2 emissions. For example, the recent EU-ETS carbon price were unforeseen by many commentators. On the other hand, our sensitivity analyses of timing of events and behavioural assumptions indicates that the results are robust. Still, we see opportunities to improve and extend the GLO-COV model in the future. One direction of research is to spatially disaggregate the model through identifying global regions with distinct features in terms of energy, COVID-19 or climate policy. Another option would be to endogenize energy prices through inclusions of political factors or a variable carbon market price.

Appendices

A. The GLO-COV model: extending the GLO model with COVID-19 impacts

GLO-COV extends the GLO model of Zeppini and van den Bergh (2020). This model describes the competition of four different energy sources in a global market, namely coal, gas/oil, solar and wind. The competition dynamics translates into time patterns of carbon intensity of the economy and CO_2 emissions. In particular, the model simulates a distribution of transitory patterns before an equilibrium state is attained, which allows identifying short-term, medium-term, and long-term effects of policy interventions.

The GLO approach represents a behavioural as well as evolutionary approach, since it models the sequential decision-making process of energy adopters within a large population. Technologies for power generation are available to agents, including producers – notably of electricity – and consumers, especially in their role of users of transport fuels. Agents make decisions sequentially, one in each time period, according to a probability distribution of choices options. This is captured formally by the following set of equations:

The market shares of energy sources are described by a vector x_t with components $x_{a,t}$ that represent the share of energy source a; the shares vector is updated at each time step t according to the following difference equation:

$$\mathbf{x}_{t+1} = \mathbf{x}_t + \frac{1}{w + t}[\alpha(\mathbf{x_t}) - \mathbf{x_t}],$$

Here w is a parameter that allows to calibrate initial conditions; α_t is a vector that counts adoption events for each energy course, according to the following binomial random variable:

$$\alpha_{a,t}(\mathbf{x}_t) = \begin{cases} 1 & \text{with probability} \quad q_a(\mathbf{x}_t) \\ 0 & \text{with probability} \quad 1 - q_a(\mathbf{x}_t), \end{cases}$$

Here the probability q_a follows a logistic distribution:

$$q_a(\mathbf{x}_t) = \frac{e^{\beta u_a(x_{a,1},\ldots,x_{a,t})}}{\sum_{b\in A} e^{\beta u_b(x_{b,1},\ldots,x_{b,t})}}.$$

The attractiveness u_a of each energy source a, shapes dynamically the probability distribution, as it is a function of the market shares of energy sources x_t. In this model, at a given time t market shares increase or decrease according to the binomial random variable α, which is endogenously driven by market shares of the previous time period t.

The next set of equations describe the profitability levels u_a that drive agents' decisions. These include three main factors: intrinsic profitability, increasing returns to scale and learning (c stands for *coal*, o for *oil/gas*, s for *solar* and w for *wind*):

$$u_c(x_{c,t}) = u_{c,0} + \rho(1 + \sigma_c^M)x_{c,t} - \nu\tau e_c,$$

$$u_o(x_{o,t}) = u_{o,0} + \rho(1 + \sigma_o^M)x_{o,t} - \nu\tau e_o - pX_{o,t},$$

$$u_s(x_{s,t}) = u_{s,0} + \rho(1 + \sigma_s^M)x_{s,t} - \frac{(X_{s,t})^{-L_s}}{(1 + \sigma_s^R)},$$

$$u_w(x_{w,t}) = u_{w,0} + \rho(1 + \sigma_w^M)x_{w,t} - \frac{(X_{w,t})^{-L_w}}{(1 + \sigma_w^R)}.$$

The first two terms in each equation describe the intrinsic profitability level and a positive spillover due to increasing returns to scale, respectively. The first two equations, for fossil fuels, include a carbon tax τ which adds an extra cost that is proportional to the CO_2 emission intensity e; specifically for oil we have a peak-effect describing scarcity due to exhaustion. Finally, renewables enjoy market subsidies through an enhanced positive externality described by the parameter σ_a^M, and R&D subsidies fostering their learning curve through the rate parameter σ_a^R. Both the peak-oil and learning curve terms make use of the variable X_a which denotes the cumulative use over time of energy source a. The presence of positive externalities due to increasing returns to adoption, scale economies and infrastructure complementarities is an essential feature of the model which allows to explain positive feedback mechanisms in technology competition which are widely recognized to be relevant for explaining their long-term patterns.

Parameter β controls the shape of the logistic distribution of choices, and since this depends on profitability levels, β is essentially a measure of the rationality of the decision process. As for ρ, this describes the intensity of the positive externality due to increasing returns to scale of technological investments and infrastructures. This parameter can also be interpreted as another behavioural dimension, namely the social influence on agents' behaviour. For a more detailed description of the model, we refer to Zeppini and van den Bergh (2020).

B. Policy analysis

The basic climate policies that we investigate with the GLO-COV extension are already built into the GLO model. These comprise a stimulus policy to compensate the negative economic effects of COVID-19. To achieve beneficial effects in terms of climate this takes the form of market subsidies aimed at stimulating the adoption of renewable energy, as implemented already by the EU stimulus response to COVID-19. These subsidies are modelled to start 2 years after the COVID-19 outbreak and to last for five years. They are equally divided between solar and wind technologies. Parameter σ capturing the subsidy effect is set at value 15. In addition, we model a climate policy focused on a carbon tax. Its value is set at 42 $/t$CO_2$, which was assessed to be a threshold value that divides regimes of continuation versus phasing out of coal (see Zeppini and van den Bergh, 2020).

C. Empirical calibration

The GLO model was empirically calibrated on historical energy demand, economic growth and emission intensity. For details see Zeppini and van den Bergh (2020, Section 3). This calibrated version forms the basis for our GLO-COV assessment of the impact of COVID-19, which occurred after the calibration period. In line with this, we start the simulation in 2015. Upon this we superimpose a timeframe structure describing the unfolding of COVID-19: an initial time set at 5 years (2020) and a final time 3 years later (2023). We assume that the COVID-19 shock upon the economy, through health and lock-down consequences, reduces global energy demand with 4%, and that no demand growth occurs during the pandemic period (2020-2023). In addition, we account for relatively intense COVID-19 effect on oil/gas, reflecting limits on transport and travel, through adding a negative shock in the associated profitability function. These assumptions are motivated in more detail in the next section.

The choices above are motivated by a number of empirical observations. The pandemic has had a noticeable impact on global economic growth, with estimates suggesting it could reduce global economic growth by 2.0% per month and global trade by 13-32% (Jackson et al., 2020). To assess the impact of COVID-19 on global fossil fuel consumption, Smith et al. (2021) employ a global vector autoregressive (GVAR) model combining cross-sectional and temporal patterns of countries. They apply this to 32 countries that jointly cause 81% of global CO2 emissions from fossil fuel use, for the time period 1984Q1-2019Q4. The estimated model is used to predict coal, natural gas and oil consumption for advanced and emerging economies, conditional on GDP forecasts by IMF and three scenarios: (a) no outbreak; (b) one virus spread in 2020Q1-Q2; (c) two waves of virus spread in 2020Q1-Q2 and 2021Q1-Q2. The results suggest that fossil fuel consumption and CO2 emissions return to pre-crisis levels, and even exceed them, within the two-year horizon – despite large reductions of output in the first quarter following the outbreak.

An important user of oil, aviation, has seen a big drop due to the COVID-19 crisis. According to the international trade association IATA demand in May and June 2020 was more than 80% and in 2021 more than 60% lower than in equivalent months in 2019, the year before the pandemic broke out. To arrive at a more complete perspective, one has to know – next to allocation among fossil fuels like oil, gas and coal – how renewable energy sources like solar PV and wind performed under COVID-19 conditions. A study by Wan et al. (2021) analyses investment during COVID-19 in clean energy versus fossil fuel firms. Daily stock returns were obtained from the China Stock Market & Accounting Research (CSMAR) database for 201 firms, covering 91 clean energy and 110 fossil fuel firms. The period covered is 25 November 2019 to 16 March 2020, with 20 January 2020 as the event date for the Chinese and global COVID-19 pandemic, which results in a symmetrical window of eight weeks before and after the event date. To test for robustness, the ending date was extended by sixteen weeks to 6 July 2020. The results indicate that COVID-19 negatively affected clean energy and fossil fuel firms, but that the negative impact was more significant for the latter.

To calibrate our model, we use the most recent data from the IEA (2021) which indicate that global energy demand in 2020 fell by 4% and, global oil demand is still low due to the consequences of the COVID-19 pandemic, and is unlikely to catch up with its pre-COVID trajectory.[4] In 2020 oil demand was 8.7 mb/d below the level of 97.7 in 2019 (8.9% lower), and it is not expected to return to that level before 2023. IEA expects oil demand in 2021 to rebound by 6% which means it remains 3% (3.1 mb/d) below 2019 levels. By 2026 global oil consumption is projected to reach 104.1 mb/d, 4.4% higher than 2019. Oil demand in 2025 is expected to be 2.5 mb/d lower than forecasted a year ago in the IEA's Oil 2020 report (so 2.4% lower than the pre-COVID expectations).

	2019	2020	2021	2022	2023	2024	2025	2026
Oil demand (mb/d)	99.7	91.0	96.5	99.4	101.2	102.3	103.2	104.1

Figure A1 shows that oil is mostly affected at a global scale by COVID-19, related to effects on commuting, holidays, and transport more generally. This motivates our adaptation of the profitability equation for oil/gas in the GLO model.

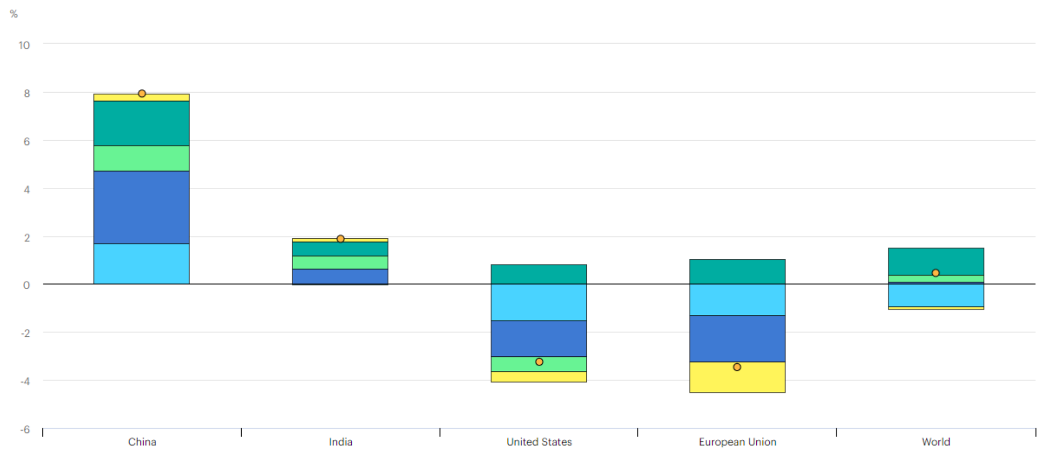


Figure A1. Change of primary energy demand by region and by fuel in 2021 relative to 2019
Source: IEA (2021).

[4] IEA (2021) says "Building on Q1 data, projections for 2021 indicate that as Covid restrictions are lifted and economies recover, energy demand is expected to rebound by 4.6%, pushing global energy use in 2021 0.5% above pre-Covid-19 levels. The outlook for 2021 is, however, subject to major uncertainty. It depends on vaccine rollouts, the extent to which the Covid-19-induced lockdowns scarred economies, and the size and effectiveness of stimulus packages."

D. Sensitivity analysis

We conduct a sensitivity analysis with the GLO-COV model to evaluate the robustness of scenario outcomes regarding the default assumptions. This sensitivity analysis encompasses two dimensions: the time structure of COVID-19 events, and the behavioural parameters of the decision-making process. With respect to the time structure of events, we evaluate the transitory dynamics of CO_2 emissions for alternative timing settings, namely: the introduction of the stimulus package after 1, 2 (default) and 3 years since the outset of the pandemic; and the duration of the pandemic, set to last 2, 3 (default) and 4 years. As for the behavioural parameters, we have assessed the effects of halving or doubling their default value: i.e. the rationality parameter β takes values 2, 4 (default) and 8, while the positive externality parameter ρ takes values 1, 2 (default) and 4.

Statements and Declarations

Compliance with Ethical Standards
Not applicable

Competing interests
Authors have no competing interests to declare that are relevant to the content of this article.

Authors' contributions
Jeroen van den Bergh and Paolo Zeppini wrote the manuscript, Paolo Zeppini implemented the simulation model, Jeroen van den Bergh calibrated the model. Jeroen van den Bergh and Paolo Zeppini reviewed the manuscript.

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Availability of data and materials
The simulation model is described in Appendix C, where references are given regarding the source of calibration numerical values. Simulated data are available upon request from authors.

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